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Transmission System

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Comparative Analysis of Power Frequency Electric Field and Power Frequency Magnetic Field Tests under AC Transmission Line

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Abstract

In order to improve the testing technology of electromagnetic environment and ensure the accuracy of test data, 23 companies carry out the comparison of power frequency electric field and power frequency magnetic field tests at UHV AC test base. After the result data is obtained and Grubbs criterion is used to reject the abnormal values, standard deviation and Z value are obtained after the average value is got. Through data statistics, the main factors affecting the results of power frequency electric field and power frequency magnetic field tests are analyzed from three aspects of test operation, measuring instrument and test environment. It is hoped that it can provide technical guidance for personnel engaged in electromagnetic environment detection.

Key words: UHV, power frequency electric field, power frequency magnetic field, comparison

1. Introduction

With social progress and rapid power grid development, the government and the public have higher and higher requirements for the environmental protection. In recent years, the environmental impact on the power grid construction and operation has gradually become the focus of attention of the people, and many regions have had the dispute due to the worry about the electromagnetic environment health effect of power transmission and transformation projects. As the subject of UHV power grid construction, State Grid Corporation of China expands the power grid planning and construction. Meanwhile, on one hand, in view of the possible environmental impact issues during the process of engineering operation, it publicizes the popular science of power grid positively and vigorously, and facilitates the public to understand the environmental impact of power grid correctly, to eliminate the unnecessary psychological burden. On the other hand, it sets about building "three-level" environmental monitoring network workstation [1], promotes the capability building of company laboratory at all levels, and ensures that the laboratory detection personnel, instruments and detection methods meet the requirements of relevant standards, laws and regulations, so as to provide the powerful technical support in the case of electromagnetic environment complaint and dispute resolution.

To promote the test detection capability of "three-level" environmental monitoring network workstation, entrusted by State Grid Corporation of China, China Electric Power Research Institute takes the lead in organizing 22 companies inside and outside the power grid system to carry out the comparison of power frequency electric field and power frequency magnetic field tests below the single circuit at UHV AC test base, analyze the reason for dissatisfactory results through test data statistics, and summarize the main factors influencing the results. This comparison test effectively propels the technical exchange and resource sharing between monitoring stations at all levels, provides the technical guarantee for power transmission and transformation project construction and environmental dispute resolution, and also provides the data support for green grid construction.

2. Comparison Scheme

According to the requirements of ISO/IEC 17043:2010 (CNAS-CL03:2010), to ensure the uniformity and stability of power frequency electric field and power frequency magnetic field sources during the period of comparison measurement and ensure the data comparability of all comparison participation companies, this comparison is conducted below the single circuit at UHV AC test base. The test line section has stable voltage and flat terrain around, without interference of trees and other communication lines as well we broadcasting lines, as shown in Fig.2-1.

Fig.2-1 Comparison test site

2.1 Comparison basis

The organization company is recommended to use DL/T 988-2005 *Methods of Measurement of Power Frequency Electric Field and Magnetic Field from HV AC Overhead Transmission Line and Substation*. The probe frame should be set at the height of 1.5 m above the ground. During the test of power frequency electric field, the distance between the measurer and instrument probe should not be less than 2.5 m, and the distance between the instrument probe and fixed object should not be less than 1 m. During the test of power frequency magnetic field, based on the different instruments used, the probe can be supported by a small dielectric handle or handheld by the measurer, and can also be consistent with the measurement method of power frequency electric field [2].

To avoid current leakage from the bracket of measuring instrument, the measurement environment humidity should be below 80%.

2.2 Determination of standard value (consensus value)

The electric field and magnetic field can not be seen or even touched, but the law between theoretical calculation and actual measurement is consistent [3]. Fig.2-1 shows the side wire to earth of 25 m to 30 m, and the electric field distribution is calculated below the single circuit at UHV test base at intervals of 0.5 m. From the Figure, it can be seen that the maximum value of power frequency electric field is between 3 m and 5 m outside the side wire to earth projection.

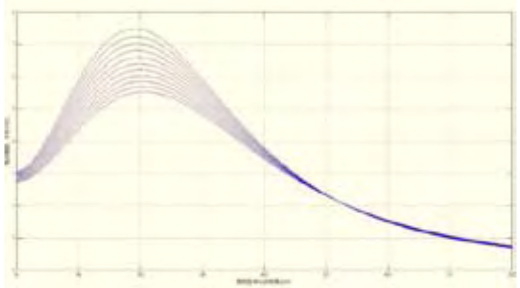

Fig.2-2 Theoretical calculation of electric field at different heights of wire

The measurement of power frequency electric field is influenced by the environment temperature and humidity greatly and the existing condition is difficult to provide a standard field outdoors. The organizer rejects the site test result through Grubbs criterion in reference to theoretical calculation data basis in Fig.2-2, and then regards the average value obtained as the standard value (consensus value) of the comparison.

The rejection process of Grubbs criterion is [4] to firstly obtain the average value of measurement results, as follows:

$$\bar{x} = \frac{\sum_{k=1}^{n} x_k}{n} \tag{2-1}$$

The residual error v_k and experimental standard deviation $s(x_k)$ corresponding to the measurement results are respectively

$$v_k = x_k - \bar{x} \tag{2-2}$$

$$s(x_k) = \sqrt{\frac{\sum_{k=1}^{n} (x_k - \bar{x})^2}{n-1}} \tag{2-3}$$

Assume v_i as the maximum absolute value among all residual errors, and meet

$$|v_i| \rangle G(\alpha, n) \cdot s(\mathrm{x}_k) \tag{2-4}$$

Then, this value is the outlier and should be rejected. In the formula, $G(\alpha, n)$ is the Grubbs critical value relevant to significance level α and number of measurements n. After rejecting the outlier, calculate the average value of the rest, i.e. standard value (consensus value). Without the outlier, take the average value directly as the standard value (consensus value).

The single circuit at UHV AC test base has no load, and the magnetic field measured below the circuit is the background value. Grubbs criterion is still adopted during determination of magnetic field standard value (consensus value) for rejection before calculation.

2.3 Evaluation method

The comparison data is analyzed with the difference value D, percentage relative difference D%, and z value method. For the statistical result obtained through difference value D and percentage relative difference D%, the organizer recommends the maximum control range of percentage relative difference D% to be ±10% in this report. The difference value D and percentage relative difference D% within control range are satisfactory results, and those beyond the control range are dissatisfactory results.

(1) Difference value D

$$D=x-X \tag{2-5}$$

In Formula (2-5), x is participant result, and X is designated value.

(2) Percentage relative difference D%

$$D\%=100\%*(x-X)/X \tag{2-6}$$

In Formula (2-6), x is participant result, and X is standard value (consensus value).

(3) z value

For the detection result of the company participating in comparison, calculate the Z value by the following formula:

$$z=(x-X)/s(x_k) \tag{2-7}$$

The statistical result obtained by z value is evaluated as satisfactory result in the case of $|z| \le 2$, problematic result and alarm signal in the case of $2<|z|<3$, and dissatisfactory result (outlier) in the case of $|z| \ge 3$.

3. Comparison Test Organization

3.1 Comparison companies and instruments

There are 23 companies participating in comparison, with the detection capability of power frequency electric field and power frequency magnetic field. To protect the data information of comparison company, 23 companies are numbered by 01~22. Each company carries the power frequency field strength meter voluntarily, enables that the field strength meter is within the validity period of calibration / detection and can be used, and provides the calibration / detection report for reference in the case of doubtful site measurement data.

3.2 Comparison implementation

The comparison measuring point is selected in the side wire to earth of 28.8 m, and 5 m outside the projection. When the voltage is stabilized at 1,050 kV, the theoretical calculation value [5] of electric field in measuring point is 5.73 kV/m.

All participation companies conduct measurements in the specified point successively in the sequence arranged. After the instrument reading is stable during measurement, a resultant quantity is read every 5 seconds, and two significant digits after decimal point are recorded. Each participation company records 10 numbers and then obtains the average value, as the ultimate measurement value of this comparison activity. During reading, the electric field unit is required to be kV/m, and the magnetic field unit is required to be nT.

The environment temperature is 28°C and the humidity is 67%~73% on the comparison site.

4. Comparison Test Result Statistics and Analysis

4.1 Result statistics

After the abnormity judgment of all test data by Grubbs criterion, the statistical results are shown in Table 4-1and Table 4-2.

Table 4-1 Comparison result of power frequency electric field

Laboratory code	Measurement result	Standard value	Difference value D	Percentage relative difference D%	∣Z∣ value	Result evaluation
01	6.00	5.88	0.12	2.04%	0.51	Satisfactory
02	6.18	5.88	0.30	5.10%	1.28	Satisfactory
03	5.51	5.88	-0.37	-6.29%	1.58	Satisfactory
04	5.78	5.88	-0.10	-1.70%	0.43	Satisfactory
05	5.71	5.88	-0.17	-2.89%	0.73	Satisfactory
06	5.87	5.88	-0.01	-0.17%	0.04	Satisfactory
07	5.80	5.88	-0.08	-1.36%	0.34	Satisfactory
08	5.73	5.88	-0.15	-2.55%	0.64	Satisfactory
09	6.19	5.88	0.31	5.27%	1.32	Satisfactory
10	5.72	5.88	-0.16	-2.72%	0.68	Satisfactory
11	5.85	5.88	-0.03	-0.51%	0.13	Satisfactory
12	5.61	5.88	-0.27	-4.59%	1.15	Satisfactory
13	5.98	5.88	0.10	1.70%	0.43	Satisfactory
14	6.19	5.88	0.31	5.27%	1.32	Satisfactory
15	5.92	5.88	0.04	0.68%	0.17	Satisfactory
16	6.02	5.88	0.14	2.38%	0.60	Satisfactory
17	5.73	5.88	-0.15	-2.55%	0.64	Satisfactory
18	6.16	5.88	0.28	4.76%	1.20	Satisfactory
19	6.67	5.88	0.79	13.44%	3.38*	Dissatisfactory
20	6.06	5.88	0.18	3.06%	0.77	Satisfactory
21	6.07	5.88	0.19	3.23%	0.81	Satisfactory
22	5.29	5.88	-0.59	-10.03%	2.52*	Dissatisfactory
23	5.90	5.88	0.02	0.34%	0.09	Satisfactory

Table 4-2 Comparison result of power frequency magnetic field

Laboratory code	Measurement result	Standard value	Difference value D	Percentage relative difference D%	∣Z∣ value	Result evaluation
01	125.96	125.56	0.40	0.32%	0.06	Satisfactory
02	126.08	125.56	0.52	0.41%	0.08	Satisfactory
03	132.50	125.56	6.94	5.53%	1.03	Satisfactory
04	126.56	125.56	1.00	0.80%	0.15	Satisfactory
05	-	-	-	-	-	-
06	134.90	125.56	9.34	7.44%	1.38	Satisfactory
07	125.38	125.56	-0.18	-0.14%	0.03	Satisfactory
08	131.68	125.56	6.12	4.87%	0.91	Satisfactory
09	130.20	125.56	4.64	3.70%	0.69	Satisfactory

10	131.33	125.56	5.77	4.60%	0.85	Satisfactory
11	123.85	125.56	-1.71	-1.36%	0.25	Satisfactory
12	119.45	125.56	-6.11	-4.87%	0.90	Satisfactory
13	114.60	125.56	-10.96	-8.73%	1.62	Satisfactory
14	126.07	125.56	0.51	0.41%	0.08	Satisfactory
15	112.08	125.56	-13.48	-10.74%	1.99	Satisfactory
16	127.06	125.56	1.50	1.19%	0.22	Satisfactory
17	113.30	125.56	-12.26	-9.76%	1.81	Satisfactory
18	119.99	125.56	-5.57	-4.44%	0.82	Satisfactory
19	135.90	125.56	10.34	8.24%	1.53	Satisfactory
20	126.47	125.56	0.91	0.72%	0.13	Satisfactory
21	127.83	125.56	2.27	1.81%	0.34	Satisfactory
22	-	-	-	-	-	-
23	-	-	-	-	-	-

The standard deviation, maximum value, minimum value and range statistics for Table 4-1 and Table 4-2 are shown in Table 4-3.

Table 4-3　Summary of comparison statistics

Statistical data	Power frequency electric field (kV/m)	Power frequency magnetic field (nT)
Number of results	23	23
Average value	5.88	125.56
Standard deviation	0.23	6.76
Maximum value	6.19	135.90
Minimum value	5.29	112.08
Range	0.9	23.82

It can be seen from the statistics in Table 4-3 that, for 23 companies participating in comparison, the average value of power frequency electric field is 5.88 kV/m and the standard deviation is 0.23 kV/m. Among 23 companies, the power frequency electric field measured by 21 companies meets $|Z| \leq 2$, and the percentage relative difference is between ±7%. For the laboratories with code of 19 and 22, the $|Z|$ value of power frequency electric field test result is respectively 3.38 and 2.52, and the percentage relative difference D% is respectively 13.44% and -10.03%. The $|Z|$ value and percentage relative difference D% are dissatisfactory.

After reference to the calibration report of power frequency field strength meter used by the laboratory with a code of 19, it is found that the calibration range (1 kV/m~10 kV/m) and calibration date are valid. The maintenance record has ever been kept in May 2011. The technician adopts such ways as replacing the measurement bracket, replacing the optical fiber transmission line, and changing the test site, but the test value of power frequency electric field still exceeds the range of allowable error. The outlying reason for the power frequency electric field test result with code of 19 is preliminarily judged as longer service years and unstable performance of instrument. It is recommended to stop using the power frequency electric field test function of this instrument. After reference to the calibration report of power frequency field strength meter used by the laboratory with a code of 22, it is found that the calibration range is 5 V/m~30 V/m and fails to meet the measurement requirements of practical work. It is recommended to recalibrate the instrument and define the measurement range.

In Table 4-3, the average value of power frequency magnetic field is 125.56 nT and the standard deviation is 6.76 nT. Among 23 comparison participation companies, the measurement data of only 20 companies are valid. The Z value of power frequency magnetic field test result meets $|Z| \leq 2$, and the percentage relative difference is between ±10%. After reference to the calibration report of field strength meter used by 3 laboratories and the instrument operating manual, it is found that the small range of power frequency magnetic field measurement fails to meet the measurement requirements of background environment, i.e. the lower limit of magnetic field measurement is more than the environmental background value.

4.2 Result analysis

The Z values are arranged as the column shape in order of size, as shown in Fig.4-1 and Fig.4-2. From the column chart, it can be seen that each laboratory easily compares the result with the results of other participation laboratories, and understands the level of the result in this test comparison [6].

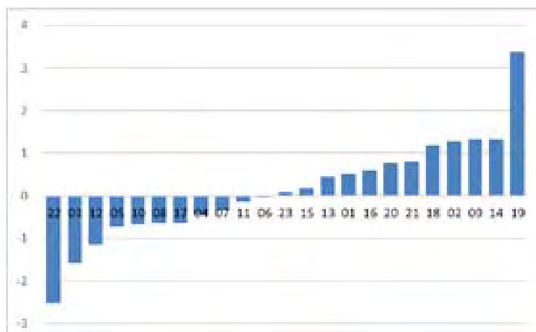

Fig.4-1 Z value results of power frequency electric field

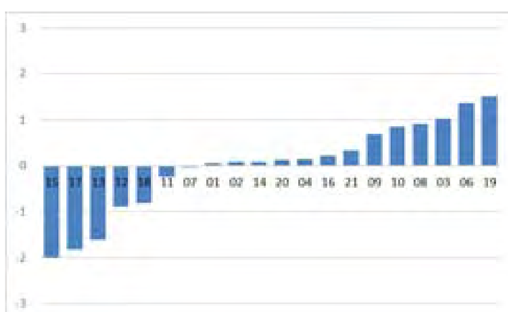

Fig.4-2 Z value results of power frequency magnetic field

In combination with the above data result analysis, the following aspects such as test operation, measuring instrument and test environment are mainly considered to analyze the factors influencing the power frequency electric field and power frequency magnetic field test results.

(1) Test operation: During the comparison process, the probe is supported by the bracket. Some detectors ensure the probe at the height of 1.5 m away from the ground, but the bracket supporting the probe fails to stretch to the maximum, to make the lower bracket close to the probe and the degree of the measured electric field distortion greater, thus causing the error of measuring result [7].

(2) Measuring instrument: The detector should calibrate / detect the instruments in accordance with the electromagnetic environment test range of power transmission and transformation projects, and should consider whether the range of application of instrument can meet the measurement range while purchasing the instruments [8].

(3) Test environment: The measurement should be made in the fine weather with the humidity not higher than 80%. However, even if the test environment meets the requirements, the wooden bracket is still dampened easily. Especially, as the bracket exposure time is longer, the measuring result will be influenced. For the outdoor test, it is recommended to use the insulating plastic bracket.

5. Conclusion

The test comparison activity is designed to promote the detection capability of all companies, ensure that the skills, instruments and detection methods of detectors meet the requirements of relevant standards, laws and regulations, ensure the accurate and reliable detection data, and provide a full transparent and credible guarantee mechanism for the society and the public. This paper expatiates the process of power frequency electric field and power frequency magnetic field test comparison below UHV transmission line. The data statistics show that, among 23 companies participating in comparison, 21 companies gain the satisfactory results of power frequency electric field, and 20 companies gain the satisfactory results of power frequency magnetic field. The analysis indicates that, the personnel operation process, measuring instrument range and test environment condition are main reasons influencing the results. It is recommended that, the companies with electromagnetic environment detection capability can strengthen the supervision in the above three aspects, so as to ensure more accurate and reliable detection data.

REFERENCES

[1] State Grid Corporation of China, Regulations on Environmental Protection Technology Supervision of State Grid Corporation of China, GW (K /2) 539-2014.

[2] WAN Baoquan, WU Xiong, ZHANG Guangzhou, et al. DL/T 988-2005 *Methods of Measurement of Power Frequency Electric Field and Magnetic Field from HV AC Overhead Transmission Line and Substation.*

[3] WU Xiong, WAN Baoquan. Electromagnetic Environment of Power Transmission and Transformation Projects [M]. Beijing: China Electric Power Press, 2009:95-100

[4] MA Xiucai, NIU Yonghong. Application of Grubbs Criterion in Laboratory Comparison [J]. Inner Mongolia Science Technology and Economy, 2017, 10:88-90.

[5] Compilation Group of *Electric Field, Magnetic Field and Environmental Impact of Power Transmission and Transformation Facilities*, Electric Field, Magnetic Field and Environmental Impact of Power Transmission and Transformation Facilities [M], Beijing: China Electric Power Press, 2007.

[6] Beijing: China National Accreditation Service for Conformity Assessment. CNAS-GL02-2014 Guidance on Statistic Treatment of Proficiency Testing Results and Performance Evaluation [S]. Beijing: China National Accreditation Service for Conformity Assessment, 2014.

[7] LIU Wenkui, PANG Dong. Electromagnetic Radiation Pollution and Protection and Treatment [M]. Beijing: Science Press, 2003.

[8] XIA Zhengzheng, LIU Zhuohui. Basic Knowledge of Laboratory Accreditation and Management [M]. Beijing: China Metrology Publishing House, 2003.

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Reduction of Number of Patrols around Transmission Facility using Deep Learning

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Japan

SUMMARY

One of the purposes of patrols is to check whether construction is taking place near the transmission lines. In rural area, a patrol person cannot find a sign of under construction because there are few constructions, and it is wasteful for people to patrol. Thus, we have attempted to reduce the number of patrols using a surveillance camera system. When using a surveillance camera, it is necessary to confirm the content of the images that are taken. To avoid watching a large number of images, we have attempted to use Deep Learning, for which many data is required for learning. Therefore, we have developed a scheme for reducing the number of confirmation tasks. The scheme creates a combined image which is the sum of all images using a weighting coefficient that is determined by the magnitude of scene change every hour. We confirm the effectiveness of the scheme. Finally, we apply Deep Learning to detect heavy machines using the result of learning based on images gathered by the scheme and confirm that Deep Learning is effective for the detection of heavy machines.

KEYWORDS
Transmission Line, Patrol, Heavy-Machine Detection, Deep Learning, Image Processing

1 INTRODUCTION

Electric power utilities in Japan periodically carry out patrols. One of the purposes of patrols is to look for signs in the early stages of constructions. When they are found, them, the firm is asked to be careful to avoid the transmission lines.

In terms of the patrols, utilities have often patrolled to realize stable supply of electric power, on the other hand, it is necessary to improve the efficiency of maintenance work, such as by reducing the number of field trips.

The recent progress of a wireless transmission technology has accelerated the introduction of the image-data transmission systems, for examples, surveillance cameras has been installed to monitor the condition of transmission line facilities and the surrounding area under transmission lines. The use of surveillance camera systems enables the frequency of patrols to be reduced. On the other hand, increasing the number of camera systems requires many boring works that a worker confirms a large number of acquired images. With this background, we have been attempting to develop an efficient method of confirming the images obtained by still camera.

The Efficient confirmation of images that include objects related that to construction requires techniques for the extraction of objects. Deep Learning is one of techniques that can be used for the extraction. Deep Learning, which is an artificial intelligence technique and uses statistical data processing methods requires large amount of image data. However, at the initial stage of installing surveillance camera systems, there are few images, particularly those containing objects related to construction. This necessitates a scheme for collecting image data for Deep Learning at the initial phase. At the same time, the scheme supports the search for objects related to construction without the need for patrol. The scheme must be able to find objects without examining a large number of images, and here we propose a scheme that realizes the efficient confirmation of images.

In this paper, we describe our scheme for collecting images while checking whether or not they contain objects related to construction. We also demonstrate the detection of heavy machines by Deep Learning based on the collected images.

2 Surveillance camera system [1]

In this section we describe the surveillance camera system. We assume that the camera system takes two pictures every hour in daytime. In construction projects, work is carried out throughout the day. We thus assume that objects related to construction remain at the site all day long.

Under this assumption, a surveillance camera system takes two pictures every hour from 8am to 6pm, where the two pictures are taken with interval of about a second. twenty-two images are thus taken.

Figure1 shows the surveillance camera system. The camera is a digital still camera that can be controlled to take photos at specific times. The camera is attached to a tower. Every hour, after the two images are taken, the images are sent to the office of an electric power office through a secure network.

3. Scheme for collecting images at initial phase using installed surveillance camera system

In this section, we discuss how to reduce the numbers of images required for the detection of construction work.

3.1 Combined image using weighting coefficient determined in accordance with scene change

After receiving a pair of images sent every hour, the system subtracts the brightness values of two images. At the end of the day, the system creates a new image that is combination of one of the two images taken at every hour. In short, eleven images (from 8am to 6pm) are combined.

A simple way to combine images is to average the pixel values (RGB values) of all images. In short, the combined pixel value at each pixel is equal to the sum of 1/11 of the pixel value at each pixel every hour. That is, 1/11 is the weighting coefficient.

When there are objects related to construction, the weighting coefficient becomes greater than 1/11. To achieve this, we use the difference in the brightness values of the two images every hour. When the difference is large, something related to construction may have occurred.

The weighting coefficient from the difference in brightness values is determined. A combined image is created using the weighting coefficient based on difference value. Figure2 shows how to determine the weighted coefficient and Figure3 shows its effectiveness. Figure3 (a) shows an image created by averaging pixels and Figure3 (b) shows an image created using the weighting coefficient. We can see workers engaged in an activity under a transmission line. In fact, they were carrying out preparation for the installation of solar panels.

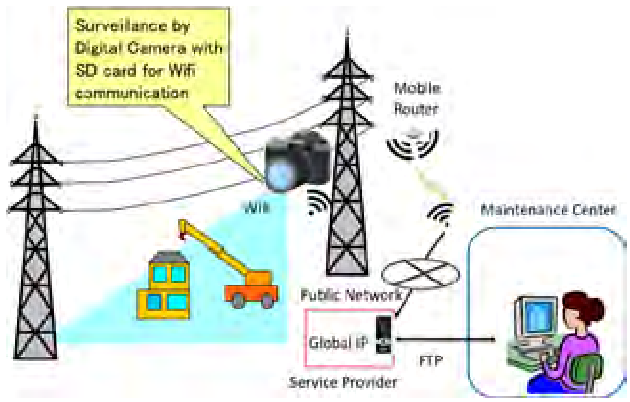


Figure1 Surveillance camera system

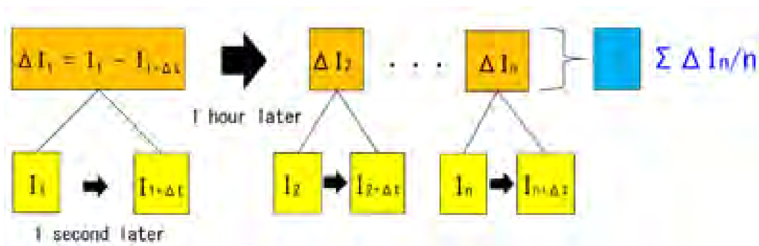


Figure2 Schematic showing how to create a combined image
(I_n: Brightness Value at the time of n)

(a) Simple combined image (b) Combined image using the weighting coefficient

Figure3 Example of observing construction of solar panel installation

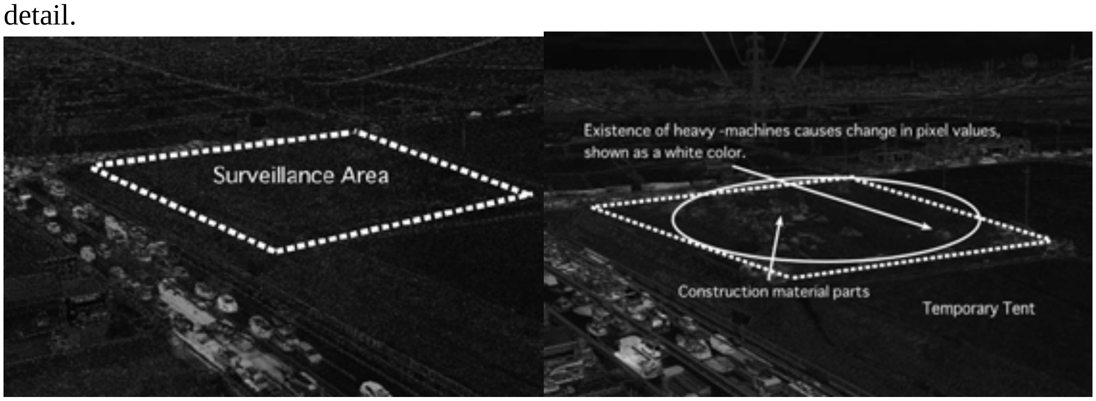
3.2 Detection of the events related to construction

We stated that it is possible to check images efficiently by focusing on the changes caused by the movement of workers and heavy machines. In addition, we will consider the automatic detection of images based on the changes, by setting an area near transmission line in an image and focusing on the pixel values with larger changes within this area.

As a means of automatically detecting changes, we focused on the magnitude of the differences in the pixel values within the observation area compared with those in the previous day. An example of a differential image that detected site preparation work before the construction a warehouse construction is shown in Figure4. Figure4 (a) shows a differential image for a day in which no changes occurred.

No white areas indicating changes can be found in the observation area. On the other hand, Figure4 (b) shows an image reflecting installation of a temporary lavatory, in which the construction materials moved by workers are shown in white, indicating larger pixel values. As can be seen from Figure4, the differential image for the day before work starts has smaller pixel values than those in the image for the day, when work starts within the observation area.

A point to bear in mind is that larger pixel values might be taken from areas where there was no change owing to abnormal values resulting from the fluctuation of images. We considered detecting changes within an observation area by focusing on a square region within an area of larger pixel values. Here, to address the issue of the setting of pixel values, we investigated the size of pixel values to be detected by setting the pixel values of the differential image to 256 gradations. For an actually obtained differential image, the difference in pixel values is plotted on the vertical axis and the pixel position in the surveillance area is plotted on the horizontal axis. Figure5 shows how to plot all pixels in a row. Figure6 shows that there is not an anomalous event (Figure6(a)) and is an anomalous event (Figure6(b)). Pixel values on the day with changes that the anomalous event makes become larger, whereas pixel values on a day with no changes are small. We decided to set the pixel value threshold to 150 and perform an analysis by obtaining the square areas in the parts with pixel values above the threshold. For Figure7, the vertical axis shows the amount above the pixel value of 150, and the horizontal axis is the number of days. Changes are shown in peaks, so, scene changes (such as a heavy machine appears, grass and tree is cut) can be detected from peaks. In Figure7, we verified using three weeks' worth of images. Although the peaks in this figure vary in size, the figure indicates that a peak appears whenever work is carried out in the surveillance area. This method of detecting changes within the observation area indicates whether construction work has been occurring while checking the integrated image for a day. If we can confirm changes through this method by digitizing the changing situation within the set range, it will be used as a guideline for checking images in more detail.



(a) Differential image in the case of no scene changes

(b) Differential image in the case of scene change

Fig.4 Difference between images without and with changes

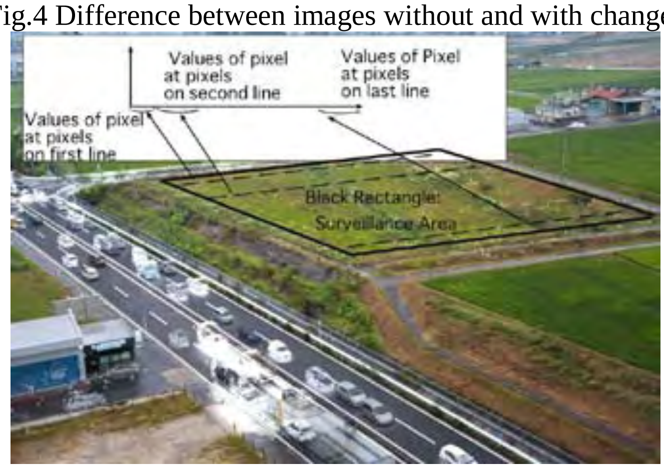
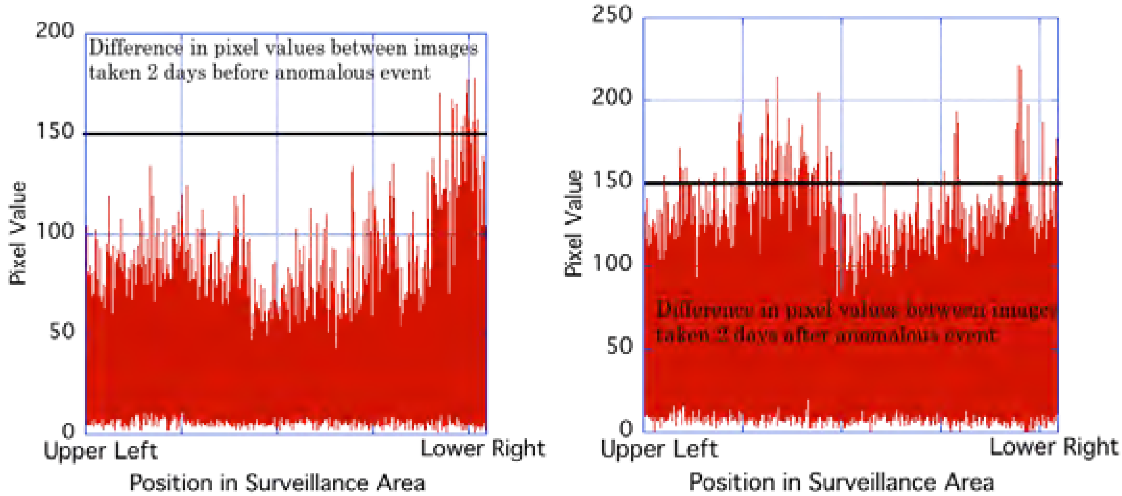
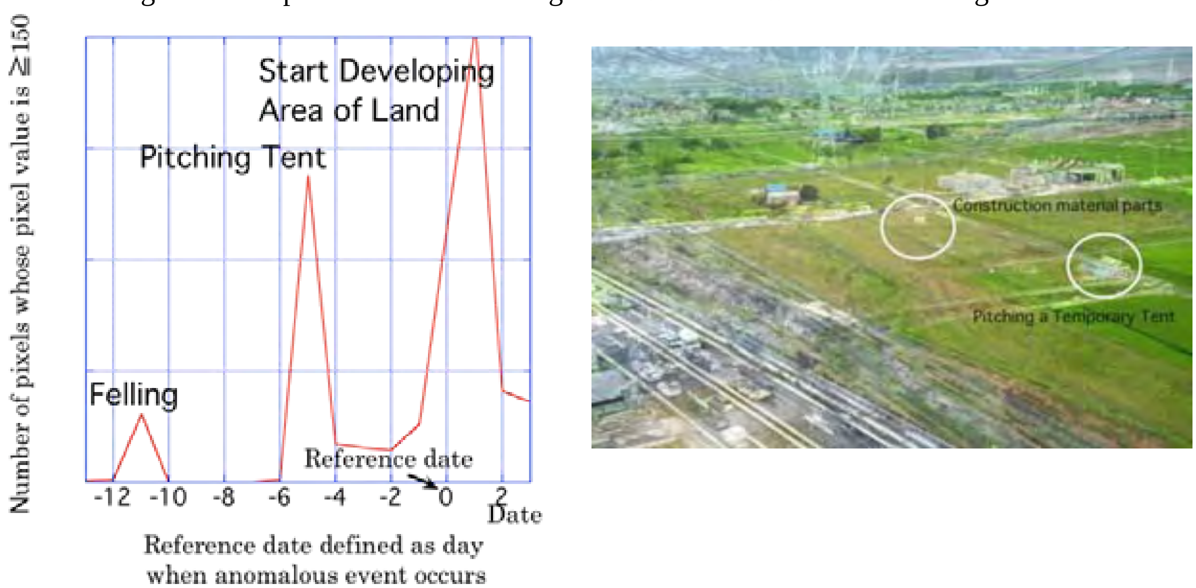


Fig.5 Two- dimensional data converted to one- dimensional data



(a) Before anomalous event (b)After anomalous event

Figure6 Example of difference of brightness values in two combined images



(a) Daily comparison of combined images of one day (for two weeks) (b) Combined image of one day (temporary tent installation)

Figure7 Detection of preparation work for construction of a new logistics warehouse

4. Heavy-machine detection using Deep Learning (second phase)

This research project was started in 2015, and since then many images have been stored. We have prepared heavy-machine images for learning process of Deep Learning. Figure 8 shows a sample of heavy-machine images. This section demonstrates the detection of heavy-machines using Deep Learning based on the heavy-machines images we have stored.

4.1 Experiment on detection of heavy-machine

We used Faster R-CNN[2], which is a Deep Learning and object detection algorithm that segments regions and judges the content of each segment is. Seventy heavy-machine images are used to learn the feature of heavy-machine.

We use surveillance images for five days taken between August and December 2016. The number of images is 1019. The use of these images means that the experiment employs during various seasons. There are 1898 regions that include a heavy machine.

We use Faster R-CNN that is one of Deep Learning and an object detection algorithm that do some region segmentations and judge what each segment is. 70 heavy machine images are used for learning of heavy machine's features.

We use surveillance images for 5 days. The number of images is 1019. Images at each day are taken from August to December in 2016. The use of these images means that experiment is carried out under the various seasons. There are 1898 regions that include a heavy machine.

4.2 Results

Figure8 shows one of the detection results, where a heavy-machine is being operated at the distance of 230m from a tower where our camera is installed. This distance is about half of a span between towers. Tables 1 and 2 show the detection results. The program detects 1911 regions where there is a heavy-machine and fails to detect 17 regions where there is a heavy-machine. There are 30 regions where the program mistakes parts of hillside for a heavy-machine. In short, the percentage of regions with a heavy-machine that were correctly detected is 99.1% and 1.5% of regions with a heavy-machine that were incorrectly detected.

Figure8 Example of heavy-machine detection

Table 1 Result showing precision of heavy-machine detection

Number of regions of containing heavy-machine:1898		
Result	Detected:1881	Not detected:17
Rate(%)	99.1(=1881/1898*100)	0.9(=17/1898*100)

Table 2 Result showing precision of heavy-machine incorrect detection

Number of detected regions		
Result	Heavy-machines:1881	Others:30
Rate(%)	98.5(=1881/1911*100)	1.5(=30/1911*100)

5. Conclusions

One of the purposes of patrols is to check whether construction is taking place transmission lines. In rural areas, a patrolling person cannot find a signs of constructions because there are few constructions and it is waste of effort for people to patrol. Thus, we have been attempting to reduce the number of patrols to check whether construction is taking place by a surveillance camera system, for which it is necessary to confirm the content of the images that are taken. To avoid watching a large number of images, we have attempted to use Deep Learning, many data are required for learning. Therefore we have developed a scheme for reducing the number of confirmation tasks. The scheme creates a combined image, which is the sum of all images using weighting coefficient that is determined by magnitude of the scene change every hour. We have demonstrated the effectiveness of the scheme. Finally, we apply Deep Learning to detect heavy machines using the result of learning based on images gathered for the scheme. Heavy machines are detected with a detection rate of 99.1%.

BIBLIOGRAPHY

[1] E.Sasaki et al., Study on Efficient Monitoring of Surveillance Images to Check Anomalous Events near Transmission Lines, ICEE, ID 90063, July 2016.

[2] R.Shaoqing, et al., Faster R-CNN: Towards Real-Time Object detection with Region Proposal Networks, Advances in Neural Information Processing Systems, 2015.

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Revamped High Ampacity Low Sag Stranded Carbon Fiber Composite Core – Aluminium Conductor Fiber Reinforced Conductor (ACFR)

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SUMMARY

Globally ACSR and AAAC conductors are commonly used as overhead conductors for energy delivery application. High density transmission corridors are the need of energy utilities to optimise the right of way. So the use of High Ampacity Low Sag conductors (HALS) has been increased to address the increasing congestions in the existing transmission network. There are several types of HALS conductor technology are tested and deployed by all major global power transmission utilities. The selection of suitable HALS technology considering the requirements with respect to increase in power transfer capacity, exiting ground clearance, existing tower loadings and cost of capital investment is not only the deciding factor but also the operational efficiency (ohmic losses) over a period of its life time and installation of those conductors in the existing terrain are the major parameters needs to be considered for the right technology adoption.

Now a day, the carbon fiber composite core conductor technology has been preferred by the utilities among the HALS conductor technology because of high strength to weight ratio, lower thermal expansion and no creep (almost zero creep). The popular composite core technology are mostly a single core or several number of single wires bunched together. But the challenges of this popular carbon fiber composite core conductor technology is flexibility, which needs careful handling and care needs to be taken during installation. After several years of research to address the challenges in the carbon fiber composite technology we developed a technology to strand the carbon fiber composite material to form a stranded carbon fiber composite core (just like stranded steel core used in ACSR conductors) to make it flexible and easy to handle during installation. This paper describes about the development, testing, deployment and applications of the revamped carbon fiber composite core conductor technology named as Aluminium Conductor Fiber Reinforced Conductor (ACFR)

KEYWORDS

HTLS Conductor, Carbon fiber composite core, ACFR, Reconductoring transmission line, Carbon composite core conductor, High ampacity conductor, High performance conductor

1. INTRODUCTION

The research and development to strand the carbon fiber composite material to make it more flexible started in the year 1980's . The stranded carbon fiber composite material is named as Carbon Fiber Composite Cable (CFCC).The CFCC was first tested for civil construction application mainly focusing to replace the steel reinforcement with CFCC to enhance corrosion resistance. The first deployment of CFCC for civil construction application was PC bridge project in Japan in the year 1986. In the year 2002 the CFCC was used instead of steel core in the overhead conductor application, the new conductor with carbon fiber composite core named ACFR was introduced, tested and deployed in one of the transmission line project in Japan. The ACFR conductor was analysed to be the best fit for overhead line which doesn't have magnetic effect in the AC resistance (where as steel core has its magnetic effect in the AC resistance), light weight, high strength, low thermal expansion and increase in corrosion resistance.

The ACFR conductor construction is as simple as ACSR conductor where the stranded steel core is replaced with stranded carbon fiber composite core. The outer conductive layer is a either a EC grade hard drawn aluminium wires used in ACSR conductor or thermal resistance aluminium wires of either of Al-Zr alloy (Thermal resistance aluminium alloy) or EC grade thermal resistance annealed aluminium wires. The selection of outer conductive layer depends on application and the preference of the energy delivery utilities. The annealed aluminium wires having little higher electrical conductivity than the hard-drawn aluminium wires used in ACSR conductors, but annealed aluminium wires are softer and are more prone to abrasive resistance and needs more care during installation. Thermal resistance aluminium alloy (Al-Zr) having marginally lesser or equal conductivity as that of hard drawn aluminium wire and easy to handle as that of hard drawn aluminium wires used in ACSR conductor. The conductive layer of ACFR can be of round wire or shaped wire (Trapezoidal, Z Shape etc) to increase the conductive area. The trapezoidal wire shaped construction of ACFR conductor is shown in the Figure -1

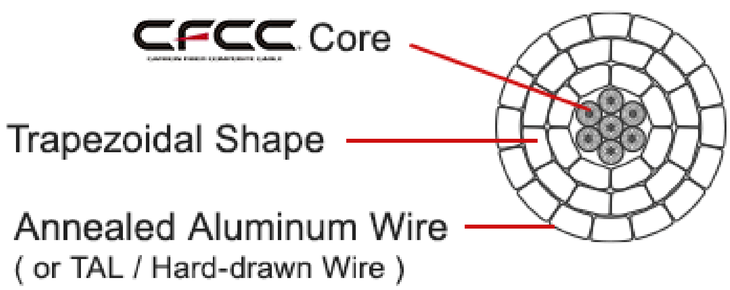

Figure-1 Construction of ACFR conductor

2. CFCC Core

The raw material carbon fiber and epoxy resin matrix are bunched together to form a composite wire and are coated with organic layer act as galvanic protection and thus formed single carbon fiber composite wires are stranded together to form a stranded Carbon Fiber Composite Cable (CFCC). The single strand size can be chosen to match the final CFCC diameter suitable for ACFR conductor that replaces the existing conventional conductor. CFCC has the same advantage as that of the single carbon fiber composite core like higher strength, lower weight, lower thermal expansion and higher corrosion resistance. But the unique stranded carbon fiber composite core CFCC address the challenge of flexibility and handling issues in the single strand carbon fiber composite core. The table-1 compares the steel core and CFCC properties

Table–I Compression of CFCC and Steel core used in ACSR conductor

Properties	CFCC	Galvanised Steel (IEC)
Construction (No./mm)	7/3.2	7/3.2
Type	CFCC	Regular
Diameter (mm)	9.6	9.6
Cross sectional area (Sq.mm)	56.27	56.27
Ultimate Tensile Load (kN)	121	69
Weight (kg/km)	93	441
Thermal expansion ($x10^{-6}$ per ^{o}C)	1	11.5

3. ACFR Conductor

The maximum continuous operating temperature of ACSR conductor is between 70^{o}c to 90^{o}c. The limit of maximum operating temperature is considering the loss of strength of EC grade hard drawn aluminium wires. So the current carrying capacity of ACSR is limited because of joules effect. The sag of ACSR is higher because of higher steel weight and higher thermal expansion of steel.

The ACFR conductor uses high thermal resistance aluminium alloy or high thermal resistance EC grade annealed wires, so the maximum operating temperature of ACFR is 180^{o}c. The maximum operating temperature of ACFR is restricted considering the resin matrix used in CFCC. The sag of ACFR is lesser than the ACSR from the installation temperature and up to maximum operating temperature (after knee point the core will take the entire mechanical load and thus the conductor mechanical characteristic behave similar to core after knee point).

The comparison of ACSR and ACFR conductor for a 132 kv transmission line is shown in the Table-II

Table-II Comparison of ACSR and ACFR for 132 kv transmission line

Properties	ACSR Panther	ACFR Himalaya
Construction (No./mm)		
Conductor Diameter (mm)	21	21
Core Diameter (mm)	9	7.8
Cross sectional area (Sq.mm)	261	312
Ultimate Tensile Load (Kn)	89.7	95.3
Weight (kg/km)	974	820
DC Resistance at 20 ^{o}c (ohm/km)	0.1390	0.1018
Current Carrying Capacity (Amperes) (Ambient 45^{o}c)		
Operating temperature – 75^{o}c	366	464
Operating temperature – 85^{o}c	466	537
Operating temperature – 180^{o}c	--	1061
Sag and Tension for 320-meter span		
Tension at 32oc full wind (52 kg/sq.mm) Kg	3324	2739
Sag at 75^{o}c and Nil Wind	6.90	5.99
Sag at 85^{o}c and Nil Wind	7.09	6.39
Sag at 180^{o}c and Nil Wind		6.66

The ACFR conductor is not only chosen for enhancing the power transfer capacity of the exiting transmission lines by replacing the existing ACSR conductor with ACFR conductor.

ACFR conductor has lesser AC resistance when compared to ACSR conductor, so it can be deployed in new power transmission line to reduce the ohmic losses and thus reduce the carbon foot print

4. **Testing**

In the recent days CFCC and ACFR conductor has been tested for Design test, Installation test and In-service test and the outcome of each test is discussed in detailed

4.1 STRESS STRAIN TEST

Stress Strain test on ACFR 315 Sq.mm was performed to room temperature and the data was collected to support for the calculations of sag tension.

The procedure two stress strain tests were conducted, first test was conducted on ACFR conductor and the other test was on the CFCC. Practically it is not possible to perform the test on the conductive layer annealed aluminium. So the stress strain characteristic of aluminium is developed by subtraction CFCC core stress from the total ACFR conductor stress at common strain.

The results from the stress strain data were used to obtain the fourth quadrant polynomials and are used to compute the sag tension results using PLS CADD software.

4.2 CREEP TEST

The creep test was performed holding the ACFR 315 Sq.mm at constant tension for 1000 hours. To obtain a perfect fourth quadrant polynomial, the creep tests were performed at different constant tension levels from 15% to 30% of RTS of the ACFR 315 conductor.

The strain due to creep will lead to increase in sag over a period of time, so the final sag needs to be considered including creep strain.

It is observed from the test that ACFR conductor exhibits creep because of the conductive layer and carbon composite core has almost zero creep. So the creep behaviour of aluminium has been considered by the separation from the stress strain data.

4.3 SHEAVE TEST

The objective of the test is to observe the mechanical performance of ACFR 320 Sq.mm conductor when subjected to simulated action of being pulled over a sheaves during installation. This test is to show the conductor is robust for installation over stringing pulleys. The ACFR 320 Sq.mm conductor was tensioned to 15% of the conductors RTS, the conductor is passed 30 times over a pulley of diameter 20 times the diameter of the conductor, After completion of the sheave test the ACFR conductor was subjected to an ultimate tensile test.

The ACFR conductor reached 128% of the conductor RTS as against the minimum requirement of 95% of the conductor RTS. Furthermore the conductor doesn't have any broken strands or fretting on completion of the sheave test.

4.4 BENDING TEST ON CFCC

Bending test on CFCC diameter of 7.8 mm was performed to find the mechanical performance of the CFCC when subjected to combined bending and tensile stress.

CFCC sample was passed through the bending mandrel of diameter not higher than 50 times of the core diameter and the sample was tensioned to 15% of the RTS of CFCC Core and kept for one minute and 30% RTS of CFCC core for 2 minutes. The UTS test was performed after bending test to find out the remaining tensile strength of CFCC, dye penetration test was also performed to find any cracks on the CFCC sample

CFCC core attained 125% of the RTS of core against the requirement of 95% of the RTS of the core. In the die penetration, CFCC has not shown any kind of cracks or flaws.

4.5 HIGH TEMPERATURE TENSILE TEST ON CFCC

The purpose of the test is to measure the tensile stress of CFCC core at the short term emergency operating temperature of 200^{o}c.

The CFCC core was heated to 200^{o}c, the sample was allowed to reach thermal equilibrium before the tensile test, once the temperature is stabilised the CFCC was tensioned until failure to determine its tensile strength.

The CFCC broke at 104% of the RTS of CFCC core against the requirement of 95% of the RTS of CFCC.

4.6 SALT SPRAY TEST

ACFR 320 Sq.mm conductor was performed for salt spray test to investigate the effect of ACFR conductor under a controlled salt atmosphere. The salt atmosphere is considered typically the most corrosive environment the conductor will experience.

Samples of ACFR 320 Sq.mm were placed on the salt spray chamber the PH of the solution was maintained between 6.68 to 7.04 at 25^{o}c through out the test. The mass of the each sample was measured prior to the test. The test was performed as per ASTM B117 for 1000 hours

The mass of each sample was measured after completion of the test and it was recorded to find the loss of cross sectional area. After completion of test aluminium wires and CFCC were tensile tested to find the loss of strength due to corrosive atmosphere.

There was no significant signs of pitting, corrosion or detoriation noted on aluminium wires as well on CFCC

4.7 HEAT STRESS TEST ON CFCC

The CFCC core size of 7.8mm was performed for heat stress test to verify the mechanical performance of CFCC when exposed to combined mechanical and thermal stresses at its short term emergency operating temperature of 200^{o}c.

CFCC core was heated to 200^{o}c and allowed for thermal equilibrium, the tensile load of 25% of RTS of core was applied to CFCC core and held for 1000 hrs. After completion of 1000 hrs the sample was tested for tensile load.

The CFCC attained 120% of RTS of core against the requirement of 95% of the RTS of the core. No damage, cracks or breaks were observed on the CFCC sample.

4.8 THERMAL AGING TEST ON CFCC

CFCC size of 7.8 mm was performed for thermal aging test to find the loss of strength of CFCC while exposed to continuous operating temperature for long time.

CFCC sample was placed in the inside the tube furnace and temperature was raised to 180^{o}c after attained the thermal equilibrium, the sample was exposed to 8736 hours (52 weeks). The samples were collected at an interval of 400, 1500, 2500, 5000 and 8736 hours. After completion of 52 weeks the sample was tensile tested

CFCC tensile value achieved was 116% RTS as against the requirement of 95% of the RTS. From the collected data and using logarithmic formula CFCC will degrade its UTS to 95% of RTS after 15 million years of service

5. TESTS AND RESULTS

ACFR Conductor and CFCC core samples were tested for all the needed relevant test as per the test requirement specified in international standards and guidelines for High Temperature Low Sag conductors the test results shows that the ACFR and CFCC core exceeds the expectations of the acceptance criteria required for all the tests.

From the test results, ACFR conductor is proved to be robust in design, installation and in-service operation

6. HARDWARE

The important hardware fitting is tension clamp and mid span joint, because for any composite core overhead conductors the challenge is to hold the composite core. The remaining other hardware and accessories can be designed considering other HALS type conductor

6.1 TENSION CLAMP

The tension clamp of ACFR is same as ACSR conductor. ACFR tension clamps are compression type as like ACSR. It has major three components composite core compression unit, Aluminium tube as a buffer and Outer aluminium compression unit. The aluminium buffer is used to reduce the crushing of composite core during compression of the core potion. Figure 2 and Figure 3 shows the components of tension clamp for ACSR and ACFR conductor respectively

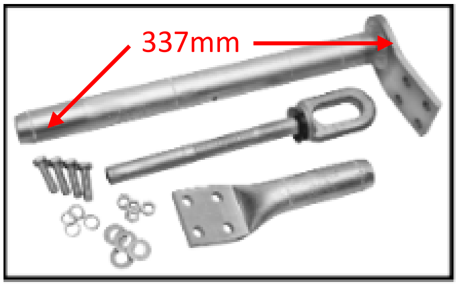

Figure 2 ACSR Tension Clamp

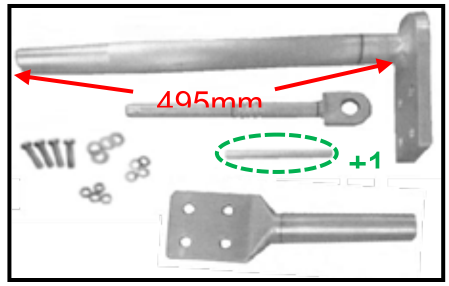

Figure 3 ACFR Tension Clamp

The tension clamp of ACFR is little longer than the ACSR conductor which supports secured current density and grip strength.

6.2 MIDSPAN COMPRESSION JOINT (MSCJ)

Figure 4 and Figure 5 shows the diagram and component of ACSR MSCJ and ACFR MSCJ respectively

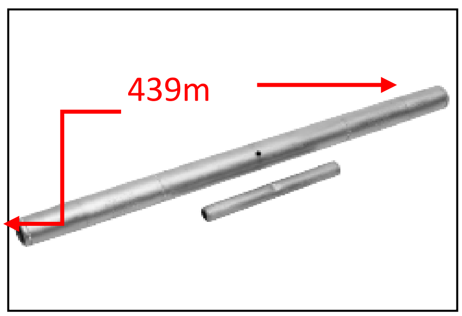

Figure 4 ACSR MSCJ

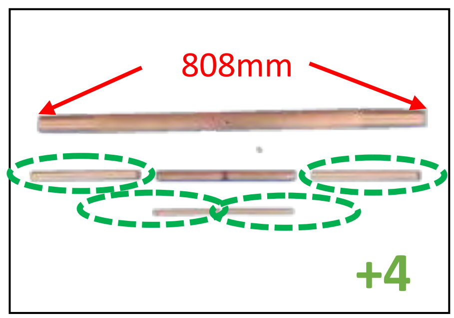

Figure 5 ACFR MSCJ

7. INSTALLATION

ACFR uses a stranded carbon fiber composite core CFCC, so ACFR conductor is more flexible. Thanks to the flexibility of ACFR, the installation method of ACFR is similar to ACSR. The tolls and tackles used for ACFR is same as that of ACSR. So the stringing method as conventional as ACSR.

The Table – 3 shows the requirement for ACSR and ACFR during installation, It should be noted that if ACFR uses outer conductive layer as annealed aluminium then the only exception is recommended pulling angle is 45 degrees considering annealed aluminium may get loose and bird cage may occur.

Table 3 Installation Requirement for ACSR and ACFR

Description	ACSR	ACFR	
Outer Conductive Layer	HAL	Annealed Al	TAL
Bull Wheels	40 X D	40 X D	
Sheave Wheels	20 x D	20 X D	
Recommended pulling angle	60 degrees	45 degrees	60 degrees
Dead End Installation time	15 minutes	15 minutes	
MSCJ Installation time	30 minutes	30 minutes	

D – Diameter of Conductor

8. Conclusion

ACFR conductor has the following advantages and the best choice for power transmission overhead lines.

8.1 Stranded Carbon Fiber Composite Cable (CFCC) is having lesser weight. High strength and lower thermal expansion

8.2 CFCC is more flexible than the single carbon composite core

8.3 Aluminium Conductor Fiber Reinforced (ACFR) can be produced by any one of thermal resistance alloy wire, annealed aluminium wire or hard drawn aluminium wire.

8.4 The outer conductive layer used in ACFR conductor can be produced by either round wire or shaped wire depends on application need

8.5 ACFR is the best choice for reconductoring line to increase the transmission capacity by more than 2 times of the existing capacity without any reinforcement of tower and maintaining the same ground clearance

8.6 The new transmission line using ACFR will reduce the ohmic losses thus towards green solution for energy delivery utilities

8.7 ACFR conductor has been tested for all the test requirements considering design, installation and in-service operation

8.8 Test results exceeds the expectation and acceptance criteria specified for all the tests

8.9 The dead end clamp and midspan joint of ACFR conductor is same as that of ACSR conductor

8.10 Due to the more flexibility of ACFR conductor, the installation is same as that of ACSR conductor

8.11 Quicker installation and easy to handle than any other composite core conductor used in power transmission line

BIBLIOGRAPHY

[1] Working Group SC B2.26 CIGRE 426. “Guide for Qualifying High Temperature Conductors for use on overhead Transmisison Line” (426 August 2010)

[2] Working Group SC B2 Session paper “Development of a low sag aluminium conductor carbon fiber reinforce for transmission line” (Reference Number 22-203_2002, Year 2002)

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Enhancement of Power Transmission Capacity of existing AC transmission lines by refurbishing to HVDC Transmission

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SUMMARY

The ever increasing demand for electricity augmented with industrialization and economy growth in developing countries like India has motivated the integration of new generating sources both conventional and Renewable Energy Sources (RES). Over a period of time, this has led to transmission congestion on the existing AC transmission lines. With integration of various RES distributed along the transmission sections, their power evacuation is being challenged with the existing transmission capacity infrastructure. The generation from RES is also intermittent that transmission system cannot be planned for its peak generation for economic reasons. Construction of new transmission lines is becoming difficult due to non-availability of right of way (RoW). Owing to these reasons, it has forced the system planners and Transmission system operators (TSO) to look for alternative technologies for enhancing the power transmission, integration of distributed RES, optimal use of existing right of way, etc. which has become a subject matter of interest at the current scenario. One such alternative technology is the use of High Voltage Direct Current (HVDC) transmission, which has many advantages like enhanced transmission capacity up to thermal limit, low losses, ease of controllability, less RoW, etc. Especially voltage sourced converters (VSC) based HVDC technology is capable of independent control of real and reactive power, voltage support to the connected ac system, black-start capability and better reliability. Thus conversion of existing AC transmission infrastructure into HVDC transmission is taken as the study case to understand the challenges and opportunities during such refurbishment.

KEYWORDS

Voltage SourcedConverter (VSC), High Voltage Direct Current (HVDC) transmission, AC to DC conversion, Right of Way (RoW), Renewable Energy Sources (RES)

1. Introduction

The promotion of use of Renewable Energy Sources (RES) by the government bodies has created positive motivation in achieving increased penetration of RES into the existing grids. This has resulted in more generation which is intermittent in nature and is also posing difficulties in their power evacuation with the existing transmission capacity infrastructure. At times, the wind power is curtailed owing to lack of transmission facilities inspite of electricity deficit. However construction of new transmission facilities is also being challenged for need of RoW, among others. Thus there is a need for system planners and TSOs to look for alternative technologies that can strengthen the power evacuation facility of the existing grids. One way of overcoming the present scenario is to refurbish the existing AC transmission system into HVDC transmission. In AC transmission, the maximum power transmission capacity is limited to its surge impedance loading (after suitable line compensation) for voltage stability which is usually around 50-60 % of the thermal limits in the transmission line. In case of HVDC transmission, the line can be operated up to its thermal limit with adequate system security, thereby enhancing the power transmission capacity[1]. Moreover HVDC offers several added advantages like lower line losses, improved stability and system security, reduce unnecessary line flows and associated line losses, support the ac system with reactive power and facilitate integration of RES. Thus this paper focuses and discusses the challenges and opportunities in converting the existing AC transmission lines into HVDC transmission system for enhancing its power transmission capacity.

2. Factors to be considered during AC to DC Conversion

In conversion of AC to DC transmission system, the transmission expansion planning involves the followingforemostEnvironmental, Engineering and Economic (EEE) considerations as listed in Table 1. Afterhaving a carefulconsideration of thesefactors, AC to DC conversion of existing transmission system iscarried out if beneficial.

Table 1 EEE considerations in AC to DC conversion

Environmental	Engineering	Economic
Pollution zone of the AC system to beconverteddecides the creepage requirements of DC insulators	The conversion canbe monopole, bipole or Hybrid HVDC configuration	Inspite of converter station losses, OPEX isalwayslower for DC compared to AC owing to low line losses and enhanced transmission capacity
Weather conditions decides the Audible noise / Radio interferencelevelgenerated by the converted line. Fairweatherisdecisive for HVDC	DC Voltage selectionbased on the clearances in the transmission line towersand DC currentbased on the thermal limit of the conductordecides the maximum power transmission capacity of the conversion	CAPEX mainlydependsupon the type of AC transmission tower, HVDCconverter station and configuration planned, alongwith the transmission distance
Corona and fieldeffectdepend on the voltage and currentlevels and on the configuration and positioning of the conductors	Modificationisrequired for insulator and if neededfortower/conductorto achievedesireddc voltage and current	Time for conversion islesscompared to gettingpermits and construction of new line thatdepends on the modification neededwithtower, conductor and insulator

In HVDC conversion, the system canhave different configurations namely, symmetric / asymmetric monopole, bipole or hybridthatdepends on the tower configuration and the clearances as shown in Figure 1. In case of horizontal single circuit AC transmission line, either one or twosymmetric monopole HVDC conversion is possible. Alternately a bipole configuration of HVDC conversion isalso an option. In case of double circuit and multi circuit, either one or few AC systemscanbeconverted to HVDC as shown in Figure 1. Howeveritis not straightforward and simple whichwillbeunderstoodwhen the clearance requirements are presented in the later section of thispaper. This conversion require modification to either one or all of themnamely, tower structure, insulator and conductor[1]. The AC ceramicinsulatorsare generally to bereplacedwithHigh ResistivityToughened Glass (HRTG) or composite insulators to meet the clearance requirements[2]-[3].

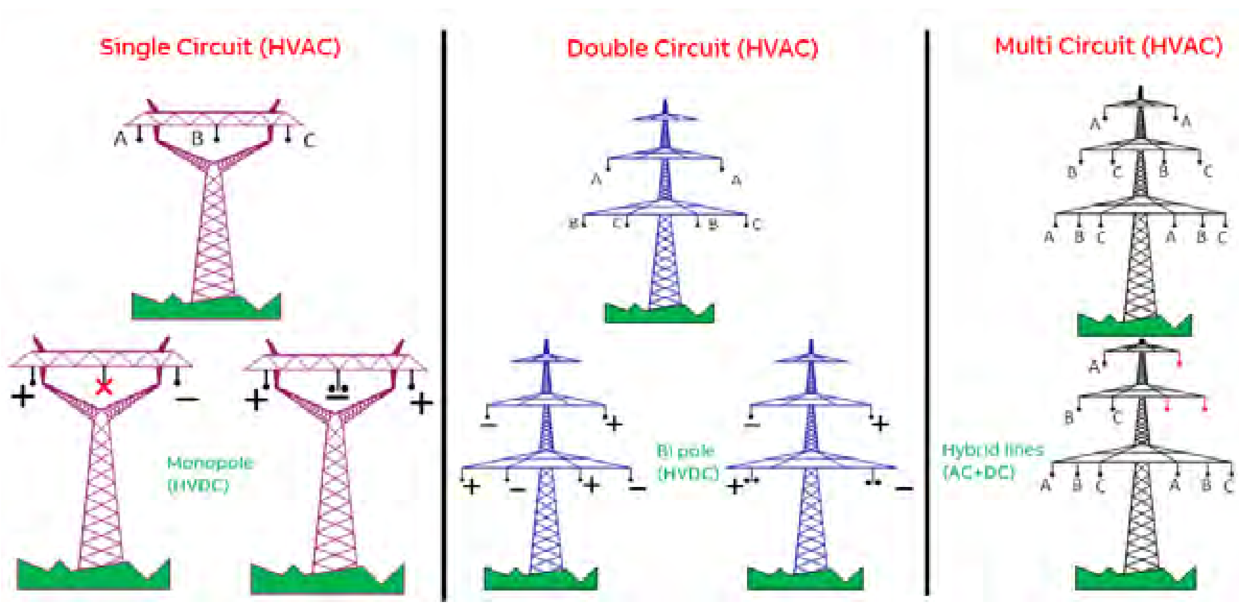

Figure 1Some possible configurations of conversion from AC to DC for the sake of illustration

3. AC to DC Conversion instances in the past

There has been few instances of AC to DC conversion in the past, to enhance the power transmission capacity of the existingRoW. In Germany, the existing multi circuit AC transmission system isconverted to HVDC transmission [4]. The multi circuit originally has two 380 kV AC system and two 110 kV AC system running over the distance of 340 kms betweenNorth Rhine-Westphalia and Baden-Württemberg. In the planned conversion, one of the 380 kV AC system isconverted to 380 kV DC system as shown in Figure 2thatwillfacilitate a power transmission capacity of approximately 2000 MW fromwindfarms in the NorthSea to the industrialtown in the South of Germany. The power transmission capacity of the corridor furtherdepends on the dc voltage selection on the clearances and the ambient temperature as canbeobservedfromFigure 3, consideringthat the existingconductors are retained. For DC voltage operation as in AC, the power transmission capacityisalmostdoubled for the sameRoW. If the existing transmission infrastructure allows for provision to increase the dc voltage, then the power transmission capacitygetsenhancedfurther. However the ambient temperature of the existingRoWhighly influences the power transmission capacitythatislimited by the conductorsagduringoperation as canbeobservedfromFigure 3.

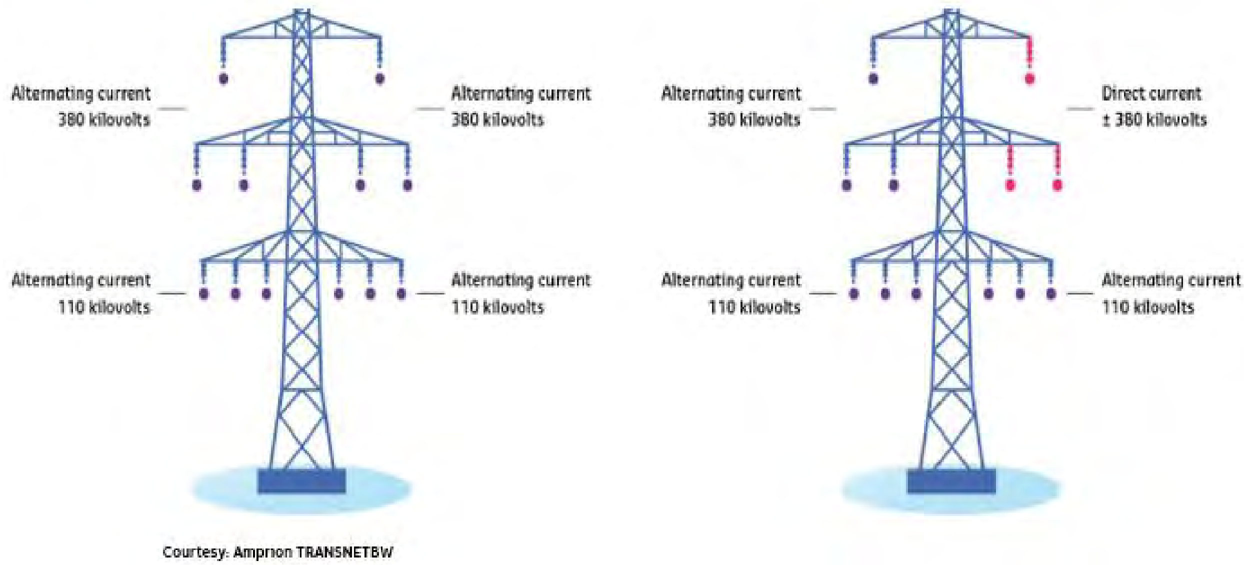

Figure 2 AC to DC Conversion in UltraNet Project in Germany [4]

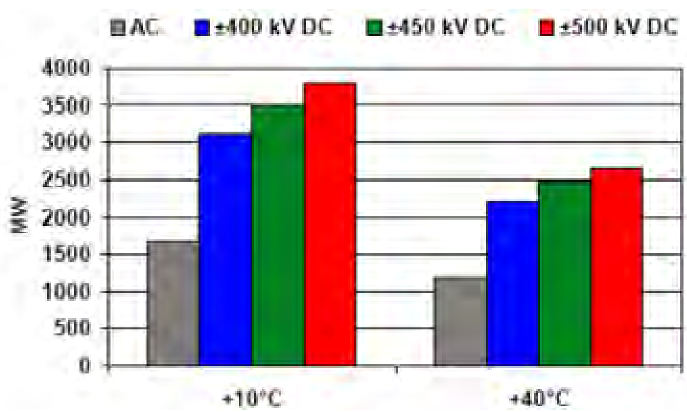

Figure 3 Power transmission capacity of existing RoW based on dc voltage selection and ambient temperature [3]

AC to DC conversion is also studied in 33 kV AC system in UK in angle dc project[5] as shown in Figure 4 . The existing 33 kV AC line isconverted to 27 kV symmetric monopole HVDC line to achieve 23% increase in power transmission capacity for an operating temperature of 50°C. Whereas by allowing the operation of the cable to the current operating temperaturelevel of 65°C, itis possible to enhance the power transmission capacity by 35% on the existingRoW as canbeobservedfromFigure 5.

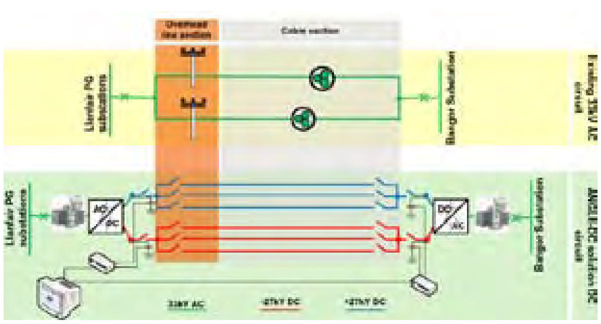

Figure 4 Angle DC Project [5]

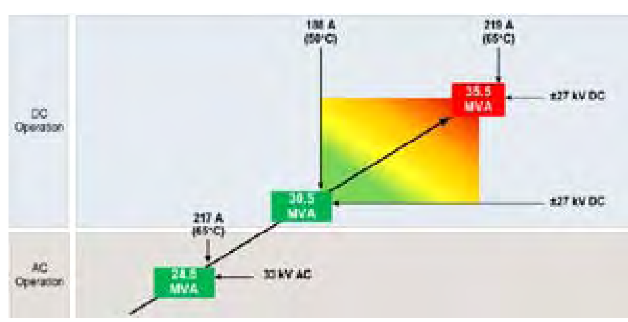

Figure 5 Enhancement of Transmission capacity in Angle DC Project [5]

4. Selection of DC voltage at AC to DC conversion

In DC conversion, the string lengthhelps in predicting the available clearance which in turnisdecisive in the selection of dc voltage. The thermal rating of the conductordecides the currentcarryingcapacity of the transmission system. The selected dc voltage and the thermal current rating of the conductortogetherdetermines the maximum power transmission capacity of the line after conversion.

The string lengthdepends on the creepage distance requirementbased on the pollution zone underwhich the transmission system isidentified for conversion. The creepage distance requirement for HVDC ishigherthanthat of AC [6]. For conversion of a typical 220 kV AC transmission system assumingthat the string length of 2030 mm isretained (to maintainallowablesagduringoperation), the DC voltage selection for operationfalls in the range of 146kV to 206kV for symmetrical monopole HVDC configuration, based on the creepage requirement for DC thatdepends on the pollution zone. This isdepicted in Figure 6 for twodifferent HRTG insulator arrangementsfromSediver – C170DR and C195DRwithleakage distance of 550 mm and 635 mm repsectively[2]. Accordingly, the power transmission capacityranges between 520 MW and 740 MW when the thermal current rating of the conductorisassumed at 1800 A withsymmetric monopole HVDC configuration asshown inFigure 7.

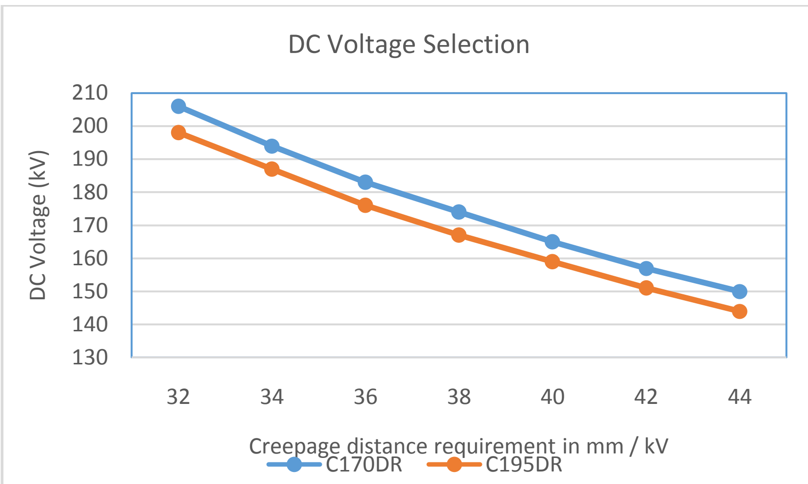

Figure 6 Range of dc voltage selection for diff creepage distance requirements

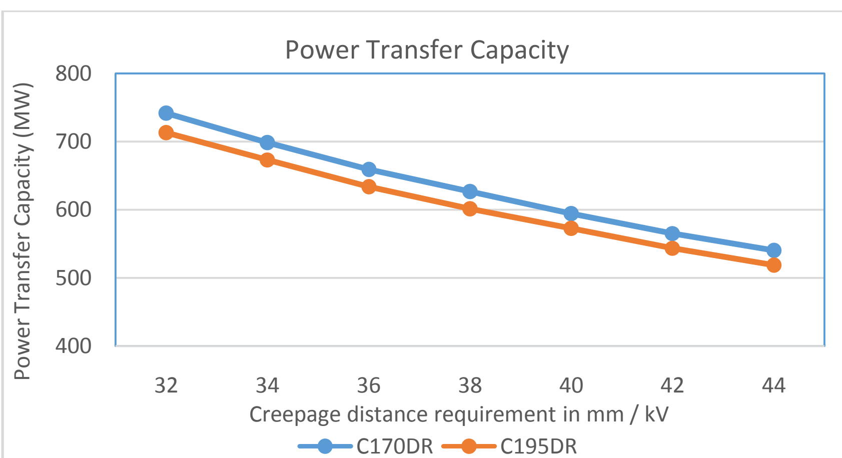

Figure 7 Power Transfer Capacity as a function of creepage distance requirement

The use of composite insulatorscanfurtherimprove the power transmission capacityeither, by means of higher dc voltage selection, or handle the heavilypolluted zone of the transmission section in the presented dc voltage selection range. Suitable modification to the cross arm arrangements canalsoensureadequate clearance and higher dc voltage selection as shown in Figure 8. The thermal current rating of the conductorcanbeincreasedeither by adding more subconductors or replacingwith new conductor. This in turnenhances the power transmission capacity in the existingRoW.

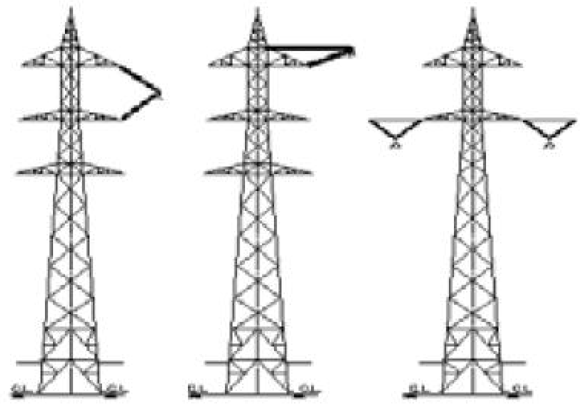

Figure 8 Conversion to higher dc voltage by suitable modification in tower structure [7]

5. Conclusion and Discussion

The opportunities and challenges in refurbishing the existing AC transmission to DC transmission in the existingRoWisdetailed. Prior to conversion, variousfactorsthatneed to beevaluatedisdiscussed and various configurations of HVDC thatcanbeconsidered in the conversion isalsopresented.

From the presentedresults for a typical 220 kV AC system, itisobservedthat the pollution levels / creepage distance requirementssignificantly influences the selection of DC voltage. The use of composite insulatorsmayresult in selection of higher DC voltage. Alternately, modification to the cross arm or tower structure canalsoallow for higher DC voltage selection. The thermal rating of the conductorcanbeincreasedeither, by adding more sub-conductors or replace the conductorwithhigher thermal rating sothat the power transmission capacity of the transmission system in the existingRoWisenhanced. In all the above scenarios, economics of AC to DC conversion have to bestudied on case to case basis to arrive at a decisionbeforeitistaken for implementation.

BIBLIOGRAPHY

[1] Michael Hausler, Gernot Schlayer and GerdFitterer, “Converting AC power lines to DC for higher transmission ratings”, ABB Review, Vol 03, 1997

[2] Sediver datasheet for HRTG insulators for HVDC Applications - http://www.sediver.com/downloads/img_downloads_toughened_glass/pdf_glass/Catalogue_HVDC_USA2013.pdf

[3] J. Lundkvist, I. Gutman, and L. Weimers, “Feasibility study for converting 380 kV AC lines to hybrid AC / DC lines,” in EPRI High-. Voltage Direct Current & Flexible AC Transmission Systems. Conference, Westminster, USA, Nov. 2009, pp. 1-25

[4] https://www.amprion.net/Grid-expansion/Our-Projects/Ultranet/

[5] https://www.ofgem.gov.uk/sites/default/files/docs/angle_submission.pdf

[6] Guide to the conversion of existing ac lines to dc operation, Cigre TB 583, 2014

[7] M.I.Khan and R.C.Agrawal, “Conversion of AC line into HVDC”, IEEE PES Conference and Exposition in Durban, South Africa, 11-15 July 2005

Asset Management Using CCTV and Thermal Cameras

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ABSTRACT

We are well aware that CCTV cameras are playing critical role in various areas like crime prevention, traffic monitoring, Industries process monitoring, sports, offices, school and , home security etc. by providing digital medium of continuous monitoring at very low cost as compared to human deployment.

In this paper firstly we are discussing use of CCTV cameras with VCA (Video content analysis technology) for cable route monitoring on roads which can help in reduction of tripping due to external damage to underground cables during uninformed excavations on roads. This can also save crore of rupees which utilities are spending on manual patrolling.

Secondly we are discussing use of Thermal CCTV cameras and sensors with automated software system inside power station switchyards for remote fault detection, alarm generation and immediate analysis of dynamic conditions. This can also reduce tripping in switchyard components by generating early of defects. Financially this can also save lacs to crore of rupees depending upon type of equipment's.

1. INTRODUCTION

Closed-circuit television (CCTV), also known as video surveillance is the use of video cameras to transmit a signal to a specific place, on a limited set of monitors. CCTV cameras are playing critical role in various areas. A 2009 systematic review by researchers from Northeastern University and University of Cambridge used meta-analytic techniques to pool the average effect of CCTV on crime across 41 different studies.[1] The results indicated that

1. CCTV caused a significant reduction of crime by on average 16%.

2. The largest effects of CCTV were found in car parks, where cameras reduced crime by on average 51%.

3. CCTV schemes in other public settings had small and non-statistically significant effects on crime: 7% reduction in city and town centers and 23% reduction in public transport settings.

CCTV cameras are also helping in traffic monitoring, Industries process monitoring, sports, in offices, in schools for safety purpose and home security etc.

Instead of crime we will discuss here usefulness of CCTV cameras in reduction of tripping due to external damages to cables. Underground utilities like power, telecommunication, gas, water line, sewerage line gets damaged during excavation by various authorities and utilities on roads for various new development infrastructural work or repair and maintenance work. These damages results into safety risk to nearby persons, interruption in utility service and high cost for repairing the damaged utility. For one 11kv high voltage power cable damage repair it costs around Rs.1.5 Lacs. So it costs around Rs.1 crore annually if 70 damages happens to 11KV Cables of a power utility. External damage cable fault also affects reliability indices like CAIDI, SAIDI, and SAIFI. Thus increasing damages to underground utilities during excavation activities has become major problem in present days.

Other problem is that each utility have different manual patrolling activities for avoiding damages during excavation. Thus each utility spends crore of rupees individually for patrolling activities while they are at common roads. There are many reasons of damages but it is observed that 50 % of damage cases are due to non-prior information about excavation to utilities while each utility is having their separate patrolling activity.

In this paper it is proposed that instead of having individual manual patrolling we can use CCTV cameras with VCA (Video content analysis technology) for cable route monitoring on roads which can help in reduction of tripping due to external damage to underground cables during uninformed excavations on roads. This can also save crore of rupees which utilities are spending individually on manual patrolling.

Secondly we are discussing use of Thermal CCTV cameras and sensors with the help of automated software system inside power station switchyards for remote fault detection, alarm generation and immediate analysis of dynamic conditions. This will reduce error which generally happens due to human involvement. This can also reduce tripping in switchyard components by generating early of defects. Financially this can also save lacs to crore of rupees depending upon type of equipment's saved from failure.

1. EXTERNAL DAMAGES TO UTILITIES

As we can see in our cities majority of utilities like power, gas, telecommunication, water line, sewerage line are laid underground. If we take example of Mumbai then there are following major underground utilities & authorities.

1- Tata Power

2- Reliance Infra

3- BEST (Power Utility)

4- Mahanagar Gas Ltd.

5- Reliance Jio

6- Airtel

7- Vodafone

8- Idea

9- Reliance communication

10- Tata Telecommunication

11- MTNL

12- Sewerage Line (MCGM & MBMC)

13- Water Line (MCGM & MC+BMC)

14- DTH Services

15- CCTV & Signal systems (MCGM & MBMC)

16- MCGM & MBMC for various (Roads, drainage and other works)

17- MMRDA & PWD (Bridges & Highways)

Total road length of Mumbai City is 1941 KM [5]. Each utility has multiple lines on same roads so we can say that there is very huge network of utilities in thousands of KMs on Mumbai roads. It is observed by Tata Power patrolling reports that daily minimum approximately 100 excavation happens on Mumbai roads during nine months of fair season from October to June. Majority of these excavations are for new infrastructural work by MCGM for roads, water line, drainage, sewerage bridges etc.

To make it easily understood that how external damage takes place let's take a case of new concrete road construction work which was started by MCGM at Mindspace on 6th Jan 2016. Tata Power cables were laid along that road. JCB operator and his supervisor was not aware about the cable or utilities laid under the road. MCGM or his vendor has also not pre informed to other utilities that they are taking excavation on particular road on particular day and time. MCGM road contractor suddenly started excavation work with JCB at 8 am in the morning. JCB bucket punctured Tata Power cable and other communication utilities also. Similar to above example utilities get damaged during excavation work by other authorities and utilities. Such damages happen because excavation happen without pre information to other utilities due to which no utility representative can be present to guide excavation party about presence of his utility lines. There are also other reasons of damages to utilities but non prior information contribute in majority.

2-EFFECTS OF EXTERNAL DAMAGES

In the above example external damage has resulted into tripping of power supply and consumers got shutdown till restoration. Reliability indices like CAIDI, SAIDI, and SAIFI get affected by such tripping. Some time when there is no back up or main and back up feeders get damaged then consumer face complete shutdown sometimes up to 24 hours. We can imagine that how difficult is that to live in a city like Mumbai without power for 24 hours. There are critical consumers like hospitals, schools, colleges and airports which get affected by such power failure. Patients who are in ICU can face emergency situations if backup is not available. In similar way damages to other utilities like Gas, Water Department, communication etc. creates difficulties to public.

In above example it costed approximately Rs.1.5 lakh to Tata Power to repair the cable. Taking a case where minimum approximate 70 high voltage cable damages happen to a power utility which cost around Rs.100 Lacs. Similarly huge cost occurs to other utilities also. So cost of damages repair is unnecessary financial loss to utilities. There is also revenue loss to utilities if interruption happens in utility services due to damages.

Whenever damage happens to high voltage power cables it result into big flashover due to direct grounding of high voltage power to earth. There are incidences when nearby persons got injured due to such flashovers. In similar way damage to Gas line can injured to nearby persons or fire can take place in the area.

3-CURRENT PRACTICES OF PATROLLING TO AVOID DAMAGES AND DIFFICULTIES.

Individual patrolling activities - Patrolling activity means covering all roads where utility lines are present with the help of bike or other methods. Patrolman covers their assigned roads on daily basis and reports if any excavation is observed on their utility routes. As per current practice Individual utility have individual patrolling activity to cover their network on roads. Following are the difficulties in this.

(1) In Patrolling activity patrolman cannot stay at one location all the time as he has to move to cover certain route in a day. So there are cases when excavation starts before he reach at excavation location or after he leave that location. So patrolling activity can capture only those excavation information which are already started and continue for at least two days. So it is not possible to capture 100% live information by manual patrolling.

(2) There are around 10 utilities which monitor their utility routes on Mumbai roads with individual patrolling activities. Generally multiple utilities can be found on same roads in Mumbai as all utilities are basic needs of public residing in all over of Mumbai. Though there are multiple utility on same road but that road is being patrolled manually multiples times by different utilities. If there are 10 different utilities then 10 different patrolling teams are assigned to patrol their individual utility routes on roads

(a) One of the consequence of individual utility patrolling activities is that sometimes few utilities get missed for pre intimation as working authority or utility do not bother to inform all utilities or they forget to inform due to large no. that is 10 no. of utilities.

(b) Second consequence is burden of unessential cost on individual utilities by multiple patrolling activities on same routes. For an example if a utility spend Rs.2 crores on their patrolling activity then it will cost Rs.20 crore for 10 utilities. It is clear that same activity can be done by spending only 50 % cost on single patrolling activity with the help of CCTV cameras in the city

Figure 1: Patrolling with bike

3. PROPOSED MODEL OF PATROLLING WITH USE OF VCA BASED CCTV CAMERAS:

Basic idea behind CCTV based patrolling is to get 100% continuous information about excavation on roads which are having underground utilities, to reduce crore of rupees cost of individual manual patrolling activity and to avoid human involvement in patrolling activity. Excavation information will be collected through CCTV cameras installed throughout the city and then will be shared to all utilities, Figure2

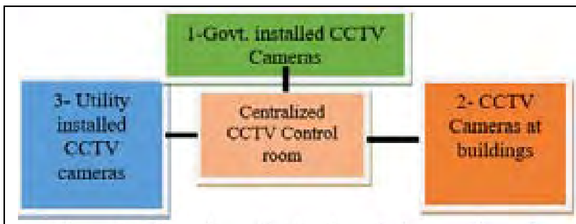

Figure 2: Information collection through three medium of CCTV cameras

Following is the proposed model of CCTV based monitoring of cable routes.

1. There will be three mediums by which CCTV cameras will be used

1.1. Govt. Installed CCTV cameras for police surveillance.

1.2. CCTV cameras installed at buildings for personnel security.

1.3. Utilities installed CCTV cameras for monitoring purpose at special locations.

2. If we take an example of Mumbai there is nearly 5000 cameras already installed in Mumbai area for 24X7 watch on more then 80 % area of city [3]. CCTV cameras range vary minimum 100 mtrs upto 500 mtrs. So approximately 1000 KM of Mumbai roads are being continuously monitored with CCTV cameras. These cameras can really help for monitoring of cable routes in replacement of manual patrolling.

3. It is also a current trend that shops, houses, schools, hospitals, multistory buildings etc. install CCTV cameras in front of their entry gate for security reasons. These cameras covers 100 mtr range at both directions. We can found CCTV cameras in almost every roads in Mumbai which can be easily used for monitoring purpose by connecting them to centralized server.

4. Considering above point no. 2 and 3 there may be 10 % areas where we cannot find pre-installed CCTV cameras in Mumbai as well as in other metro cities. In those areas utilities can install CCTV cameras for ensuring 100 % monitoring of cable routes on roads.

5. It is proposed that all CCTV cameras of above 3 mediums in a city will be connected to centralized control room by adopting various advanced IT network methodologies.

6. Centralized control room server will be equipped with VCA (Video content analysis), AI (Artificial Intelligence) and Machine learning software.

7. For cable route monitoring purpose JCB's, HDD machine or any other related excavation activity identification parameters will be loaded in CCTV camera software. If any JCB, or HDD machines will pass through any camera or any excavation activity will happen at any area then software will

automatically generate a pop up with google location and will automatically send to all concerned to further safeguard the cables at excavation location.

8. Centralized control room may be governed by Govt. or by private company. This centralized control room will serve for agencies like police, Power utilities, Gas utilities or any other agency which require CCTV data for their use.

9. Centralized control room will share information to agencies on the basis of decided charges. The share of charges will also be paid to owners of CCTV cameras weather it may be govt., buildings owners or utilities.

10. If any excavation information is received from outside medium and any agency wants to see live situation at that location then centralized control room can check live video of that location through CCTV and can share it to concerned person automatically through mobile app.

11. Approved users of various agencies can be given access of CCTV cameras of their areas on smart phone so they can easily track excavation over phone after reporting.

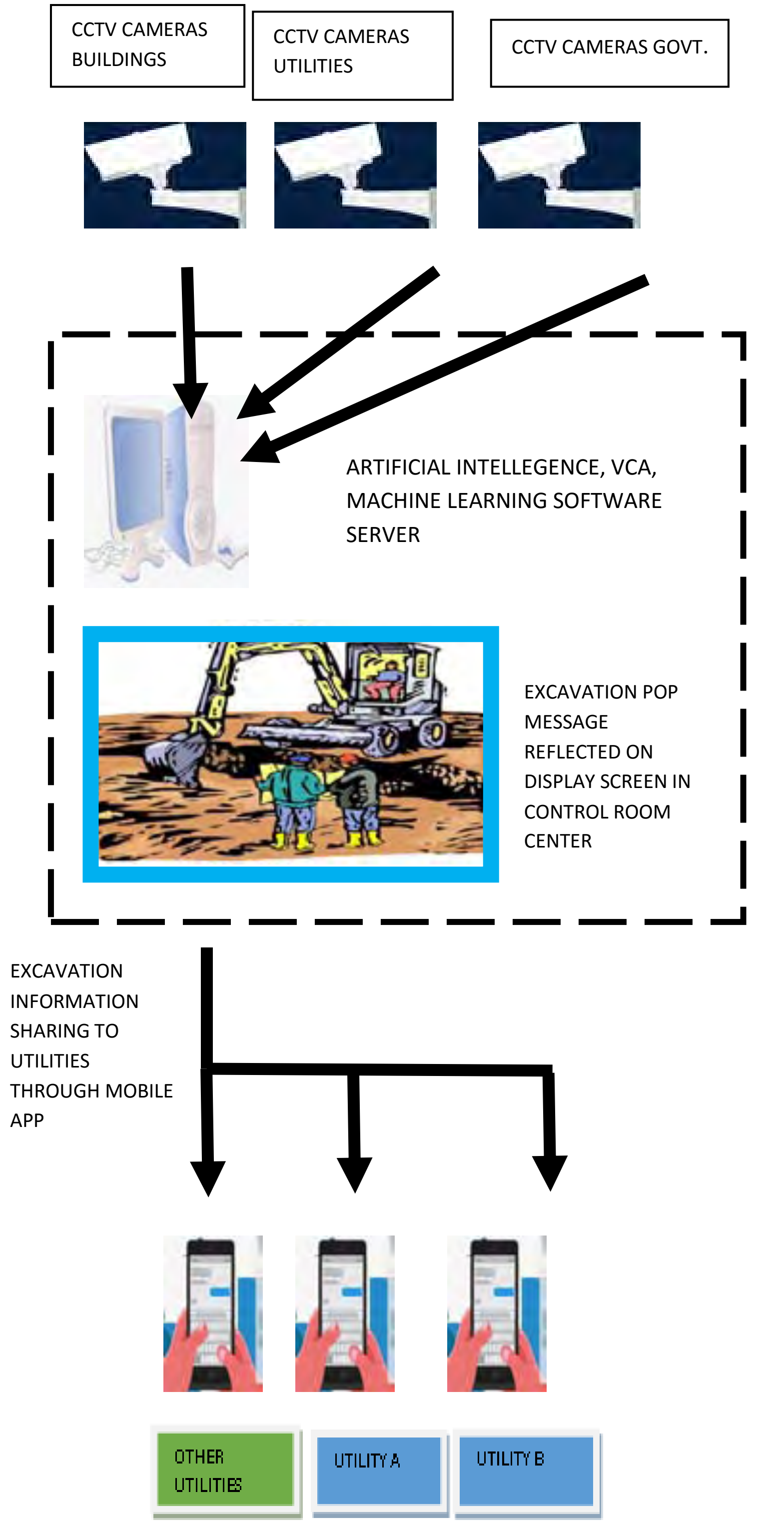

Figure 3: Model of CCTV based monitoring of excavations on cable routes

5. COST SHARING AMONG UTILITIES FOR GETTING LIVE EXCAVATION INFORMATION THROUGH CCTV

Charges to be paid to CCTV control room center for getting live excavation information- Agencies would use CCTV cameras for monitoring purpose only if they find it cheaper then manual patrolling. It is proposed that control room center should charge at maximum of 50 % of manual patrolling cost to utilities so that utilities can opt for CCTV control room center for patrolling purpose.

We propose that cost of sharing excavation information to utilities can be in multiplication of their network road lengths. There are 10 no. of utilities having major network on Mumbai roads but just for easy understanding let's take an example of 3 utilities A,B&C with their network road length 1000 KM, 500 KM, 250 KM, respectively. These road lengths are in common area. Suppose that manual patrolling cost for 100 Km is 24 Lacs annually or Rs 2 lacs monthly for individual utility then maximum excavation information charges to utilities can be as below.

Utilities	Road length X	Manual patrolling cost Y= X*.24 Lacs	Maximum cost can be charged to utility Z= Y*.5	Profit to control room center and utility = 50 % of manual cost
Utility A	1000	240	120	120
Utility B	500	120	60	60
Utility C	250	60	30	30
Total H	1750	420	210	210

Table 1: Profit calculation to utilities and control center with use of CCTV cameras

We can say that if no. of utilities will be more then collection of information sharing charges by control room center will be more so charges can be reduced further.

Service charges to be paid to owners of CCTV Cameras by CCTV control room - As we have seen in 4.1 above that there will be three mediums which will provide CCTV cameras for continuous monitoring of any city. So it is necessary to pay certain charges to owners of CCTV cameras so they can get return for service they are providing. It is assumed that profit sharing among Control room center and owners of CCTV cameras should be 50-50. So in above case Rs 105 lacs which is 50 % of Rs 210 Lacs should be paid to CCTV camera owners. For example there are CCTV cameras which has approximately 200 mtr range for monitoring then in 1000 KM area total 5000 Cameras would be installed . As per below calculation each CCTV will earn at least Rs 0.024 lacs or Rs 2400 annually from one utility for providing service of CCTV cameras to CCTV Control Room . This value can be more if more utilities will be involved in using CCTV camera service.

Secondly we can see that CCTV cameras are already being used for security purpose by building owners while this will be an additional income to CCTV owners.

Utilities	Road length X KM	Total Annual Profit to be shared with CCTV camera owners Y = 50 % control room center profit	No. of CCTV cameras used with example of 200 mtr Range Z= X*1000/200	Annual Profit in Lacs to one CCTV=Y/Z
Utility A	1000	120	5000	0.024
Utility B	500	60	2500	0.024
Utility C	250	30	1250	0.024
Total H	1750	210	8750	0.072

Table 2: Profit calculation to CCTV camera owners

6 - BENEFITS OF CCTV BASED PATROLLING

Performance improvement - There are approximately 50 % utility damage cases which happens when authorities and utilities do not provide prior excavation information to other utilities. With the help of CCTV control room centre it is expected that 99 % live information about excavation will be received. So 50 % damages can reduce to minimum 20 % as all excavation information will be received. Utility performance index SAIFI, SAIDI , CAIDI is linked to uninterrupted availability of utility services. So if damages will reduce then tripping will reduce and this will improve utility performance index.

- Cost saving - 11 KV High Voltage Power cable damage repair cost is approximately Rs.1.5 Lacs. Considering a case that a utility is having 70 damages in a year costing then it cost around Rs.105 Lacs. If 30 % of 50 damages that is 20 no. of damages will reduce with the help of CCTV Center then this will save around Rs.30 Lacs annually. We can also see in Table 1 that Rs. 210 Lacs will be saving against manual patrolling

- Safety to society - Damages to power and gas lines can create flash over and fire which can cause injury to nearby passing persons. Thus reduction in damages to power and gas utilities with the help of CCTV will improve safety to public.

- Improvement in utility services to public - As damages will reduce tripping to essential utility services like power, gas, telecom, water will reduce thus utility service to public will improve.

- Revenue through uninterrupted service - If damages to utilities will reduce then tripping in utility services like power, gas, telecom, water will reduce. Uninterrupted service will provide more revenue to utilities.

- Help to Govt. authorities - Government municipal authorities will also be the member of CCTV so data of excavation activities will be available for them to track the excavation on roads coming under their judiciary. Police can also use that data to manage traffics and issue traffic permission to utilities.

7 Current practices of condition monitoring with manual condition monitoring and difficulties.

- Condition-based maintenance (CBM), shortly described, is maintenance when need arises. This maintenance is performed after one or more indicators show that equipment is going to fail or that equipment performance is deteriorating.

- Basically we are discussing here only Thermoscanning method of condition monitoring by which we try to identify hotspot in various parts of components in switchyard and attend it before it result into fault.

- As per existing practice one person goes to substation switchyards and takes thermal images of various equipment's and try to find out hot spot manually with higher temperature above then maximum limit.

¯ If any hotspot with temperature above then limit is observed then he arrange maintenance of that component to avoid hotspot and further failure of equipment.

¯ Difficulty in manual Thermoscanning are as

1. It does not provide continuous thermal monitoring of equipment's.

2. Error prone manual thermal inspection

3. Do not Identify transient thermal events as not detectable with manual inspections

4. Manual analysis is required for data captured during thermal imaging for predicting health of equipment.

8 Proposed model of condition monitoring with use of VCA based Thermoscannig cameras

This model allows us to continuously monitor the temperature profile of assets within an electrical power substation remotely. It helps us detect temperature devia-tions from normal operation conditions to ensure safe and reliable operations.

An overview schematic of the system is shown below. The system consists of thermal and visible cameras mounted on a positioner with continuous 360° pan range and tilt range of ±45°. A junction box with all of the necessary hardware for power and data transfer is also included. This allows for quick access to the camera's thermal readings and configuration options. Fixed image cameras and pyrometers can also be added to the system.[4]

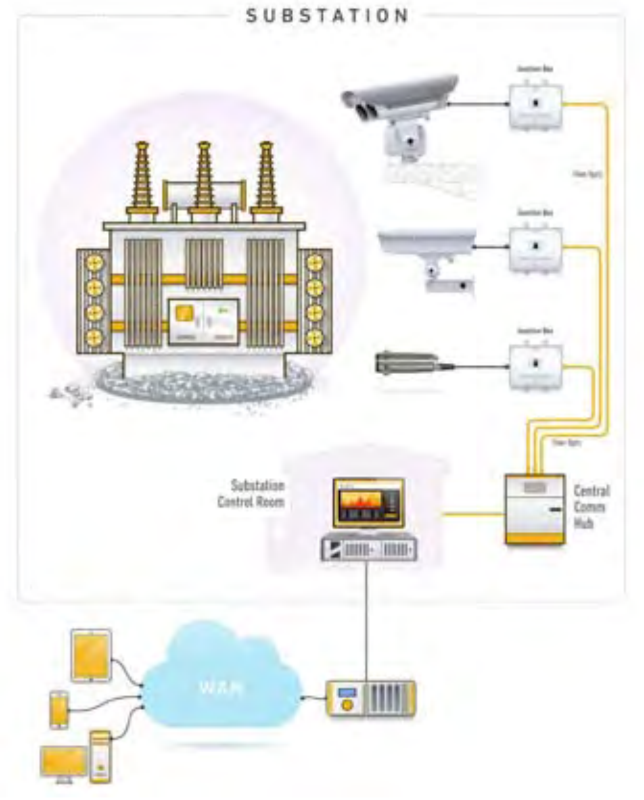

Figure 4: Proposed model of condition monitoring with use of VCA based Thermoscannig cameras

9 Cost analysis of remote Thermoscanning.

This is not easy to calculate cost of manual Thermoscanning as it varies with respect to different company's condition monitoring procedures and size of switchyards. Here we are taking an example of switchyard having one power transformer with other required switchgear accessories. Remote Thermoscaning setup will cost around Rs 10 Lacs. If one person is deputed in shifts for similar round the clock Thermoscanning Job then it will cost around Rs 60,000 per months and Rs. 7.2 Lacs annually for 3 persons in shifts. So we can save installation cost of Rs. 10 Lacs in first 1.5 years.

Secondly if any power transformer, jumper, terminations etc. fails it could cost from Rs 1 Lacs to Rs 50 Lacs including revenue losses so we can say that at critical substations if we install above remote condition monitoring setup then we can save huge cost due to failure of equipment's.

10 Benefits of remote Thermoscanning.

1. Automated, continuous thermal and visual imaging of substation for performance and safety

2. Early and remote fault detection

3. Monitor newly installed assets or older assets after maintenance to identify risk for infant mortality or faults

4. Continuous monitoring without personnel constraints

5. Replace error prone manual inspection process with more rigorous and continuous automated monitoring

6. Identify transient thermal events not detectable with manual inspections

7. Remotely monitor multiple, distant substations from a central location

8. Automated analysis with built-in industry-standard analytics

Conclusion -

Above model of CCTV based cable route monitoring states that damages to individual utilities during infrastructural or repair and maintenance work can be easily reduced as continuous monitoring of excavation on roads can be easily achieved. Utilities can timely safeguard cables and pipes if early information of excavation will be received by utilty. This can also save crore of rupees which utilities are spending on manual patrolling activities.

Secondly, we also discussed above model of remote Thermal CCTV cameras and sensors with automated software system inside power station switchyards for remote fault detection, alarm generation and immediate analysis of dynamic conditions. This can also reduce tripping in switchyard components by generating early alarm of defects. Financially this can also save lacs to crore of rupees depending upon type of equipment's, by saving equipment from failure.

REFERENCES

1."Public Area CCTV and Crime Prevention: An Updated Systematic Review and Meta-Analysis". Journalist's Resource.org.

2.https://en.wikipedia.org/wiki/Artificial_intelligence_for_video_surveillance

3.https://www.thequint.com/tech-and-auto/tech-news/eyes-mumbai-4700-cctv-cameras-traffic-crime-city-surveillance-project-larsen-toubro

4.https://www.lumasenseinc.com/EN/products/temperature-measurement/thermal-imagers-systems/lumaspection-systems/thermalspection-724-system/thermalspection-724.html

5.https://timesofindia.indiatimes.com/city/mumbai/No-of-cars-up-34-in-6-years-Mumbai-roads-same-for-50-years/articleshow/17864082.cms

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Investigation of Diagnostic Technique for Thermal Fault on Natural Ester Oil-immersed Transformer by Dissolved Gas Analysis

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SUMMARY

Dissolved Gas Analysis (DGA) of insulating oil has been widely used as an essential diagnostic technique for condition assessment of oil-immersed transformers. Many researches and investigations have been reported for the DGA of mineral oil-immersed transformers and guidelines have been proposed to assess the condition of oil-immersed transformers in the world. Recently transformers using alternative insulating oil such as natural ester oil have been installed extensively because of its good environmental and fire safety aspect such as biodegradation, carbon-neutral and high flash point. Consequently there is an increasing demand for the diagnostic techniques and guidelines for DGA of the natural ester oil-immersed transformers.

This paper describes the behaviour of gas generation obtained by heating test of natural ester oil simulating thermal fault of natural ester oil-immersed transformer. Natural ester oil were continuously heated for 10 minutes at the temperature from 100 ^{o}C up to 900 ^{o}C with the step of 100 ^{o}C. After the heating tests, combustible gases such as hydrogen, methane, ethylene, acetylene and ethane were detected and the correlation was observed between heating temperature and concentration ratio of decomposed gases.

Further improvement of the accuracy of estimation of overheating temperature, a diagnosis map using a combination of multiple ratios of gas concentrations is also commonly used for diagnosis of thermal fault. The diagnosis maps selected from combination of gas including acetylene are most effective diagnosis map to diagnose overheating temperature of ester oil-immersed transformer. Even in case when acetylene is not detected or high concentration of hydrogen only detected such as Stray Gassing, the overheating temperature of natural ester oil-immersed transformer can be estimated by using the diagnosis map with another indicator gas not using acetylene or hydrogen.

KEYWORDS

Transformer, Natural ester oil, Internal fault, Thermal Fault, Overheating, Dissolve gas analysis (DGA), Concentration ratio, Diagnosis map.

1. INTRODUCTION

Dissolved Gas Analysis (DGA) has been widely used as an essential diagnostic technique for condition assessment of mineral oil-immersed transformers. Much research and experience has been reported for the DGA of mineral oil-immersed transformers and the guidelines have been proposed to diagnose the condition of transformer [1]. On the other hand, alternative insulating oils such as natural ester oils have become more widely used because of their good environmental and fire safety aspect such as biodegradation, carbon-neutral and high flash point (Figure.1), and standards for natural ester oils have been established and revised in recent years [2]-[4]. Consequently there is an increasing demand for diagnostic techniques and guidelines for DGA of natural ester oil-immersed transformers [5]-[10].

This paper describes the experimental results of the gas generation behavior by conducting heating test in natural ester oils. From the result of heating tests, combustible gas such as hydrogen, methane, acetylene, ethylene and ethane were detected and the temperature dependence of the detected gas concentration ratio was observed. Technique of gas concentration ratio is effective for estimation of overheating temperature of natural ester oil-immersed transformer.

Fig.1 Natural ester oil-immersed transformer (77kV / 20MVA)

2. EXPERIMENTAL PROCEDURE

Heating tests of natural ester oil was conducted by using the experimental apparatus which consists of following major parts as shown in Figure 2.

1. Experimental tank with conservator which mitigates the expansion of the oil in the experimental tank due to heating
2. Heater with AC source
3. Thermometers measuring the temperatures of heater surface and natural ester oil
4. Magnetic stirrer and stirrer bar
5. Syringe for the oil sampling

After sufficient degassing, both ester oils were continuously heated for 10 minutes at the temperature from 100 ^oC up to 900 ^oC with the step of 100 ^oC. After conducting the heating tests at each temperature, ester oil was stirred by a magnetic stirrer to uniform the concentration of generated gases in ester oil and the oil was sampled by syringe to analyze dissolve gases in the oil by gas chromatograph with the stripping type gas extraction system. Well-known decomposition gases in oil of hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4) and ethane (C_2H_6) were analyzed. Since carbon monoxide (CO) and carbon dioxide (CO_2) are regarded as typical decomposition gases generated from solid insulating materials such as pressboard and coil insulating paper, they have been excluded from candidates for indicator gas. The summary of testing conditions is shown in Table 1. Figure.3 shows the natural ester oil after heating test.

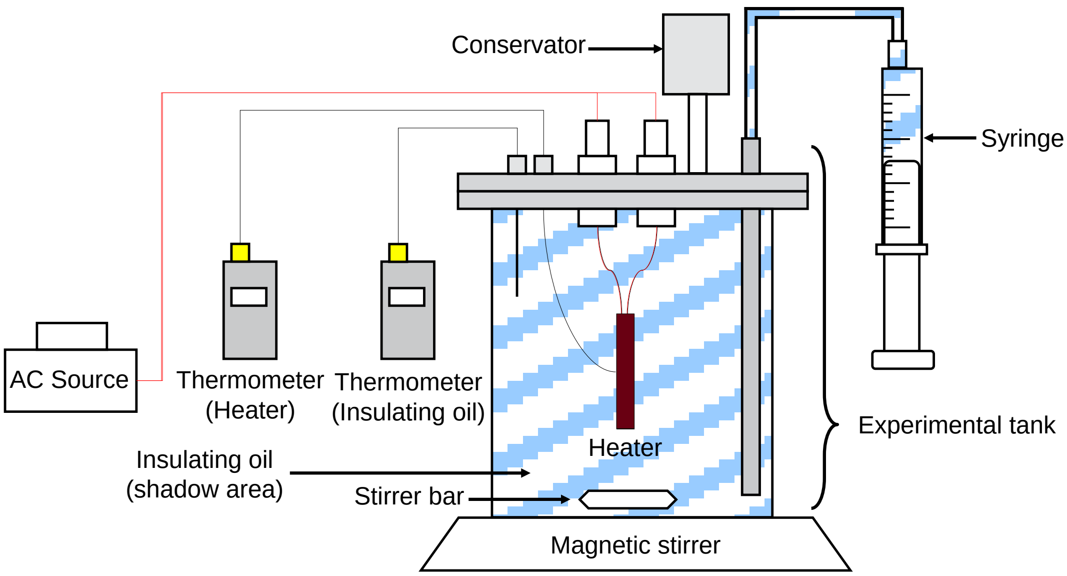


Fig.2 The apparatus for heating test of the ester oils

Table.1 Test Conditions

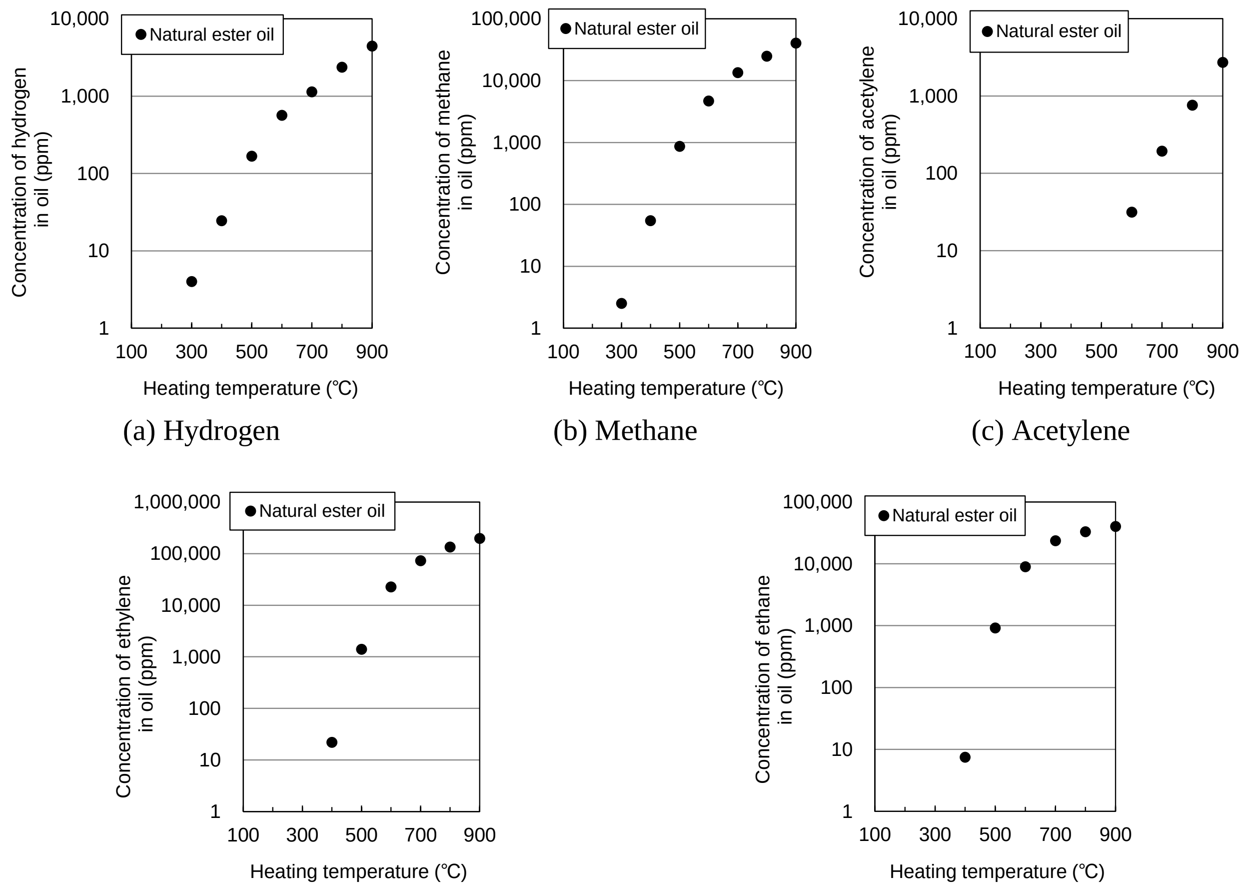
Items	Conditions
Heating temperature (°C)	100, 200, 300, 400, 500, 600, 700, 800, 900
Heating duration (min)	10
Amount of oil (mL)	1,000
Oil Type	Natural ester oil
Analyzed gas component	Hydrogen (H_2), Methane (CH_4), Acetylene (C_2H_2), Ethylene (C_2H_4), Ethane (C_2H_6)

Fig.3 Natural ester oil after heating test

3. RESULT AND DISCUSSION

3.1 Relationship between heating temperature and concentration of gases in ester oil

The analyzed gas components were detected in natural ester oil. The relationship between heating temperature and concentrations of gases in oil are shown in Figure 4. These gases are defined as indicators of an internal fault in the mineral oil-immersed transformer. As shown in Figure 4, concentrations of decomposition gases of natural ester oil, such as hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4) and ethane (C_2H_6) increased as the heating temperature increased. Acetylene was detected at 600 °C or higher. Although concentration of gases other than acetylene tended to saturate at 800 °C or higher, concentration of acetylene was increased in proportion to the heating temperature at 800 °C or higher.



(a) Hydrogen (b) Methane (c) Acetylene

(d) Ethylene (e) Ethane

Fig.4 Relationship between heating temperature and concentration of each gas in oil

3.2 The pattern of gas generation by heating of ester oil

The patterns of DGA results for natural ester oil are shown in Figure 4 which are commonly used in Japan for internal fault diagnosis of mineral oil-immersed transformer [11]. In Figure 4, concentrations of gases are shown in ratio which the highest concentration gas among those 5 gases is set to 1.0. Internal fault such as discharge and overheating was diagnosed by the pattern of DGA.

Although the gas pattern of both ester oils showed a decreasing trend in methane and ethane ratios with increasing heating temperature, the ethylene leading type continues even the heating temperature is 500 ^{o}C or higher. Since the gas pattern of ester oil was not change significantly as compared with mineral oil [11], it is difficult to evaluate the overheating temperature of ester oil-immersed transformer with gas pattern.

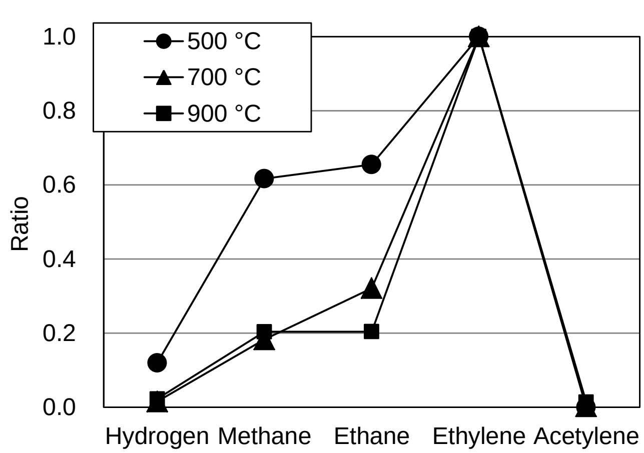


Fig.5 Gas pattern on test cases of natural ester oil

3.3 Concentration ratio of decomposed gas in ester oil

As shown in sub-section 3.2, the decomposition behavior of natural ester oil depends on the heating temperature, and concentrations of the gases were different from each other in heating temperature. In order to analyze the gas generation behavior in detail, concentration ratios of two decomposed gas among five gases, hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4) and ethane (C_2H_6) were evaluated. The concentration ratio of decomposed gases in ester oils as a function of heating temperature are shown in Figure 6.

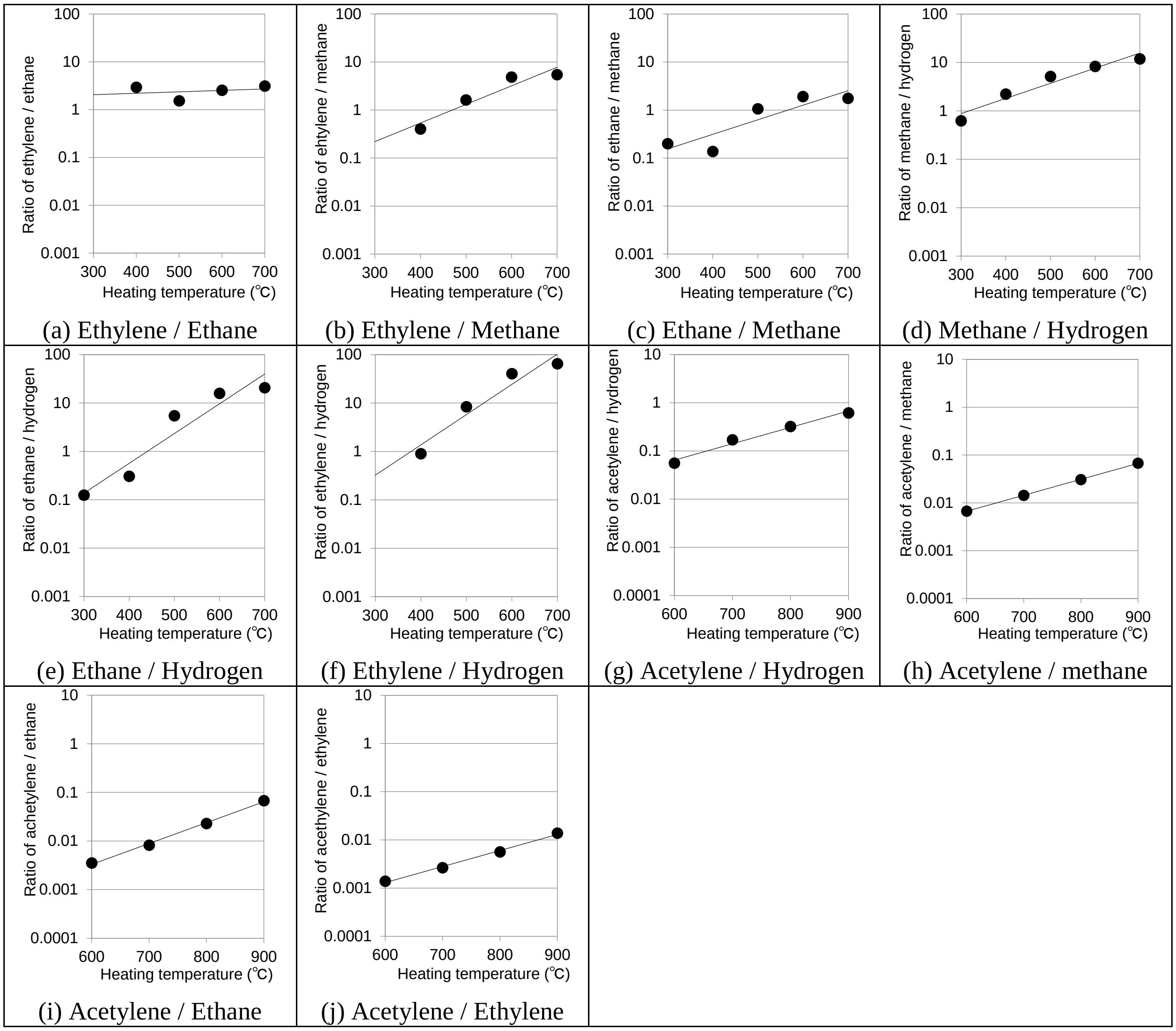


Fig.6 Relation between heating temperrature and ratio of gas concentration

The slope of the approximation formula for each graph was shown in Table 2. Since the concentration ratio of the couple of gases other than acetylene was saturated from 800 ^{o}C or higher, the approximation formula of the heating temperature and the concentration ratio of gases was calculated at 300 ^{o}C to 700 ^{o}C.

As shown in Table 2, the results suggest the possibility of the application of the gas concentration ratio for estimating the overheating temperature of natural ester oil-immersed transformer. A large slope and a high correlation between heating temperature and concentration ratio of gases mean that the gas concentration ratio of the couple of gases shows large temperature dependence, and should provide a high accuracy of the estimation of the overheating temperature.

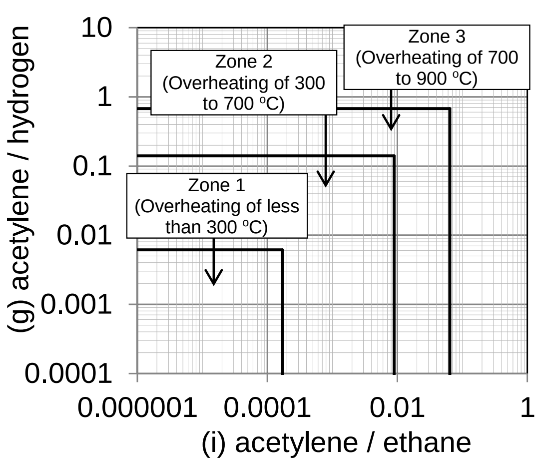
Since the combination of concentration ratios of gases containing acetylene has very high correlation even at high heating temperature (average of correlation coefficients of both ester oils is 0.9 or more) and the slope of the concentration ratio of gases is large, it is considered to be the most effective indicator gas for estimating the overheating temperature of transformer.

Table. 2 Approximation formula of the heating temperature and gas ratio

Combination of gas	Heating temperature range (^oC)	Coefficient of correlation		Slope of approximation formula k*×100000 (* : $y = a e^{kx}$)
			Average	
(a) Ethylene / Ethane	300 to 700	0.075	0.758	69
(b) Ethylene / Methane		0.902		891
(c) Ethane / Methane		0.787		698
(d) Methane / Hydrogen		0.936		720
(e) Ethane / Hydrogen		0.919		1420
(f) Ethylene / Hydrogen		0.930		1440
(g) Acetylene / Hydrogen	600 to 900	0.979	0.993	784
(h) Acetylene / Methane		1.000		768
(i) Acetylene / Ethane		0.997		989
(j) Acetylene / Ethylene		0.995		765

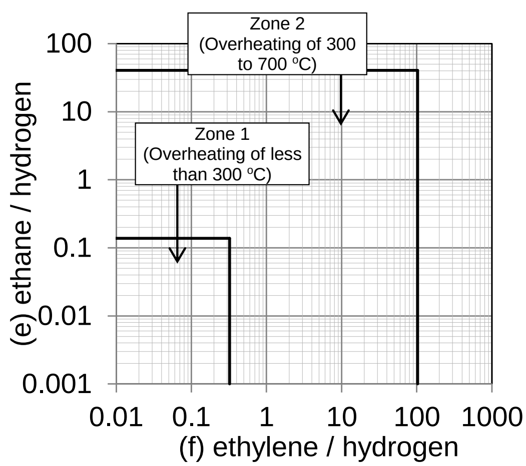
3.4 Investigation of diagnosis map for ester oil-immersed transformer

Further improvement of the accuracy of estimation of overheating temperature, a diagnosis map using a combination of multiple ratios of concentrations of gases is also commonly used for diagnosis of overheating [12]. The same method is applied to diagnosis for ester oil. Figure 7 shows the diagnosis maps which selected from the combination of concentration ratio of gas (g) and (i) in Table2. Three zones are calculated by the approximation formulas in Table 2. Zone 1 corresponds to overheating of less than 300 ^oC, Zone 2 corresponds to overheating of 300 to 700 ^oC and Zone 3 corresponds to overheating of 700 to 900 ^oC. The diagnosis maps as shown in Figure 7 selected from combination of gas (g) and (i) are the most effective diagnosis map to diagnose overheating because of their high correlation of approximation formula and large slope.



Combination of (g) and (i)

Fig. 7 Diagnosis map (In case of including acetylene for indicator gas)

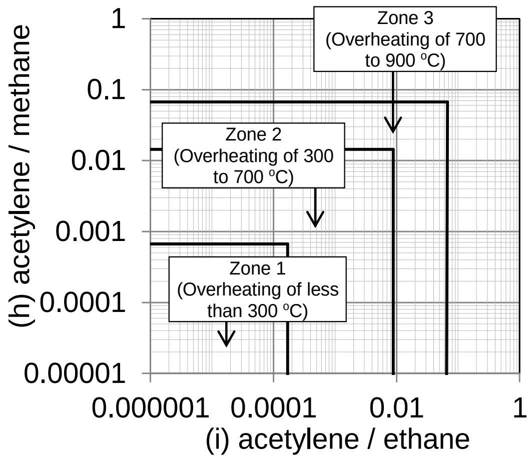


Combination of (e) and (f)

Fig. 8 Diagnosis map (In case of excluding acetylene for indicator gas)

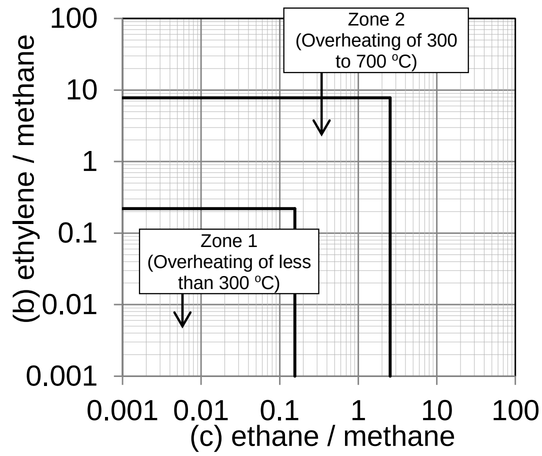
As mentioned above, the diagnosis maps as shown in Figure 7 are the most effective diagnosis map to diagnose overheating. However, in cases when acetylene is not detected or high concentration of hydrogen only detected such as Stray Gassing [13]-[15], it is necessary to evaluate the overheating temperature with another indicator gas except acetylene and hydrogen.

The combination with the largest slope of the approximation formula is (e) and (f) when acetylene is excluded as indicator gas, (h) and (i) when acetylene is included and hydrogen is excluded, (b) and (c) when acetylene and hydrogen are excluded. Figure 8 to Figure 10 show the diagnosis maps of these combinations of the concentration ratio of gas. Even in case when acetylene is not detected or high concentration of hydrogen only detected such as Stray Gassing, the overheating temperature of ester oil-immersed transformer can be estimated by using the diagnosis map with another indicator gas not using acetylene or hydrogen.



Combination of (h) and (i)

Fig. 9 Diagnosis map (In case of including acetylene and excluding hydrogen for indicator gas)



Combination of (b) and (c)

Fig. 10 Diagnosis map (In case of excluding acetylene and hydrogen for indicator gas)

4. CONCLUTION

Indicator gases for overheating on natural ester oil-immersed transformer were investigated by heating test. The conclusions of heating test of natural ester oils were shown below.

1. The gas generation behaviors of natural ester oil are investigated by the heating test simulating local heating of natural ester oil-immersed transformer.
2. There is a high correlation between the heating temperature of ester oils and the concentration ratio of gas as shown in Figure 6, Table 2.
3. The diagnosis maps selected from combination of gas including acetylene are most effective diagnosis map to diagnose overheating of ester oil-immersed transformer. Even in case when acetylene is not detected or high concentration of hydrogen only detected such as Stray Gassing, the overheating temperature of ester oil-immersed transformer can be estimated by using the diagnosis map with another indicator gas not using acetylene or hydrogen.

BIBLIOGRAPHY

[1] IEC 60599 Ed. 3.0, "Mineral Oil-filled Electrical Equipment in Service - Guidance on the Interpretation of Dissolved and Free Gases Analysis", 2015

[2] IEC 62770 Ed. 1.0, "Fluids for Electrotechnical Applications - Unused Natural Esters for Transformers and Similar Electrical Equipment", 2013

[3] ASTM D 6871-03, "Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus", 2008

[4] IEEE Std. C57. 147, "IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers", 2008

[5] CIGRE Brochure 436, "Experiences in Service with New Insulating Liquids", CIGRE Working Group A2.35, 2010

[6] CIGRE Brochure 443, "DGA in Non-Mineral Oils and Load Tap Changers and Improved DGA Diagnosis Criteria", CIGRE Working Group D1.32, 2010

[7] M. Duval, "The Duval Triangle for Load Tap Changers, Non-Mineral Oils and Low Temperature Faults in Transformer", IEEE Electrical Insulation Magazine, Vol. 24, No.6, 2008

[8] M. Jovalekic, D. Vukovic, S. Tenbohlen, "Gassing Behavior of Various Alternative Insulating Liquids under Thermal and Electrical Stress", IEEE International Symposium on Electrical Insulation, 2012

[9] N. A. Gomez, H. M. Wilhelm, C. C. Santos, G. B. Stocco, "Dissolved Gas Analysis (DGA) of Natural Ester Insulating Fluids with Different Chemical Compositions", IEEE Transactions on Dielectrics and Electrical Insulation Vol. 21, No. 3, 2014

[10] Yu Liu, Jian Li, Zhaotao Zhang, "Gases Dissolved in Natural Ester Fluids under Thermal Faults in Transformers", IEEE International Symposium on Electrical Insulation, 2012

[11] Electric Technology Research Association, No.1, Vol. 65, "Guideline for the refurbishment of electric power transformers", 2009

[12] R. Kuriyama, T. Amimoto, Y. Kimura, F. Kato, S. Hayamizu, "Investigation of Indicator Gas for Internal Fault on Silicone Oil-immersed Transformer", International Conference on Condition Monitoring and Diagnosis 2014, OA-319, 2014

[13] CIGRE Brochure 296, "Recent Development in DGA Interpretation", CIGRE Joint Task Force D1.01/A22.11, 2006

[14] M. Shirai, T. Ishii, and Y. Makino, "Evolution of Hydrogen from Insulating Oil in Transformers", IEEE Transactions on Dielectrics and Electrical Insulation, 1997

[15] Jashavant J. Patel, R Muthuraj and Nayan V. Shah, "Stray Hydrogen Gas Evolution from Power Apparatus", International Symposium on High Voltage Engineering Copyright, 2009

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Transformer On-Line Monitoring System, Key Component for Smart Grid

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Summary
Nowadays, the Smart Grid is new technology for Transmission System. Electricity Generating Authority of Thailand(EGAT) is one of utilities which has started to develop Transmission System to be Smart Grid. The purpose is to develop and refurbish Transmission System to be high performance, modernize and economize. The general understanding is that the Smart Grid is the concept of modernizing the electric grid. The Smart Grid comprises everything related to the electric system in between any point of generation and any point of consumption. Through the addition of Smart Grid technologies the grid becomes more flexible, interactive and is able to provide real time feedback. Transformer On-Line Monitoring System is key component for Smart transformer, Smart substation and Smart Grid. EGAT has installed Transformer On-Line Monitoring System since 2015 in order to study it. Bushing On-Line Monitoring System and Dissolved Gas Analysis(DGA) On-Line Monitoring System were selected to be installed at transformers. Transformer On-Line Monitoring System has some benefits such as warning aging of solid insulation, information for maintenance decision, monitoring malfunction, enable Continuous On-Line Monitoring(OLCM) and etc.

Keywords
Smart transformer, Smart substation, Smart Grid, Transformer On-line Monitoring System, Time-Based Maintenance(TBM), Condition-Based Maintenance(CBM), Continuos On-Line Monitoring(OLCM)

1. Introduction

The Electricity Generating Authority of Thailand(EGAT) was established by virtue of the EGAT Act B.E. 2511(1968) on May 1, 1969, Being a state enterprise in the area of energy under the Ministry of Energy with the Ministry of Finance as major shareholder, EGAT is responsible for generating, acquiring and supplying electricity to the Metropolitan Electricity Authority(MEA), Provincial Electricity Authority(PEA), legal power users, and neighbouring countries such as Malaysia, EGAT is also responsible for power related activities and service, producing and selling lignite and its by-products under the EGAT Act B.E. 2511(1968) and its amendment B.E. 2535(1992)

At present, the operation of EGAT is in accordance with the Electricity Supply Industry whereby, under the supervision of the Energy Regulatory Commission, EGAT is the producer and supplier of electricity and controls over the electricity production and distribution throughout the country to be efficient and adequate for the demand in parallel with environmental management for the community and society.

EGAT transmits electricity generated by its own power plants and purchased from private power producers through its own grid network covering all parts of the country. EGAT's Transmission lines comprise different voltages ranging from 500 kV, 230 kV, 132 kV, 115 kV, and 69 kV. EGAT sells electricity to two distributing authorities, namely MEA and PEA which will deliver electricity to their retail customers countrywide, EGAT also sells electricity to the power utilities of neighbouring countries, namely Lao PDR at 115 kV and at 22 kV lines and Malaysia at 300 kV HVDC lines.

2. EGAT's Transmission System

The amount of Transformers which installed in Transmission System is approximate 700 units. EGAT's has been Transformer's maintenance standard for more than ten years. It is based on Instruction Manual of equipment, International technical papers, IEC standards, IEEE standards, CIGRE's papers and EGAT's experience. It composes of Time-Based Maintenance(TBM) and Condition-Based Maintenance(CBM). It is adopted every 3-5 years. The adoption of maintenance standard is based on the maintenance records.

3. Smart Grid

IEEE's definitions is "The general understanding is that the Smart Grid is the concept of modernizing the electric grid. The Smart Grid comprises everything related to the electric system in between any point of generation and any point of consumption. Through the addition of Smart Grid technologies the grid becomes more flexible, interactive and is able to provide real time feedback.". Some features of current grid have to be changed such as the communications, Operation & Maintenance, reliability and etc. Some technologies that need for Smart Grid evolution such as control, allowing every part of grid to talk and listen, remote monitoring and etc.

4. Smart transformer for Smart Grid

Smart transformer is the key component of Smart substation and Smart Grid. It serves as a hub for collection and distribution. Smart transformer used in Transmission System is component for integration into smart grid technology. There are some differences between Current Grid and Smart Grid. For example, the Smart Grid has to have two-way , real time for communications, Remote monitoring and Condition-Based Maintenance for Operation and Maintenance, Pro-active, real-time protection and islanding for reliability. The digital monitoring in transformer has increased rapidly for a few years. Many transformer manufactures are reconizeing the growing of On-Line Monitoring products. These technologies can be used for improving grid reliability and helping utilities to avoid transformer failures and blackout.

5. Transformer On-Line Monitoring System for EGAT's transformers

EGAT has installed Transformer On-Line Monitoring system since 2015. Two types of On-Line System were selected, Bushing and Dissolved Gas Analysia(DGA) on-line monitoring systems which conform to Guide for Transformer Maintenance CIGRE Working Group A2.34(figure 1). The guide suggests the Continuous On-Line Monitoring(OLCM) is a technique, where a measurement or measurements are continuosly tracked or superviserd, normally by means of and Intelligent Electronic Device(IED). This device will immediately communite, either by means of an alarm or message, any significant deterioration in condition to alert staff to take appropriate action.

5.1 Bushing On-Line Monitoring System

Today, microprocess technology privides a sophisticated means to capture information. It adapts on-line measurement and one of challenges is the management of amount of data. The desired result is to detect the abnormal conditon of equipment, how critical is it and how to do. The level of data analysis cannot be achieved with a simple monitoring. It requires an expert system. The Bushing On-Line Monitoring System is applied for the bushing because the financial loss of bushing leads to damage of transformer as shown in some investigation reports. There are some methods applied to Bushing On-Line Monitoring System as below :

5.1.1 Detect by changing of leakage current

Generally, Oil Impregnated Paper(OIP) bushings have been installed at EGAT's transformers. They are condenser type, consist of several insulation paper layers and separated with aluminum foil for each layer as shown in figure 2. The insulating oil is filled between porcelain and conductor. That means the insulation papers is impregnated. The bushing's capacitance is devided in two parts, C1 and C2 and can be measured by passing Test tap(figure 3). Normally , the C1 is connected to the ground at Test tap. In case of no connection to ground, the float voltage will be 500-2,000 volts as terminal of Test tap. The capacitance and Power Factor will be changed if there is insulation degradation. When the capacitance is changed, it affects to the leakage current. So, The abnormal condition of bushing could be detected by current summation of three phases or comparing between two bushings in the same phase and the increasing trend can be observed and do alarm setting.

5.1.2 Detect by changing of Power Factor or Tangent Delta

Power Factor is the phase angle relationship between the applied voltage across and the current through a specimen, with the angle typically referred to as 'theta'. This angle is typically very close to 90 degrees for capacitive(insulation) circuit. Dissipation Factor is defined as the ratio of power to reactive volt-amperes(W/Var) in a circuit. The Dissipation Factor is equal to the tangent of 'Delta', where 'Delta' is the angle of 90^0 minus 'theta'. For practical insulation circuit, where 'theta' is more than 85^0, the Power Factor and the Dissipation Factor are numerically the same.(figure 4 and figure 5). Normally,the good insulation has a very low Power Factor or Tangent Delta.

5.2 Dissolved Gas Analysis(DGA)

For many years, DGA has been used as a tool of transformer diagnostics in order to detect incipient faults. The idea of DGA is based on the fact that during its liftime the transformer generated decomposition gases, under the influence of various stressed, both normal and abnormal conditions. The purposes of DGA are to have a high probability that when entering a transformer a problem is apparent, prevent and unexpected outage, reduce risk to transformer and to provide a non-intrusive means to determine if transformer incipient fault condition exist or not. The detail of analyzed gases by laboratory is as table 1 and the example of DGA test showed in table 2. The standards which evaluate possible fault type are IEEE C57.104 and IEC 60599. These standards suggest fault diagnosis such as Low-enery density arcing-PD, Arcing-High energy discharge, Thermal fault and etc.

5.2.1 DGA On-Line Monitoring System

In recent years, DGA On-Line Monitoring System has launched in the market. This system has some benefits when comparing with DGA Off-Line System such as warning aging of solid insulation, information for maintenance decision, monitoring malfunction, enable Continuous On-Line Monitoring(OLCM) and etc. The DGA on-line monitoring system has a lot of types in the market as below :

5.2.1.1 Single-gas DGA On-Line Monitoring System

DGA on-line device continuously measures Hydrogen(H2) and Mositure(H2O).

5.2.1.2 Two-gas DGA On-Line Monitoring System

DGA on-line device continuously measures Hydrogen(H2), Carbon monoxide(CO) and Moisture(H2O).

5.2.1.3 Five-gas DGA On-Line Monitoring System

DGA on-line device continuously measures Hydrogen(H2), Carbon monoxide(CO), Methane(CH4), Acetylene(C2H2), Ethylene(C2H4) and Moisture(H2O).

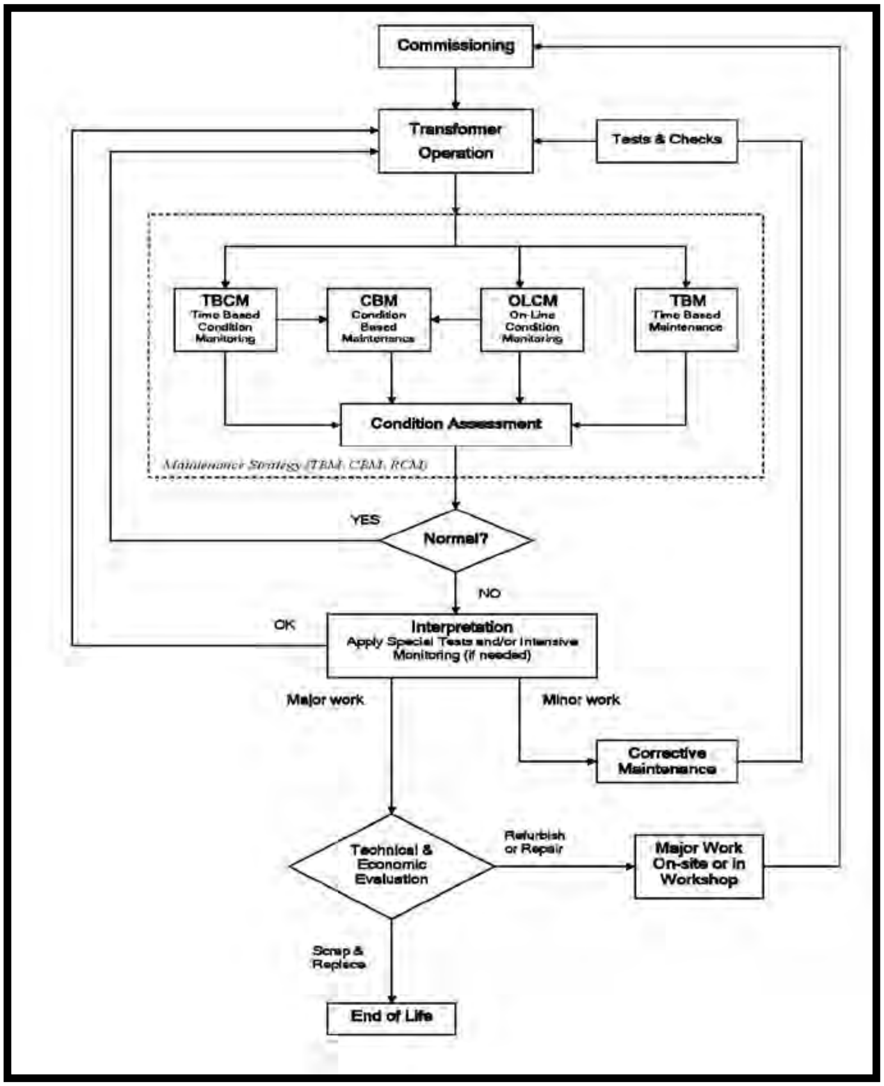
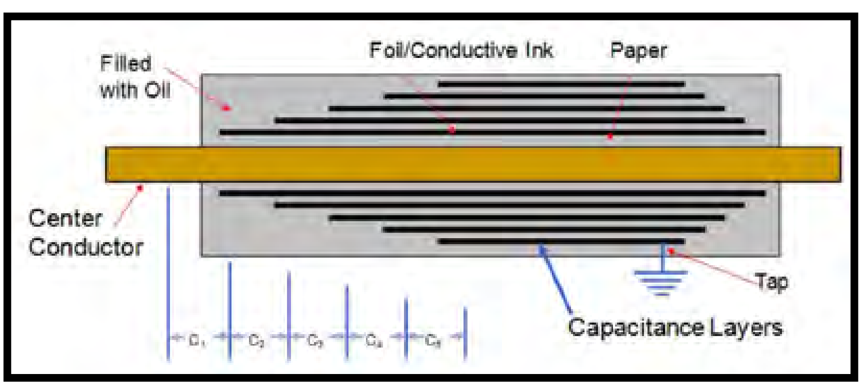


Figure 1 Transformer Operation and Maintenance Cycle



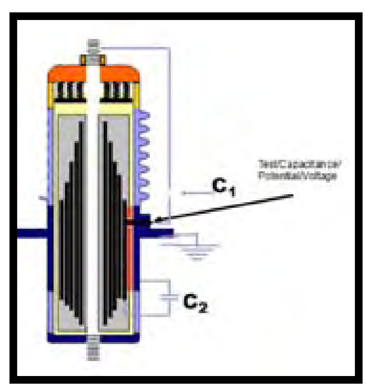


Figure 2 Typical condenser bushing

Figure 3 Test tap

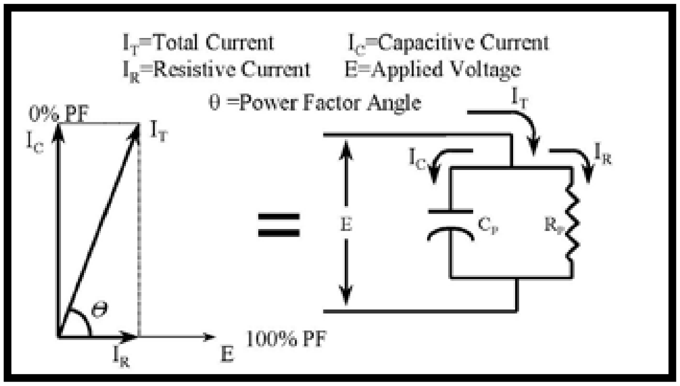


Figure 4 basic Power Factor

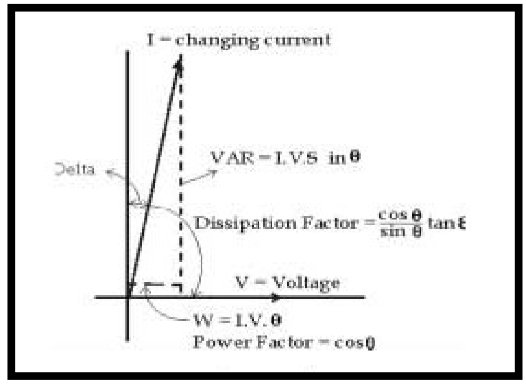


Figure 5 Power Factor/Dissipation Factor

5.2.1.4 Eight-gas DGA On-Line Monitoring System

DGA on-line device continuously measures Hydrogen(H2), Oxygen(O2), Methane(CH4), Carbon monoxide(CO), Carbon dioxide(CO2), Ethylene(C2H4), Ethane(C2H6), Acetylene(C2H2) and Moisture(H2O).

5.2.1.5 Nine-gas DGA On-Line Monitoring System

DGA on-line device continuously measures Hydrogen(H2), Oxygen(O2), Methane(CH4), Carbon monoxide(CO), Carbon dioxide(CO2), Ethylene(C2H4), Ethane(C2H6), Acetylene(C2H2), Nitrogen(N2) and Moisture(H2O).

Table 1 analyzed gases by laboratory

Item	Analyzed gases by laboratory	Formula
1	Oxygen	O2
2	Nitrogen	N2
3	Carbon dioxide	CO2
4	Carbon monoxide*	CO
5	Hydrogen*	H2
6	Methane*	CH4
7	Acetylene*	C2H2
8	Ethylene*	C2H4
9	Ethane*	C2H6
10	Propylene*	C3H6
11	Propane*	C3H8

Remark : Total Dissolved Combustible Gas(TDCG) : *

Table 2 the example of DGA test by EGAT's laboratory

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HIGH VOLTAGE TESTING AND CALIBRATION CENTER

ELECTRICITY GENERATING AUTHORITY OF THAILAND

53 Moo 2 Charansanitwong Rd., Bang Kruai,Nonthaburi 11130

No. HVT DGA T5600137-16 TEST REPORT

REGION	S21	LOCATION	RE2	NAME	KT1AB
MANUFACTURER		SERIAL NO	07MK410102	kV	525/230
MVA	333	OIL		YEAR	2008

REQUEST#	----------------------------		S2
Sampling Date (dd/mm/yy)	--------------------	19-Sep-16	19-Jun-17
Test Date (dd/mm/yy)	--------------------	13-Oct-16	22-Jun-17
COMPONENT GAS (ppm)			
O2 (OXYGEN)	--------------------	4369	1894
N2 (NITROGEN)	--------------------	18427	17172
CO2 (CARBON DIOXIDE)	--------------------	1717	1765
CO* (CARBON MONOXIDE)	--------------------	409	389
H2* (HYDROGEN)	--------------------	45	41
CH4* (METHANE)	--------------------	48	44
C2H2* (ACETYLENE)	--------------------	0	0
C2H4* (ETHYLENE)	--------------------	4	4
C2H6* (ETHANE)	--------------------	21	19
C3H6* (PROPYLENE)	--------------------	6	4
C3H8* (PROPANE)	--------------------	9	7
TOTAL COMBUSTIBLE GAS		542	508
OIL TEMP	--------------------	39	50
LOAD	--------------------	-	-

SAMPLING POINT ☑ Main Tank

TEST RESULT ☑ Normal

5.3 The existing Transformer On-Line Monitoring System of EGAT's system

The main purpose of installation Transformer On-line Monitoring Systems since 2015(table 3 and figure 6-13) is to study it and then leads to adapt the existing Transmission System to be future system such as Smart transformer, Smart substation and Smart Grid.

Table 3 Transformer On-Line Monitoring System

Installed year	Location	On-Line System	Remark
2015	BSP2-KT1A-phase A	DGA	Nine-gas system
	BSP2-KT1A-phase B		
	BSP2-KT1A-phase C		
	RB3-KT1A	Bushing	-Leakage current summation -Power Factor measurement -Capacitance measurement
	RB3-KT2A		
	WN-KT1A		
	WN-KT2A		
	SNO-KT7A		
2016	WN-KT1A-phase A	DGA	Two-gas system
	WN-T1A-phase B		
	WN-KT1A-phase C		
	WN-KT2A-phase A		
	WN-KT2A-phase B		
	WN-KT2A-phase C		
2017	PDG-KT1A	Bushing	-Leakage current summation -Power Factor measurement -Capacitance measurement
	PDG-KT2A		
	MM3-KT3A		
	KNE-KT1A		

Figure 6 Bushing On-line Monitoring System

Figure 7 warning signal of Bushing On-Line Monitoring System at Annunciator

Figure 8 continuous Trend-Tangent delta of Bushing On-Line Monitoring System

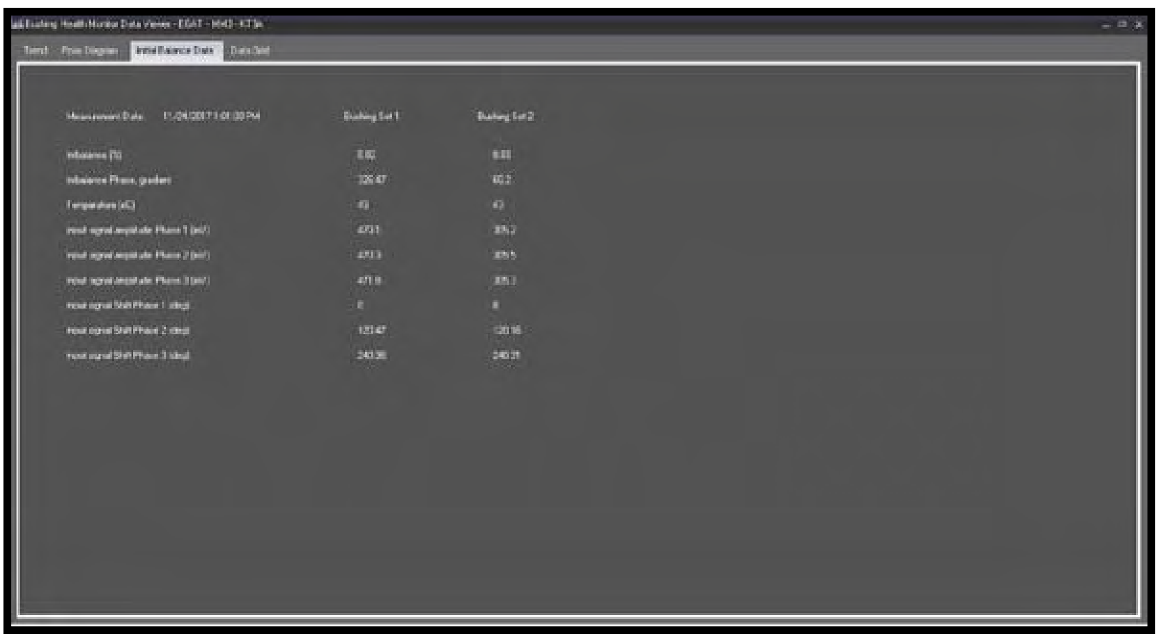

Figure 9 initial imbalance current of Bushing On-Line Monitoring System

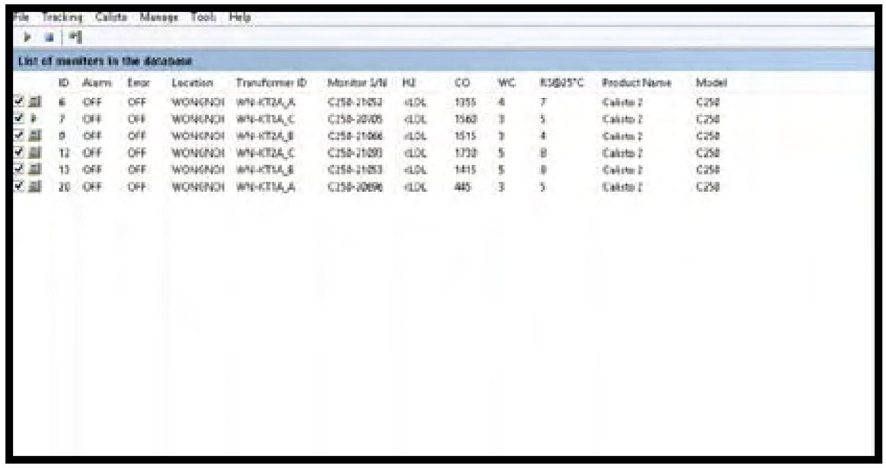

Figure 10, 11 Two-gas DGA On-Line Monitoring System

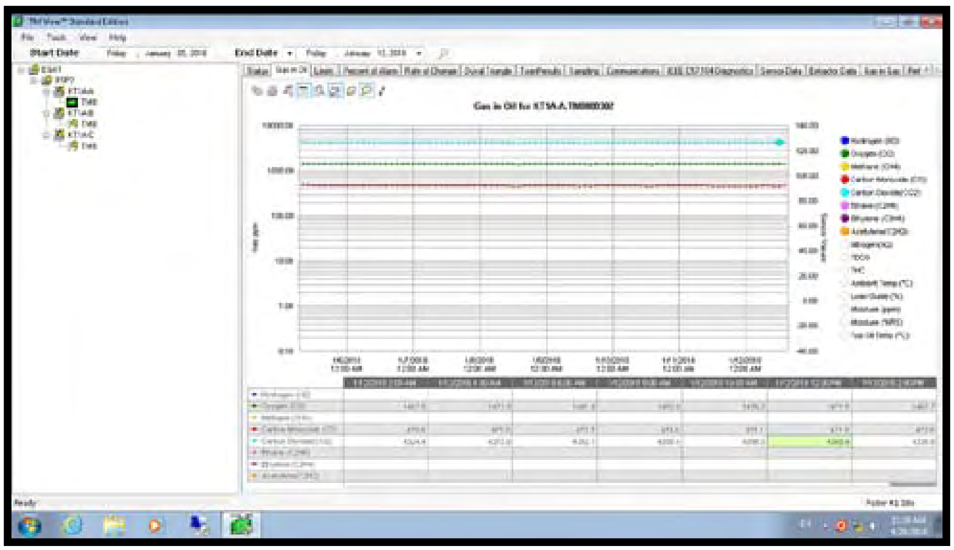

Figure 12 data of Nine-gas DGA On-Line Monitoring System

Figure 13 Duval Triangle of Nine-gas DGA On-Line Monitoring System

6. Conclusion

Transformer On-Line Monitoring System is the key component for the Smart transformer, Smart substation and Smart Grid. EGAT has installed Transformer On-Line Monitoring System since 2015 in order to study it. There are some benefits of Transformer On-Line Monitoring System such as warning abnormal condition, information for maintenance decision, monitoring malfunction, enable Continuous On-Line Monitoring(OLCM) and etc. There are a lot of very small power producers in the future, especially renewable energy power producers. So the current grid should be changed to be Smart Grid because the Smart Grid technologies becomes more flexible, interactive and is able to provide real time feedback and some features of the current grid have to be changed , for example, the communications, Operation & Maintenance and reliability. Some technologies that need for Smart Grid evolution such as control, allowing every part of grid to talk and listen, remote monitoring and etc.

BIBLIOGRAPHY

[1] Training document, Dynamic Ratings
[2] EGAT's maintenance standard
[3] Guide for Transformer Maintenance, CIGRE Working Group A2.34
[4] Basic Transformer Theory and Apparatus Testing:2004 International Conference of Doble Clients
[5] Calisto, DGA family, Morgan Schaffer
[6] Calisto-Calisto2, On-Site Training, Morgan Schaffer
[7] Insulation Power Factor Testing of Power Transformers, Oleh W. Iwanusiw, consultant EItel Industries, Bangalore, India
[8] New Techniques for the Monitoring of Transformer Condition, Thomas Prevost-Omicron electronics USA, IEEE T&D Conference, Chicago, Illinois April 17, 2014
[9] GAS-Guard 8, online disolved gas analysis sensor, Answers for energy, SIEMENS
[10] SERVERON, TM8, On-line DGA Monitor
[11] SERVERON, TM8, Installation & Commissioning
[12] SERVERON, TM8, Operation & Maintenance
[13] Are Your Transformers Ready for the Smart Grid?, Utility Products Magazine
[14] On-line Monitoring for Bushing of Power Transformer, Thanapong Suwnansri, Agkapon Pongmanee, Cattareeya Suwanasri, GMSARN International Journal 8(2014)47-52
[15] Smart Grid in Thailand, Ministry of Energy, Thailand

CIGRE-AORC Technical Meeting 2018 – International Conference on Global Energy Transition – Issues and Challenges, 24-25 May 2018, Gangtok, Sikkim, India

Analysis of High Tank Body Temperature in Large Generator Transformers

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***Abstract*—Generator transformer in a power plant forms a critical link between Generating utility and the grid. In view of above healthiness of GT is very important parameter measure in a Power Plant for smooth operation and reliable availability of Plant. The unit size of Power Plant has gone up from earlier 200MW to 800 MW, leading to increase in size and rating of Generator Transformer from three phase 200 MVA to single phase 315 MVA. The current rating at LV side has reached to a level of 14 KA approx. Special care needs to be taken when handling such a level of current in Generator Transformer. LV side lead and tank body including turret needs special attention during design stage to mitigate the effect of high temperature caused to leakage flux. These high level of flux causes localized over-heating of tank and turret which drastically reduce the life of transformers. In this paper, practical methods to reduce the temperature by localized over-heating are discussed based on actual tests and observations.**

***Index Terms*— Generator Transformer, High Current, High Flux, Turret, Eddy currents, Induced currents, Power Plant.**

I. INTRODUCTION

NTPC Limited is an India-based company engaged in generation of electricity. With an installed capacity of 53,651 MW, NTPC is the largest power generating major in the country. It has also diversified into coal mining, power equipment manufacturing, oil & gas exploration, power trading & distribution. The company has over twenty one coal based and seven gas based stations, one hydro-based station, eight joint venture stations (seven coal based and one gas based) and twelve renewable energy projects. NTPC has more than 150 Generators transformers in operation at different project location with MVA rating ranging from 82MVA to 315MVA and voltage rating ranging from 220kV to 765kV. Transformer form a vital link in the whole of power system network for a generating company. Transformers are considered to be the most reliable equipment with absolutely no moving parts except for the OLTC and with the highest equipment efficiency. However any fault in the transformer results in catastrophic loss both in term of reliability of the power system network and economic loss to power generation. A longer transformer life is always desirable and to achieve this, efforts should be put in from the very beginning stage of designing, manufacturing and testing. Transformer should be designed so as to meet the temperature rise limits, short-circuit forces, loss-limits etc.

II. DESIGN CONSIDERATION

With the increase of unit size from 500MW to 800MW there has been a tremendous increase in rating of Generator transformers from 200MVA to 315MVA and LV voltage rating varying between 21 kV to 27 kV. So the amount of LV current being handled at LV side of Generator Transformer is typically in the range of 14 KA. Handling of such a high value of current requires special consideration in the design and material to be used. Understanding and curbing/ directing the path of leakage flux due to such a high level of current is very important. The effect of leakage flux within the transformer winding results in the presence of radial and axial flux changes at any given point in space and any moment in time. These induced voltages which cause currents to flow at right angles to the changing fluxes.

The winding- leakage field of large Generator transformer can cause overheating of the core limb near winding ends and give rise to problems in the steel structures outside the windings. The large current in the LV winding can induce voltage in part of the core window which stress the insulation of the core sheets. Circulating currents due to these voltages are the result of puncture of the insulation of the outer core laminations and give rise to iron burn.

Non-magnetic steel is used as a structure material in heavy magnetic areas. Electromagnetic screens are usually used at complicated places like clamping structures and between LV connections and tank. In most of the cases the LV turrets are designed using SS with the bolts also made of SS in order to reduce the heating of turret and tank rim due to leakage flux.

The current carrying elements in power transformers such as leads and windings are also sources of Eddy current losses. Due to this some parts of tank and turret experience localized over-heating. Such local high temperature spots may affect transformer life in following ways:

1. In long run it may cause pitting in the tank internal surface due to persistent high temperatures.
2. Due to continuous contact with high temperature area at joints and rim of bell tank and turret, the life of gasket will drastically reduce and in course of time it may lead to leakage of oil.
3. If the tank is getting overheated at internal surface (in contact with oil), this may lead to decomposition of oil and low temperature fault gases may appear during DGA analysis.

III. CASE STUDY - I

TURRET HEATING OF 315MVA, 765KV SINGLE PHASE GENERATOR TRANSFORMER

The results of all routine and dielectric test of above transformer were found satisfactory as per technical requirement. However during temperature rise test of 315 MVA 765 kV single phase Generator Transformer, there was localized high temperature spots observed at the Bolted Joints in the Bushing Flange and Turret during thermography test. As shown in Fig.1 the turret temperature was observed above 102 degree Celsius.

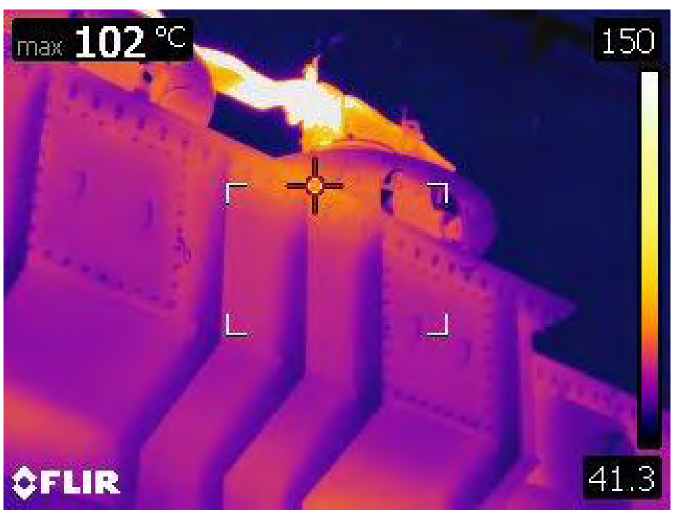

Fig. 1

A joint discussion with the OEM was carried out to analyze the root cause of such observations:

1. The OEM submitted that there is no scope of improvement in design or any internal modification to reduce the eddy current heating.

2. The material of turret was designed using SS including the bolts between turrets and tank cover.

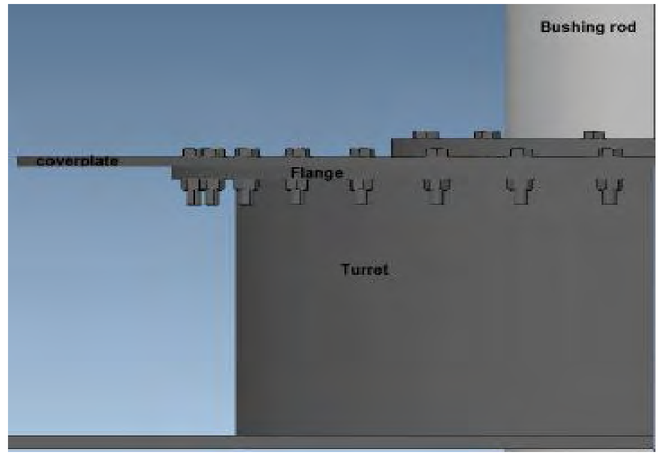

Fig. 2

3. The thermography images show that high temperature was concentrated in small patches only, it was not spread across the whole turret.

4. It was decided to take help of 3D models to study the distribution of magnetic flux generated in the turret around the current carrying conductor and explore the causes of such local hot spots.

With the help of FEM algorithms, distribution of magnetic flux was plotted (Fig. 3). This magnetic flux generates eddy current (A/m^2) in the flange and turret around the current carrying conductor in turret area was plotted (Fig.4 and Fig.5)

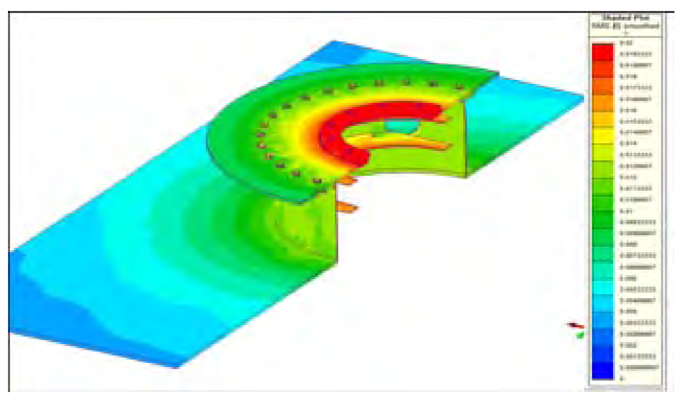

Fig.3 Distribution of magnetic flux

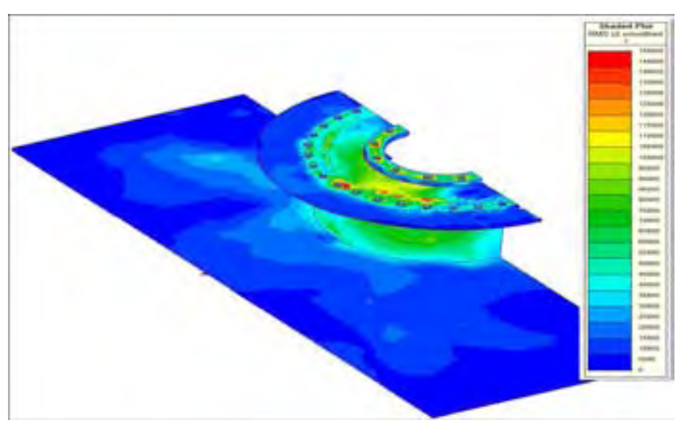

Fig.4 Distribution of eddy current

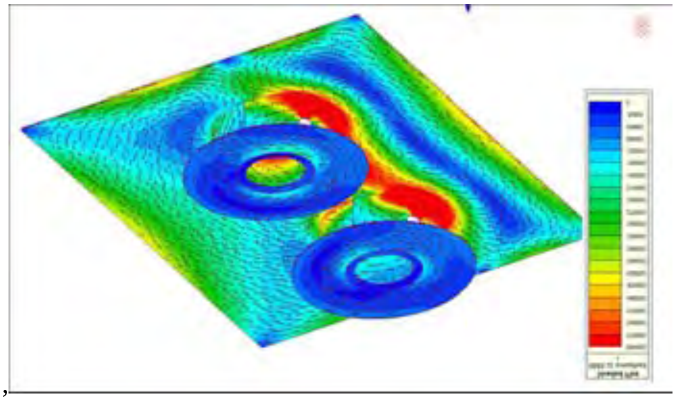

Fig. 5 The eddy current distribution in the flange and turret

By closely observing the current distribution (Fig.6), it is clear that the current passes from the cover plate to Turret through flange and some part of the current passes through the SS bolt.

The surface finish of top cover and turret was not fine enough and was causing a bad contact for flow of eddy current.

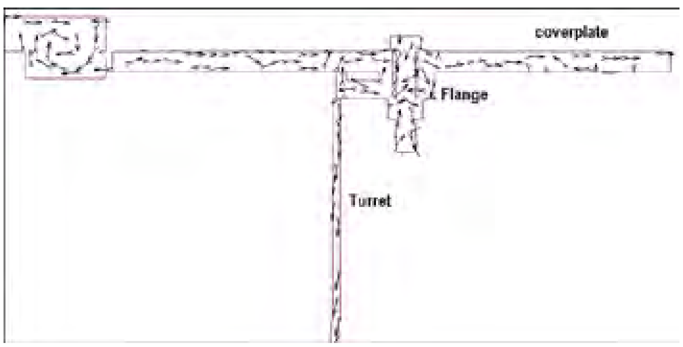

Fig. 6 Illustrative diagram of eddy current path

Further on giving a close look to the eddy current distribution and loss density distribution (Fig.7) it is clear that more losses are concentrated across the flange and consequently the theoretical high temperature zones (Fig.8) are concentrated in the same zone.

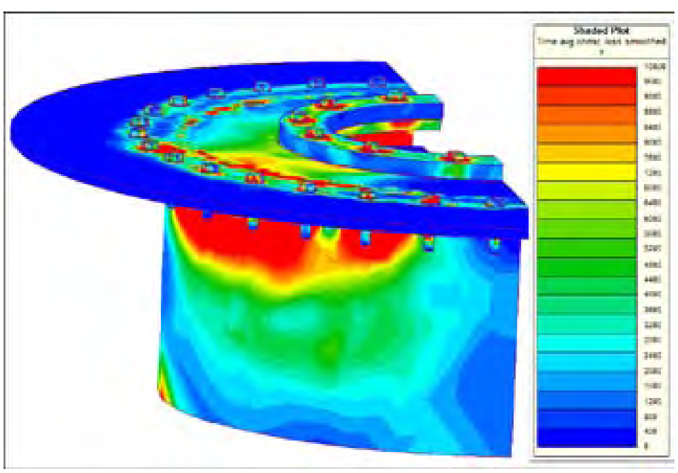

Fig 7 Loss density distribution (W/m^2)

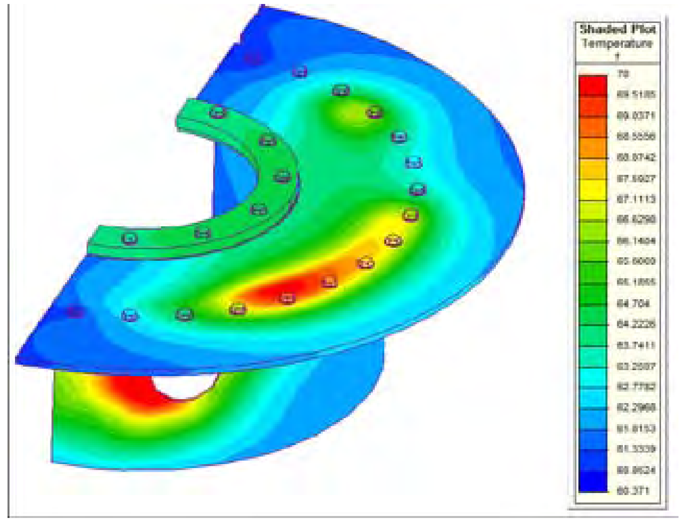

Fig 8 Temperature distribution

Fig. 8 presents a schematic arrangement across the turret flange. A "Bad Contact" as marked in figure is a low cross-section path for eddy current providing high current density.

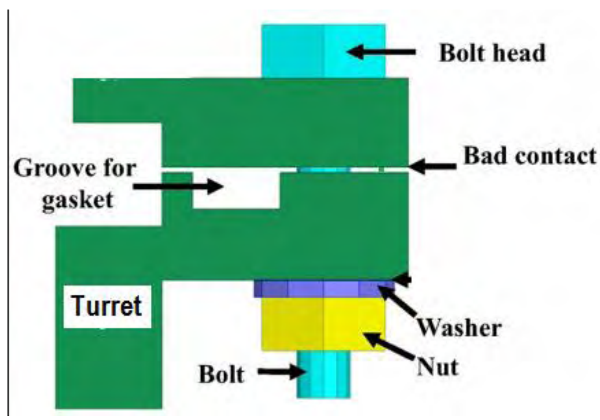

Fig. 9

The eddy current generated in the cover plate is trying to pass through the small line contact formed between the cover plate and flange. This increases the current density, loss density and hence hotspot temperature on that location.

CORRECTIVE ACTION: – PUTTING SHORTING LINKS

The hot spot temperature is due to high current density near the flange. The high current density is due to poor contact, if the turret and cover plate are connected through a conducting path then the current density will reduce. Shorting links of copper were placed across the flange as shown in the Fig. 10.

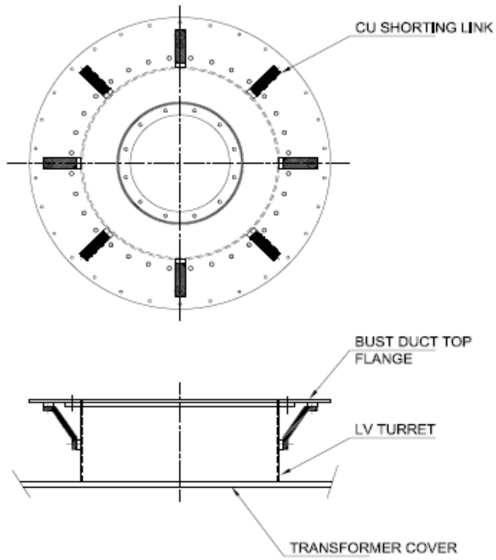

Fig. 10 Schematic view of LV Turret with copper links placed

After carrying out the above modification the thermography test including heat run was carried out again.

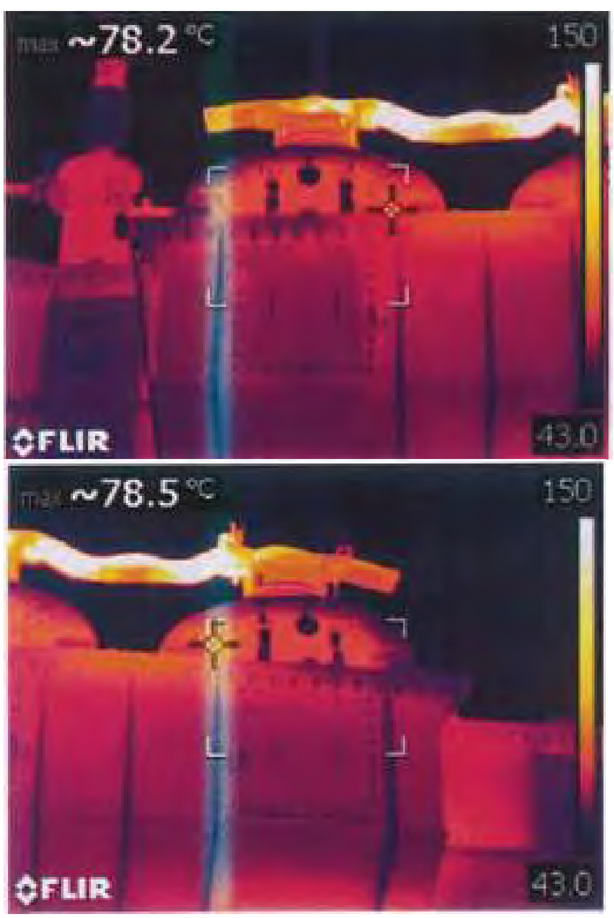

Fig. 11 View of LV Turret after placement of copper links

The hot spot temperature reduced to 78.5 degree Celsius (Fig. 11).The shorting link passes the current from flange to turret and to transformer top plate. This significantly reduced the temperature distribution in the bushing turret.

Further, some manufacturer uses copper shielding inside the LV turret in addition to SS turret.

IV. Case study -2

GENERATOR TRANSFORMER BOTTOM TANK HEATING

Generator transformer of rating 265 MVA, 21/420/√3 kV single phase, was subjected to temperature rise test including thermography. The tank design of this Generator transformer is of bell type. Localized high temperature spots was observed at tank bell joint (top and bottom tank LV side) during thermography at LV side. The maximum temperature observed was about 99.5degree Celsius.

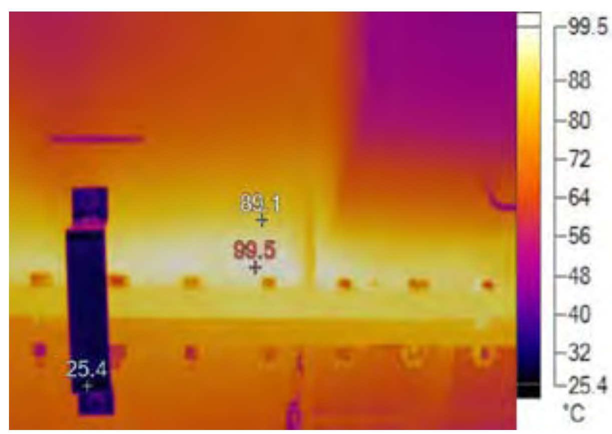

Fig. 12 View of LV side tank bell joint

Manufacturer carried out the root cause analysis for reason of such localized high temperature at tank rim between tank bottom and top cover. The analysis report indicated that “leakage flux cause localized over heating (hot spots) in metallic parts due to associated eddy currents” as root cause of the problem. The bad contact between top cover and bottom cover resulted in localized heating due to leakage flux because of such high LV current. The existing tank design already had Wall shunts on LV side to cater the tank heating, however bottom tank wall did not have any shunts. So the joint at the tank rim was exposed to leakage flux and bad contact caused overheating.

CORRECTIVE ACTION: –SHORTING TOP AND BOTTOM TANK VIA COPPER STRIP/ LINKS

The possibility of carrying out internal modification to mitigate the effect was reviewed and discarded due to practical issues. However after discussion it was decided to use copper strips at the rim joint on LV side and repeat the test including thermography. The purpose of using copper strip was to provide alternate conducting path to eddy current and get it distributed instead of it being at localized area.

The transformer was again subjected to temperature rise test and thermography was carried out. The results of thermography showed maximum tank rim temperature of 80 degree Celsius (Fig. 13).

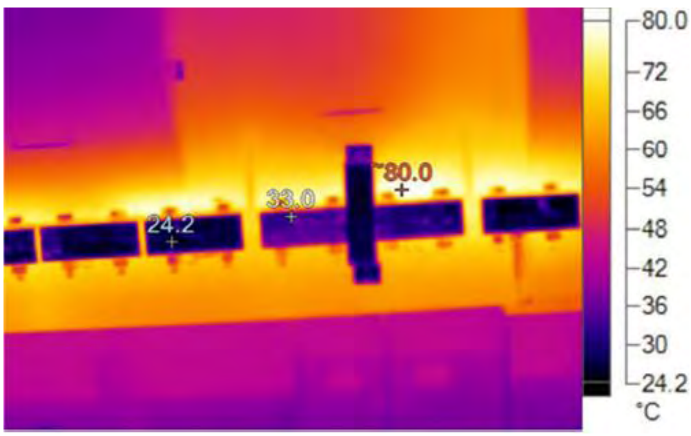

Fig. 13 Max. Temp. at tank bell joint after modification

The strips fitted across the bolts and provided a better way of shorting across the rim. "U" shaped copper strips were place across the rim (Fig. 14). This arrangement did not involve welding and provided more number of parallel paths across the rim.

Fig. 14 Actual view of copper strip at tank bell joint

V. CONCLUSION

Design of Large Generator transformer requires lot of research, experience, and detailing. Controlling of leakage flux to avoid its heating effect on tank body and turret also need special attention from the reliable operation and long life of Generator transformers. Design of transformer should encompass not only the Di-electric, Short Circuit strength but the Thermal modelling including flux distribution. Controlling and understanding the flux distribution during design stage using FEM algorithm based modelling help in design modifications and give ample resources to designer to avoid not only localized heating on tank body/turret but also damage to the core lamination and insulation in active parts due to stray loss. The above highlighted methods are also a way to curb leakage flux of tank.

It is significant to have a limiting value of tank body temperature during temperature rise test be measured by Infra-Red thermography. A limiting value of 85 deg. C considering top oil temperature rise of 35 deg. C with maximum ambient temperature of 50 deg. C may be considered to avoid tank body heating due to leakage flux.

Further, it gives confidence and highlight the importance of specifying thermography test during temperature rise test to utilities.

REFERENCES

[1] Joint Inspection Report
[2] Root Cause Analysis Report
[3] IEC 60076
[4] J & P transformer book
[5] CIGRE Paper LARGE GENERATOR TRANSFORMER by C. KROON

CIGRE- AORC Technical Meeting 2018 – International Conference on Global Energy Transition – Issues and Challenges, 24-25 May 2018, Gangtok, Sikkim, India

GIS - Critical Enabler for Operational Excellence and Enhanced Customer Experience for Utilities

Sunil Joglekar, Shriram Modak, Mahesh Yadav, Daleep Singhal and Rakesh Kadu
Tata Power

ABSTRACT

Majority of Utility business is required to work within the frame work of regulators. This makes it necessary for optimizing the resources and for effective handling of information/data with efficient processes and workflows. Application of innovation and technology for some of the value added services to its customers has now become a basic requirement.

Tata Power has implemented ***Geographic Information system (GIS)*** *in Mumbai which provides a comprehensive view of Tata Power's distribution network elements with geographic advantage. It is supporting numerous distribution business functions such as short and long term business planning which includes network, designing-monitoring-operations, asset management, compliance to regulatory queries, customer marketing, customer acquisition, connection services, customer-facing applications, different analytics, location based trends etc. Tata Power has also successfully completed integrating GIS with other enterprise systems. The integration augmented work flow management, automation and timely updating/ synchronizing of data/information along with large scale elimination of manual interventions, duplication of data entry and enabling easy access to important data for Business analysis.*

With the help of two case studies, this paper highlights approach adopted by Tata Power to implement the GIS and also its strategic leveraging of this technology for operational excellence and Customer experience with innovative developments and deployments.

INTRODUCTION

Tata Power, Mumbai, is operating in a competitive environment with multiple power distribution companies operating in same area. As such operational performance, effective marketing, creating customer delight are core and critical activities for the organisation. In line with this, the GIS implementation, its integration with other enterprise systems and its further enhancement/development was planned, focused and driven by exhaustive requirement study and clear business results envisaged.

Traditional GIS produces electronic maps to present geographic data in a location based visualisation media. A conventional utility-GIS is also limited to mapping of the assets, keeping the repository of assets information, geo-mapping the network and then deploying different query, tracing & analysis tools to create some value for the business. The role of GIS has evolved in recent times and has scaled up multiple times worldwide with its capabilities for intelligent spatial queries and diverse geo-processing algorithms, capabilities of huge geo-data processing at backend, data exchange with other enterprise systems and capacity to generate huge intelligence for business of the organisation. Cab aggregators, delivery chain services with e-commerce, location based media and advertising, marketing etc are day-to -day examples of enormous power of GIS for achieving innovation with excellence in operations and productivity.

Tata Power has strategically added similar innovative developments on its GIS platform which are not only differentiator from conventional utility GIS but are also going beyond.

"*As grid modernization of the electric power distribution industry becomes a reality, those utilities that embrace technology and become a true "digital utility" will reap the benefits of more responsive and efficient operations, as well as safer and faster outage restoration*".[1]

<u>CASE STUDY 1</u> **: Development of GIS based "*mobile-GIS assisted system for Restoration and Care* (maRC)" for technical Complaint management**

Complaints are an important way for the management of an organisation/utility to be accountable to the public, as well as providing valuable prompts to review organisational performance and the conduct of people that work within and for it. A complaint is an "expression of dissatisfaction made to or about an organisation, related to its products, services, staff or the handling of a complaint, where a response or resolution is explicitly or implicitly expected or legally required [2].

An effective complaint handling system provides three key benefits to an organisation [2].

• It resolves issues raised by a person who is dissatisfied in a timely and cost-effective way;

• It provides information that can lead to improvements in service delivery; and

• Where complaints are handled properly, a good system can improve the reputation of an organisation and strengthen public confidence in an organisation's administrative processes. [2].

Tata Power has an enterprise CRM (Customer relationship management) system for complaint management including Technical complaints. Till recent time the system was running in a standalone mode. The technical complaints from customer are received by call centre agents and are registered in CRM system as a call or ticket. There are other channels of receiving technical complaints in CRM system via SMS, Chatbot, Social-media, AMR, IVR etc. In past these complaints were assigned to LT service field crew via verbal communication methods. In actual the complete **Technical Complaint Management (TCM)** process was working mainly on manual work flow and with inconsistent data entry in spite of having CRM system and other technologies. Secondly Tata Power is having a mix of Direct wire customers and non-direct wire customers (changeover). Limited network information about changeover customers was an additional critical challenge for Tata Power while responding to their technical complaints. Huge limitations and enormous challenges were faced by all the stake holders of TCM process for this manual process and was ultimately posing a challenge for maintaining the Customer satisfaction.

Some details of challenges faced are as follows:

1. Telephonic Communication: All major complaints communication was via phone call between Call center agents, LT teams and O&M engineers.

2. Tickets assignment for respective zonal team was manually done by call center

3. Locating complaining customer at site was a difficult task for LT team based on verbal address communication by Call Center

4. No visibility of movement of LT team for call center and O&M engineers for status of complaint and site condition

5. No upfront mechanism available for sensitizing the Call center and O&M teams for situation awareness wrt to some distress condition of power failure.

6. No information was available at one place for easy visibility, for further analysis and MIS.

7. Customer feedback forms were collected in hardcopies.

For this no readymade cost effective solution was available which could meet all the requirements of the stake holders and mitigate the challenges. Readymade solution such as OMS, FCM were available but were not cost effective and were not meeting many critical requirements of TCM stake holders.

To mitigate all these challenges one innovative idea was conceptualised by Tata Power-Distribution team. A comprehensive system was designed and deployed subsequently. This new system which is in-house designed-developed and called as *"mobile-GIS assisted system for Restoration and Care (maRC)"*, is built on existing technological platforms of Tata Power. The new system is able to create ***Situation Intellige*****nce** for TCM stake holders. "*Situational intelligence combines traditional situational awareness with the collective intelligence of those at the centre of a situation, resulting in a dynamic process in which data is gathered and interpreted and the information is shared.*" [3]. It is also referred as *"..... intelligence which provides 360-degree insight into these situations, arming users with the understanding of what, where, when, why and how the situation occurred, is occurring now, or might occur in the future."*[4]

Development:

Components of Tata Power's new maRC system:

The new system is built on already established following five technology platforms of Tata Power GIS. (Fig.1)

- CRM-GIS integration
- GIS core platform
- VTS-GIS Integration
- Web-GIS
- mobile-GIS

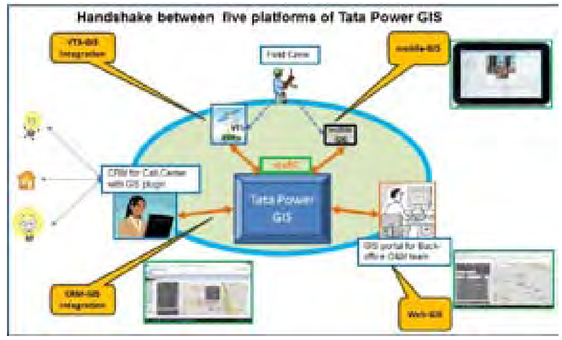

Fig. 1

The new system has 5 main user interfaces (UIs) designed and deployed for

- *mobile-GIS* enabled tablet for LT field teams.
- GIS plugin on CRM system for Call center agents.
- O&M portal for backend O&M engineers/managers for monitoring and control of field activity.
- Alert mechanisms for monitoring of TAT and also for monitoring with runtime analysis of sudden power failure in-rush cases and predicting the distress condition, if any.
- MIS and other reporting mechanism.

Key Features of the maRC system:

- **Development on existing GIS-IT infrastructure:** The system designed and Developed on existing technology platforms of Tata Power has enabled faster deployment. SOE based architecture support made it a robust solution.
- **Workflow based control mechanism for complete TCM:** Provides Workflow based control mechanism for complete life cycle of one of the critical processes of Tata Power Distribution (Fig.2). Complaint/ order closing from field and additional sub-workflow for follow-up mechanism made it more comprehensive system. This follow-up mechanism is ensuring action for providing a sustainable and permanent solutions from temporary fix for last mile

infrastructure and also creating rich information for further analysis, CAPA and MIS .

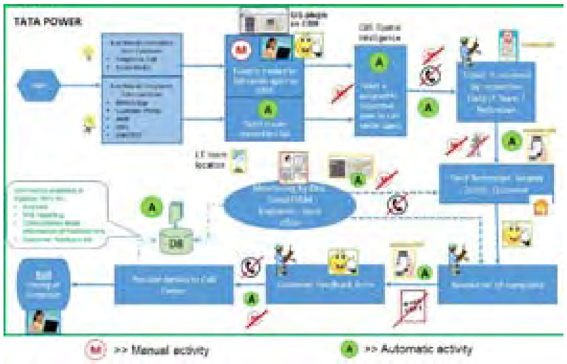

Fig. 2 : New automated Work flow for TCM (A life cycle of typical technical complaint)

➢ **Processing of all Technical complaints:** All the technical complaints including those from changeover customers are generated via call centre, AMR, SMS, IVR, Social media and processed for their complete life cycle of the complaint.

➢ **Seamless Data Visualisation:** Call centre agents, O&M back office centres are provided with an effective user interfaces (UI) of maRC system for seamless data visualisation containing intelligent Tata Power GIS map of NW and land base, dynamic dashboard, real-time crew/vehicle locations, complaining Customers' locations, NW asset location-details, visual display of extent of outage impact, dynamic popups for situation awareness etc. (Fig.3)

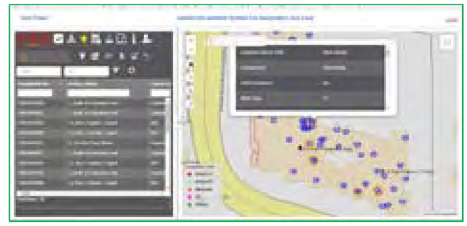

Fig. 3: UI for maRC

➢ **Mobility based solution for field crews:** The field crew (Restoration teams) is aided with Tata Power mobile-GIS enabled maRC system. User friendly features of notifications/alerts, quick customer location on GIS-map, routes, e-forms for capturing restoration/repairs details and for customer feedback, facility for site photos, signature is ensuring paperless complaints processing directly from site/field.

➢ **Processing on latest network and customer data:** The internal system processing and algorithms work on real-time basis and work on latest updated network and customer data of core GIS. This is resulting into more accurate and realistic information and agile response to customer service.

➢ **G-intelligence for run time analysis and TAT monitoring:** G-Intelligence engine is designed in-house and configured in the maRC for automatic alerts and prediction (Fig.4). This engine continuously monitors and analyses all the power failure/ trouble/outage calls. In case of any distress power failure situation or sudden inrush of calls, the system predicts on runtime the affected outage area, probable outage equipment, estimated affected customers etc. and larger impact on network. This enables to alert respective zonal teams, field crews, Call centre and other stake holders for situation awareness and better cause-effect determination. Similarly monitoring and alerting mechanism for TAT crossing is also in place which is monitoring the performance.

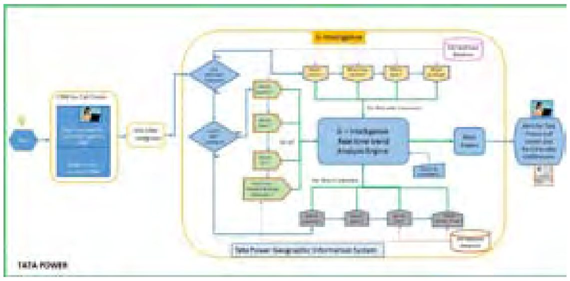

Fig 4 : Design diagram for "G-intelligence alert Engine"

Benefits of maRC:

- **Fit to purpose and customer need**: Perfect Fit to internal customers need, user friendly, strong end-customer focus and scalability. The system is successful and well received by all stake holders as it is capable of mitigating almost all the challenges faced by them.

- **Improve business agility and Reduction in cost and cycle time:** Complete work flow based automated system has eliminated restoration crew's dependency on centralised call centre. The complaint and outage details are automatically assigned to respective zonal crew members via notification, with complaint details and directly displayed with geolocation on mobile GIS map etc. Prioritisation of response, Elimination of delays and communication errors has resulted in fast, structured and optimised movement of the field crew resulting in avg @ 60% reduction of complaint response time (Fig.5). The system has also helped in drastically reducing cases of internal TAT violations for complaints (Fig.6). The inrush alert is also helping the call centre and O&M teams for better handling of distress situation and also responding to customers.

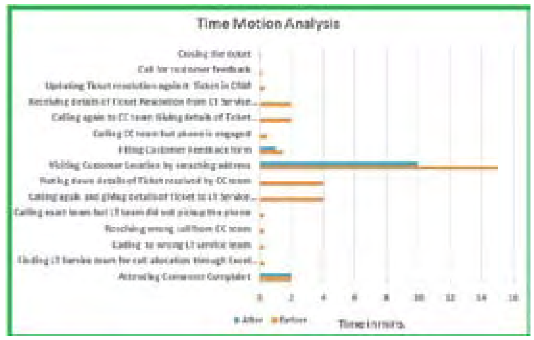

Fig.5: Time motion study of typical technical/outage complaint showing considerable improvement in response and resolution time of complaint

Fig.6: Reduction in count of complaints exceeding TAT

- **Quality information available:** Call centre agents are able to provide information and quick updates on supply restoration time to consumers. Real-time information of power failure complaints based on zone/locality/sub-locality/building etc.is available from this system. This has helped call centre to sensitize Fault duty crew for faster restoration. Complete automation of lifecycle of technical complaint is ensuring single source of truth available for sharing among Call centre agents, field crews, Dist O&M teams, management and finally for end customer. It is now giving better, faster decision-making and greater visibility for management. Overall Tata Power distribution is now in better position to manage-analyse-act on the technical complaints and outages information and keep customer, leadership and regulators well informed.

- **Major Automation-digitisation and cost effective solution:** Auto Call assigning, e-Data entry, auto activity update, auto follow up actions, e-feedback form for customer, site photos…. all are automated. Elimination of verbal communication, elimination of paper data entry, elimination of manual search has helped in achieving system based monitoring of process. As the complete solution is mainly based on existing GIS platform, the re-use of existing GIS and its other components of integration has resulted into considerable project cost saving and also resulted into easy and fast deployment.

- **System based Decision initiation and Improved decision making:** Effective data visualisation, intelligent-dynamic dash boards, automatic alerts for complaints inrush-predictions, auto mails-notifications, auto popups, workflow based system approach, digital information capture are resulting into realistic control on restoration activity and RCA. All this is leading to better support for last mile asset management, better customer service, ultimately leading to customer delight.

- **Future proof system:** The new system is future proof and is ready for many new technology initiative/integrations which will further enhance the Customer experience.

'ASE STUDY 2: Development of GIS based Spatial Patrol monitoring interface for Network ;PINe)" and development of its "RT/FDC ıobile app" for patrolling data collection.

.ssets network (such as power distribution cables, ommunication cables, gas pipelines, water supply nes or sewage line) are the backbone of any urban r rural infrastructure. These networks are spread ver a large area including public spaces. However, ıe maintenance and security of such assets is a ıallenging task for the municipal authorities, 'tility companies etc, as many other agencies are 'orking in these areas for maintain their own assets, road repairs, town planning etc. If proper monitoring is not done along the routes/roads carrying these Utility network then it can lead to huge consequences related to their damage and safety. Physical patrolling to monitor these assets is a common method among Utilities. For monitoring and evaluating the patrolling activity for its performance some additional mechanism was required.

The EHV, HV, LV cable network is a backbone/spine for any electrical utility. For Tata Power its 850+ km of network routes and 3500+ kms of cables spread across Mumbai Lic Area are very critical. All these cables are protected by protection schemes which automatically trip/isolate the concern cable network in case of cable fault due to technical failure or even cable faults due to excavation. But this is a lag measure. To avoid the cable faults happen instead what is required is a lead measure. The cable faults arising on account of excavation on roads are substantial (@30%). Shutdown to consumers, stress on other circuits, unsafe and accidental situation are main outcome of these incidences. All this leads to Consumer dissatisfaction. Repairing of these faults also has considerable cost implication on operations.

Some challenges faced as follows:

1. Patrolling physically the NW routes is one of the main methods of controlling these faults which are happening due to excavation. This activity is done with the help of teams of outsourced agencies. Tata Power is carrying out bike patrolling activity with some foot patrolling for monitoring of cable route. Although commercial mechanisms such as SLAs were part of this cable patrolling contract, lack of proper and quantifiable tracking mechanism was affecting the performance measurement of patrolling.

2. The existing integrated platform of GIS-VTS with devices fixed on patrolling vehicles was used by the cable engineer team for monitoring the patrolling activity. But to manually check for all the vehicles

coverage and unpatrolled routes for complete network on daily basis was laborious and difficult job. Secondly manual checking was also consuming large amount of time and efforts.

3. There was no ready-made solution available in the market which could meet the requirement of O&M and retrieve the quantifiable information based on VTS data and electrical cable network data. This was posing a challenge in overall monitoring of the patrolling activity.

4. No means were available with patrolmen to capture the locations of excavation, details of excavation, site conditions and also method for validation of cable safe routes etc.

5. No mechanism was available in reporting of excavation on Cable routes instantly to back office and safeguarding cable from damages

Development:

The challenges faced by the cable patrolling/maintenance team for not getting measurable performance of patrolling activity was in actual a pain area for the most critical activity of cable patrolling management system. It was felt that if the manual activity done to monitor patrolling is automated then quantifiable monitoring can be done. It was envisaged that some intelligent logics be built on the VTS-GIS platform. The conceptualization and development logics were then designed in-house with interactions with Cable patrolling team. Tata Power team conceptualized and subsequently developed a comprehensive solution made up of two modules for mitigating the challenges.

1. One complete solution (a method and system [5]) named subsequently as "SPINe" for patrolling and monitoring the unpatrolled cable routes/NWs and

2. One mobile app (RT/FDC) for capturing other patrolling data from site.

The team successfully integrated VTS with GIS in such a way that real time vehicle tracking data coming from VTS is processed on GIS platform with GIS SPATIAL analysis tools such as logical operations, geometric operations, proximity analysis etc. The analyzed data is further processed on top presentation layer of solution architecture for thematic map rendering.

Similarly mobile app was developed for collecting other data such as excavation locations, excavation details, site photos and other cable related discrepancies from the field and for its instant information transfer to back office team for further actions.

Key Features of SPINe module:

1. The new system continuously monitors the patrolling which is carried out by Tata Power patrolling-team for EHV/HV power cable routes/roads with use of VTS devices. The data is continuously sent to GIS server where system then evaluates with other geodata and numerous GIS predefined analysis spatial tools-algorithms and presents the results in quantifiable and graphical map format (Fig.7 and Fig.8) The system also addresses exceptions and also gives additional information for criticality of particular routes or patrolling areas.

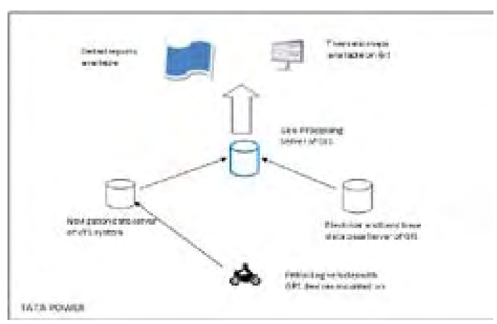

Fig.7: Solution Architecture for SPINe

2. The system helps in ensuring 100% coverage of patrolling of cable routes and thereby reducing the incidents of omission and of serious event and situations.

3. The speed at which the patrolling is done is also included in algorithm while evaluating the performance index of the patrolling activity.

4. An automatic running of the system evaluates the performance of patrolling on daily basis. The daily auto reporting is done to concern teams.

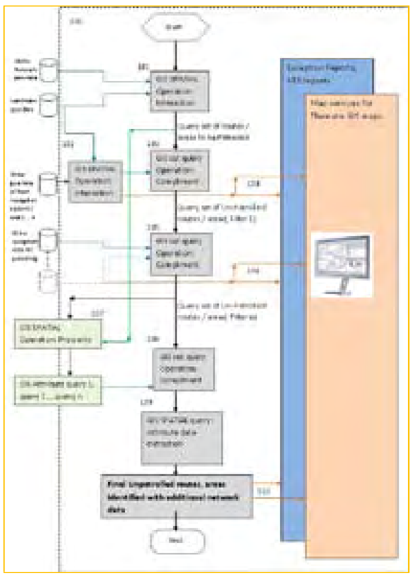

Fig.8: SPINe system algorithm

5. An additional interface (UI) has been designed on GIS to get the input from the user for selective date range. In such a case system gives output in the form of evaluation report with percentage of routes patrolled in the form of numbers or % lengths or performance index(dashboard) as per user requirement and thematic visual display on GIS map (Fig.9).

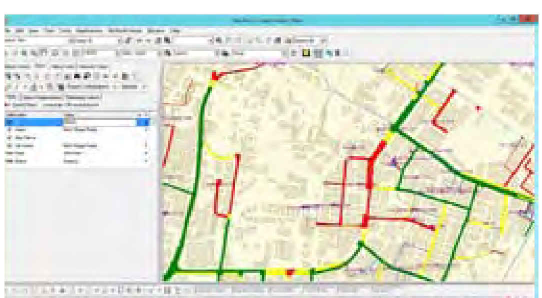

Fig.9: UI for SPINe

Key Features of RT/FDC app:

1. The app is developed for android based system making it cost effective for deployment, development and less device dependent

2. The Patrolman can see his assigned route on mobile map and also can track his uncovered route any time in the day (Fig.10).

3. Foot patrolman can now also be tracked through this app for SPINe system.

4. During patrolling the patrolman can capture on app different excavation activities happening along the route with help of attribute, geo-location, photos etc. (Fig.11) and immediately sharing it to back office maintenance team for viewing them on GIS map. Fast mobilization at excavation site is now possible to avoid the cable damage and help the external agencies doing excavation safely.

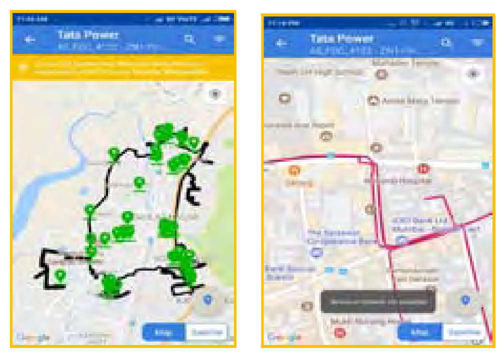

Fig.10: RT app UI

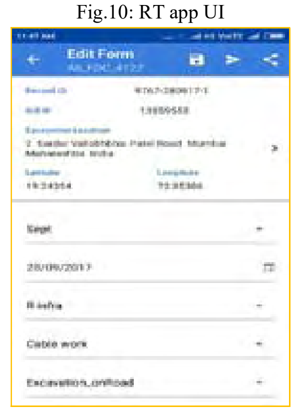

Fig.11: FDC app UI

Benefits of SPINe system and RT/FDC app:

1. All the reporting is now made automatic. The automation eliminated huge daily efforts of user (Daily @ 8 man hours) to consolidate the reporting and use it for correction or for SLA linking.

2. The automation also ensured proper reporting with deviation data available for user without accessing GIS system.

3. The monitoring and evaluation is also helping the outsourced vendor to monitor & improve the productivity and quality of deliverables from his field team and enabling him to sustain the contract commercially.

4. The overall impact of these system has helped Tata Power to control the cable faults happening due to increasing infrastructure activities in Mumbai (Fig.11)

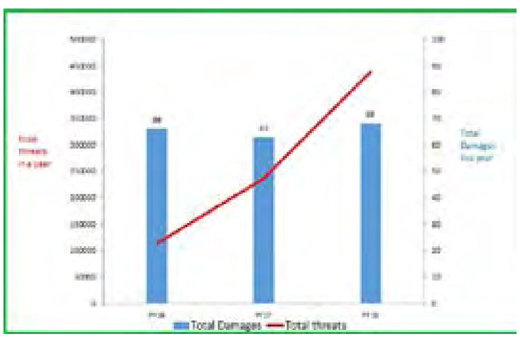

Fig.11: The number of damages are controlled//restrain irrespective of sharply increasing "Threat". (Threat is a type of an annual index figure which is derived after considering the number of excavations done along the route of the network, number of NWs beneath the excavations and the duration of excavation in open condition.)

5. Cost savings and cycle time reductions are achieved due to single Data entry in the system, repair cost of cable damage, Cycle time for excavation information sharing and for getting cable route drawing reduced from 24 hours to 5 minutes.

6. Reduction in power failure due to reduction in damages improves community satisfaction. Damages can result in flashovers which can have a potential public hazard. Thus reduction in damage results in safety to public.

Conclusion:

Careful mix of customization and out of box features of all related systems is necessary for handling technical challenges due to varying technological platforms and business challenges. Clear balance between "wish" and "necessity" is critical for successful development and deployment of this type of projects to avoid cost over runs and time delay.

Tata Power GIS in standalone mode and also in integrated landscape is able to critically support numerous functions of distribution utility with its ability of digitizing and geo-processing the data coming from omni-channels, generating different business intelligence from its analytical capabilities and deliverables. It's finally supporting planning, decision making and operations with its powerful strategically deployed SPATIAL and network analysis systems with innovative and fit to purpose in house developed utilities.

The future is all about technology based secure-convenient solutions and towards making digital utility. In same line Tata Power is also working towards making the systems SMART, robust and leveraging the advantages of an integrated landscape to enhance Business Intelligence, data analytics capabilities, strategic decisions making, improve consumer services at last mile and creating a competitive advantages. GIS in Tata Power distribution is contributing for this vision and emerging as a critical enabler for operational excellence and enhancing Customer experience. It has also enabled Tata Power to become more productive, aware, and more responsive to daily business requirements and challenges.

REFERENCES:

[1],[3] Situational Intelligence across the Digital Utility for Outage Response- GEGridsolutions.com

[2] GUIDELINES Effective handling of complaints made to your organisation - An Overview Ombudsman Western Australia

[4] The Need for Situational Intelligence - Space Time Insight, Inc.

[5] "A method and system for Patrolling and monitoring of utility networks aided with GIS and GPS" - Tata Power application for patent

Testing of Complicated Bus Bar Protection Using Smart Testing Methodology

K N Dinesh Babu
Megger

ABSTRACT : In this paper, protection of a complicated bus arrangement with dual bus coupler and bus sectionalizer using low impedance differential protection applicable for very high voltages like 220kV and 400kV is discussed. In many power generation stations, several operational procedures are implemented to utilize the transfer bus as main bus and to facilitate maintenance of circuit breakers and current transformers (in each section) without shutting down the bay(s). Owing to this fact, the complications in operational philosophy have thrown challenges for the bus bar protection implementation. Many bus topologies allow any one of the main busses available in the station to be used as an auxiliary bus. In such system, pre-defined precautions and procedures are made as guidelines, which are followed before assigning any bus as an auxiliary bus. The procedure involves, shifting of links, changing rotary switches, insertion of test block and so on thereby causing unreliable operation. This kind of unreliable operations or inadvertent procedural lapse may result in isolation of the bus bar from the grid due to unpredictable operation of bus bar protection relay which is a commonly occurring phenomenon due to manual mistakes. With the sophisticated configuration and implementation of logics in modern intelligent electronic devices, the cumbersome procedures are totally eliminated and the operator is free to choose the transfer arrangement without compromising the protection need of a bus differential system for a reliable operation. This paper deals with the procedure to test the security logics for such special scenarios using Megger make SMRT, implemented in bus bar protection relay to ensure system stability and eliminate all the special operational precautions / procedure.

Keywords – Bus bar protection, by-pass isolator, blind spot, breaker failure, Intelligent electronic device (IED), end fault, bus unification, directional principle, zones of protection, breaker re-trip, under voltage security, smart megger relay tester (SMRT)

I. Introduction

Increasing demand in power sector has resulted in need for more inter connection substations and addition of more bays [1] in existing substations (SS). Addition of bays at later stages in a substation may result in situations where the newly added bays have current transformers (CT) from different manufacturers and hence the error percentage of the measured current varies enforcing a need for better tuning of the protection system settings. Bus bar protection gets further complicated with various arrangements like bypass isolator or transfer bus arrangement for circuit breaker (CB) maintenance, single CT arrangement in bus coupler (BC) and bus section (BS) for cost reduction. The bus bar protection relay should be capable of handling any type of operational philosophy without intervention of operational personal. In case of improper indication of the switchgear status to the relay, prevention of unwanted operation has lead to enhanced challenges in the logics of bus bar protection. Sample single line diagram (SLD) with complicated switchgear arrangements are considered and the solution is discussed in this paper.

II. System Description

A simplified version of the system under consideration is shown in Fig.1 (Complete system can have higher number of bays). This is a complicated system with various types of arrangements which leads to discussions about how the logic in the relay can be adapted to accommodate these variations. A double bus arrangement with two generators and two lines are shown. The bus bar is divided into two sections using bus section CB. Each side of the BS has a BC. The top bus is divided into two buses using 452CB as bus A and bus B. The bottom bus is divided into two buses using 552CB as bus C and bus D. Each bay is named in sequence and the associated equipments start with the respective bay number. The BS and the BC are provided with a single CT on the left side of the CB. The generator bays have the CT located on the bus side whereas the line bays have the CT located on the line side. Line 1 (L1) has a bypass isolator for CB maintenance which isolates the CB and the CT, whereas line 2 (L2) has a bypass isolator which excludes the CT. This difference has a huge impact in bus bar protection which is discussed in the next section.

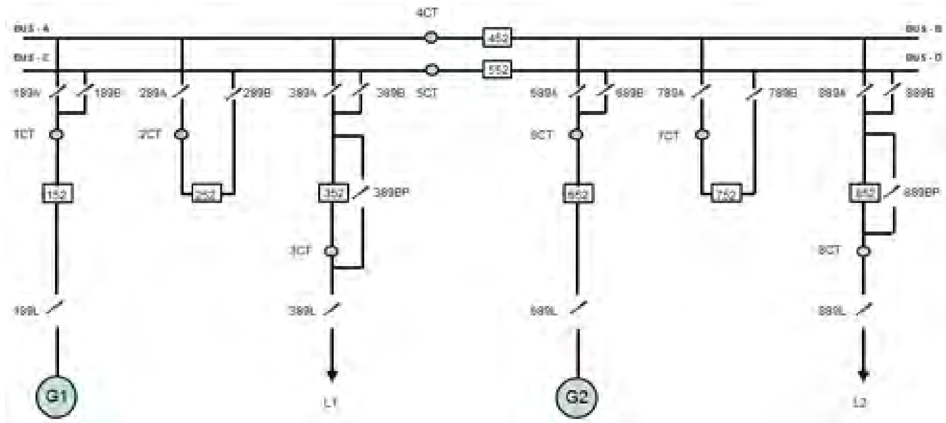

Fig. 1. Description of the system

III.OPERATIONAL PHILOSOPHY

Various operation philosophies have been carried out to maintain the CB or CT and the relay logic has to be fine-tuned to ensure that no area of the bus bar is left unprotected. Typical conditions are 389BP (By-pass) and 889BP which leads to specific protection complication which is discussed independently below:

A. By-pass isolator isolating the CB and the CT (389BP close scenario)

The generators and lines will normally be connected to a single bus bar from which the power is evacuated. If maintenance activity is planned for 352CB/3CT, where closure of 389BP isolator isolates them, then bus C will be fed from bus A through 252BC and L1 will be fed from bus C. On closure of 389BP, the distance protection of L1 will switch its CT from 3CT to 2CT and bus C of bus bar protection will be blocked. Bus C is now treated as a line as it carries only L1 current. In case of any fault in bus C or in the line, the distance protection relay detects the fault in forward zone and 252CB will be tripped, hence there is no unprotected zone in this operation. If 2CT and 3CT have different ratios, then by utilising group settings, this can be handled in the distance protection relay. Fig 2 shows the blocking logic implemented in B90. Based on the isolator position, the respective bus in B90 is blocked to prevent unwanted operation of bus bar relay, without compromising protection to the bus bar. In this scenario, VO73 would be sealed in and bus C will be blocked. Virtual output (VO) shown in Fig 2, is a programmable logic of B90 relay where any kind of logic can be designed and assigned to it and the same can be used for any other application depending on the requirement.

In this case, it is to be noted that bus C is treated as an extension of line and the bus differential zone for bus C is blocked.

Fig. 2. Bus blocking logic during bypass isolator closing

B. By-pass isolator isolating the CB (889BP close scenario)

If maintenance activity is planned for 852CB where closure of 889BP isolates only the CB, then bus D will be fed from bus B through 752 BC. In this condition, bus D would not be blocked in B90 since the CT is not eliminated from the circuit and will actively contribute in determining the differential current of bus D. In case of any bus fault in bus D, the only CB in bus D is 752CB which will be tripped by B90 as bus D fault. The fault is still being fed from the remote end and to accelerate the tripping, the remote end would be tripped on a direct trip transfer method since the remote end is directly connected to bus D with remote end CB.

In this case bus D is treated as an extension of the remote line and bus differential zone is kept intact and for the fault on the same the local CB (752CB) and the remote CB are tripped.

The main zone blocking logic (case A) and remote end tripping logic (case B) for different bypass isolator conditions were detailed in this section and the main zone segregation philosophy is discussed in the next section.

IV. ZONES OF PROTECTION

Fig. 3 shows the four main zones of protection in different colours for this system. In generator and line bays [1], the CTs form the boundary of the zones if the isolator is closed, else the isolator acts as the boundary. In BC and BS bays, the zone extension will depend on the CB and not the isolator. The dotted area indicates that they are dependent on the CB status i.e., if 252CB is closed then the dotted area of bay 2 will be treated as zone3 else zone1. The traditional way of protecting this dotted area is by the use of end fault; however a different approach is implemented here (hence the assignment to zone1) which is detailed in section V.

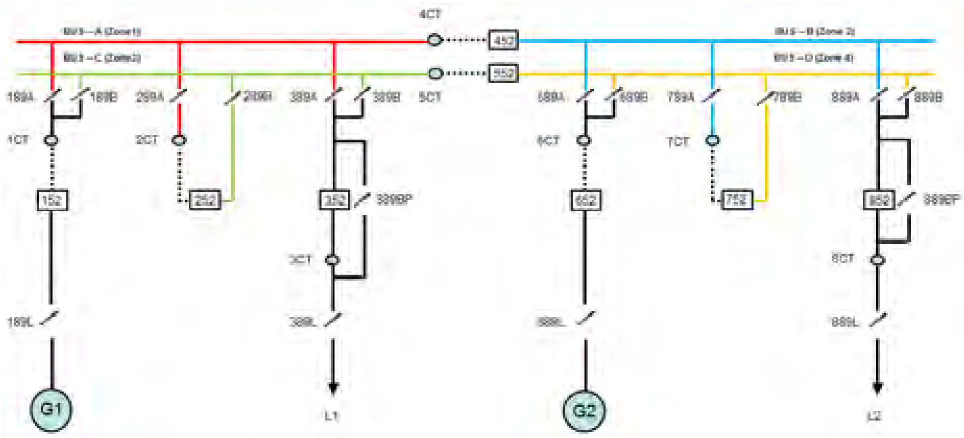

Fig. 3. Zones of protection when all isolators are open

Fig 4 shows the zone selection logic for G1. G1 bay is switched between zone1 and zone3 based on the isolator position as shown. In similar lines, the logic is repeated for L1, G2 and L2.

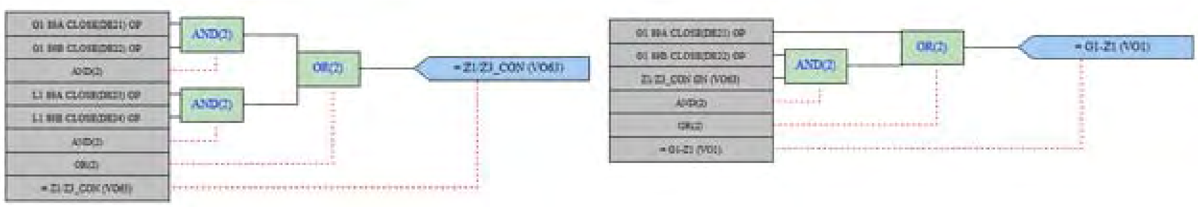

Fig. 4. Zones selection logic in IEDs

Blind spots are denoted as dotted lines in Fig 3, which is of critical importance since it is not covered under any zone when the associated CBs are kept open. The conventional philosophy of eliminating this blind spot is by providing CTs on either side of the CB, thus creating a zone overlap. This convention is modified and the blind spot is eliminated using a single CT which is explained in section V and VI.

V. BLIND SPOT COVERAGE BETWEEN CT AND CB IN BS AND BC BAY

Let us assume that 452 is closed, such that the area between 4CT and 452CB is covered under zone 2 as shown in Fig. 5 and the positions of all the isolators are shown in table1. If a fault occurs at F1, the relay will detect this fault in zone 2 (based on CT location) and it will trip all the CBs associated to zone 2. However the fault will not be cleared since the fault is located in zone 1 (based on CB position). This fault is located outside 4CT and B90 will treat this fault as external fault for zone 1 thereby creating a blind zone. This fault will be cleared after a time delay of 200ms by CB failure protection (explained in section XII), which is not acceptable. In order to provide an accelerated tripping for this scenario, this blind spot has to be covered under zone 1 when 452CB trips. This logic has been incorporated in the relay as shown in Fig 6.

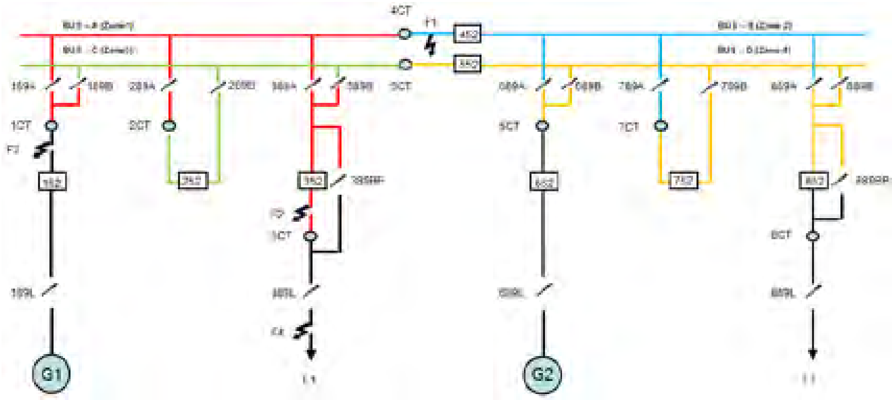

Fig. 5. System with various fault locations

Table1 : Isolator positions of Fig 5

Isolator position in bus A and bus C	
Closed	**Open**
189A	189B
389A	389B

Isolator position in bus B and bus D	
Open	**Closed**
689A	689B
889A	889B

In BS bay, if a CB close command or the CB close feedback (derived from 52a and 52b contacts) [2] is extended then VO82 is set as shown in Fig 6. The same inputs are inverted and assigned to VO86 which is called as 452 reset. The above logic for VO82 will set Latch 15 in high condition and it will drop off only if VO86 is high. Thus Latch 15 will be high when the CB is closed and it will be low if the CB is open. This latch 15 is in turn used in conjunction with zone1 and zone2 trip logic to make VO22 high which is used to read 4CT in zone1 and zone2 which ensures proper imitation of circuit breaker status. The first condition of VO22 being the 452CB in close position and the second condition is the absence of any zone trip which is used for additional security to ensure that in the event of absence of CB feedback due to failure of CB auxiliary contact or cable, the relay will still execute the logic perfectly after 150ms and hence B90 will execute the logic securely even in the absence of feedback.

In the absence of this logic, the relay will receive a breaker fail initiation command from BC bay and zone 1 will be tripped in breaker failure after 200ms under the assumption that the breaker failure initiation was extended for bus faults also. Tripping of bus bar on breaker failure when no CB has failed is a misconception which further complicates the fault analysis and a delayed bus bar tripping.

The logic for BC is almost similar except for an additional input that needs to be considered in the logic of VO22. It should be a three input 'AND' gate with the third input being both zones separated. This input is used to ensure that BC current transformer is not read in the zones if there is a bus unification condition, since it acts as a parallel path to that circuit resulting in wrong current measured by B90. During this scenario there will be a circulating current which will be handled by directional principle / voltage supervision ensuring stability of B90 which is discussed in section VII and VIII.

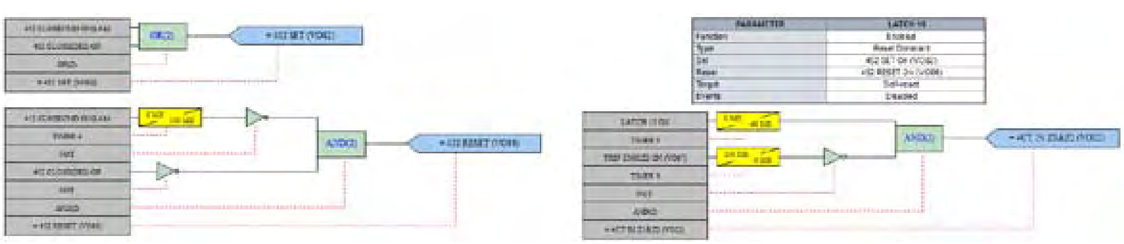

Fig. 6. B90 Logic for accelerated tripping for faults in blind spot

For operational conditions where the CB in BS or BC bays are open before the occurrence of a fault, then the logic permits tripping of only the faulted bus however during CB close conditions, tripping of both busses for faults located in F1 is unavoidable.

Using the above mentioned logic, the 4CT is switched in Zone1 and Zone2 which works perfectly for most of the cases. In case of dead bus charging, the above logic will issue an unwanted trip to the healthy zone. This can be handled in the following manner. Let us consider a scenario where Bus A is dead and Bus B is live, and F1 fault is present (e.g. grounding because CB maintenance). During this scenario, if we issue a close command to 452 CB, then based on the above logic, there will be an unwanted trip of Bus B. To prevent this Zone 2 trip, the logic shown in Fig 7 can be utilised. VO15 is a logic used to detect a dead bus charging condition based on under voltage protection and 452 CB close pulse. This logic along with non-directional zone 2 differential element will trip 452 CB and also block zone 2 trip for 2 seconds; thereby eliminating the isolation of a healthy zone.

Fig. 7. Logic for tripping only BC & Zone1 for faults in blind spot

The above mentioned scenario and logic is applicable for all BS bays (4, 5) and BC bays (2, 7). In similar lines, the blind spot issue for generator and lines are protected by a concept called as end fault. The location of the CT has a huge impact on the trip logic which is explained in the following section.

VI. END FAULT FOR DIFFERENT CT LOCATIONS

Consider the line L1 being fed from bus A with 389A isolator closed as shown in Fig 5. If a fault occurs at F2, this fault is treated as a bus fault and all associated CBs of bus A are tripped. The fault is not fully cleared as the remote end CB is intact and feeding the fault. This necessitates the tripping of the remote end for an effective clearance of the fault. This remote end tripping is facilitated through a direct trip mechanism, provided the CT reads current after successful tripping of bus bar. In this manner, protection is provided without any blind spot for CTs located towards the line side. The trip logic for CTs located towards the bus side is discussed below.

Consider the generator G1 being fed from bus A with 189A isolator closed as shown in Fig 5. If a fault occurs at F3, this fault is treated as an external fault for B90 as it is outside its zone. This fault will be detected by the respective bay protection relay and the generator will be tripped. The opening of 152 CB does not clear this fault as it is still fed from the bus bar. In this kind of bus arrangements, the bus bar has to be tripped and there are two methods of executing this logic which is explained below.

The first method incorporated in the relay for a perfect operation for the above mentioned scenario is shown in Fig 8. When CB close pulse or a CB successfully close feedback (derived from 52a and 52b contacts) [2] is extended to the relay, VO84 is set in the relay. These inputs are inverted and assigned as VO87 in the relay. In other words VO84 will be high when the CB is closed and VO87 will be high when it is open. The logic is to ensure the absence of feedback and presence of close pulse command will still execute the logic successfully as it is assigned to the latch logic. These inputs are assigned to a latch function which becomes high when the CB is closed. Latch becomes low when the CB is open. Depending on the Latch position, 1CT is switched in the zones. If 152 is open, then Latch 1 removes 1CT from B90 which operates the differential function if the fault is located at F3. The simple concept used in this application is that the CT acts as a boundary for differential function and on removal of the CT, the boundary extends till CB thus eliminates the blind spot.

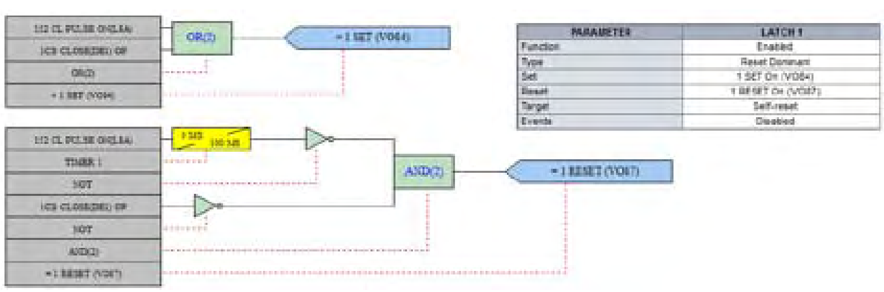

Fig. 8. Relay Logic for Blind Spot detection

The second method for clearing the F3 fault is by the use of end fault (EF) and zone selection logic. End fault protection is the well-known current monitoring feature during CB open conditions [3]. Fig 9 shows how the bus would be tripped after executing the zone selection logic for two bays. Let us assume that G1 is connected to bus 1. The zone selection logic explained in section IV will execute and VO01 will be high as described in Fig 4. After the generator trips 152CB in generator differential, EF function will detect the CB open condition and since the current is persisting, EF feature will be sealed in. EF is the internal function of B90 and if it is sealed in, it would enable VO51, which in turn would trip zone1. The same logic will repeat for VO52 if G1 is in zone3. In this manner the blind spot between the CT and the CB is still protected by B90.

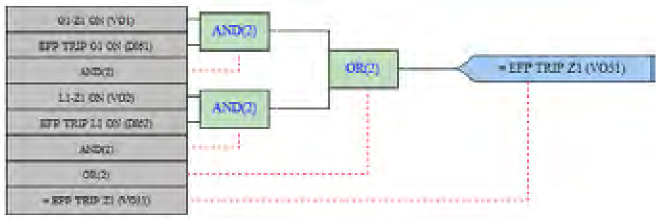

Fig. 9. End Fault Trip logic

End fault for various CT arrangements has been discussed and with the introduction of so various logics, the need for proper testing comes into picture which is taken up in the next section.

VII. Testing Methodology

All the above scenarios can be built as logics in an IED and being a man-made logic, the need for proper testing is mandatory. Bus bar relays have multiple CTs and also the concept of phase segregation will increase the complexity and testing duration. Such scenarios and complexity can be easily addressed by the use of SMRT 410 which has 10 current sources with which multiple bays can be tested with all the zone selection logics. In addition, multiple test sets can be merged and used as a single unit with many current source as shown in Fig 10.

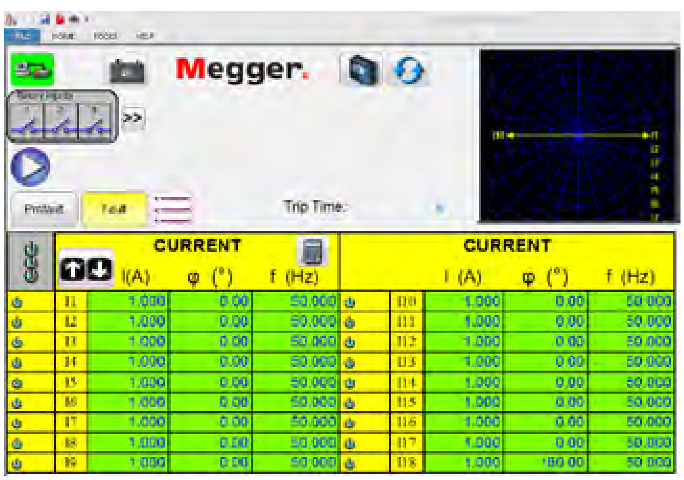

Fig. 10. Multiple bay testing option with SMRT

VIII. Conclusion

This paper presents the most effective ways of protecting a bus bar in a complicated system where the CT locations are different for different bays added with bypass arrangement across the breaker there by facilitating any bus use as an auxiliary bus which in turn challenges the protection philosophy. To handle these complications a novel solution has been discussed in this paper. The advancement of the IEDs in terms of measurement and the ability to include custom based logics permits the IEDs to adapt for complicated applications. This also helps in eliminating the long procedures and operation of many devices to implement uncompromised protection thereby improving the dependability of the system with total elimination of human intervention.

IX. References

[1]Wai-Kai Chen, The electrical engineering handbook, chapter 9, Page 789
[2]IEEE Std C37.20.1-2002, IEEE Standard for metal-enclosed low voltage power circuit breaker switchgear, Page 32
[3]GEK-119552, B90 Low impedance bus differential system, UR series instruction manual, Page 5-112, 5-131, 5-140, 5-144, 8-6.
[4]Bogdan kasztenny, Lubomir Sevov & Gustavo, digital low impedance bus differential protection review of principles & approaches
[5]IEEE C37.2-2008, IEEE standard electrical power system device function numbers, acronyms and contact designations
[6]www.gedigitalenergy.com
[7]www.megger.com

System Operation

CIGRE- AORC Technical Meeting 2018 – International Conference on Global Energy Transition – Issues and Challenges, 24-25 May 2018, Gangtok, Sikkim, India

The Plan of Power System Stability ESS of KEPCO for Energy Paradigm shift

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SUMMARY

Even though electricity is embedded deeply in all corners of our lives, it is challenging to construct power systems such as transmission lines and substations. Any project delay or absence of the system can have an impact on the stability of the power systems. The stability of the system can be classified into three types such as frequency stability, transient stability (rotor angle stability), and voltage stability. Firstly, frequency stability requires a balance of demand and supply and secures frequency reserve to maintain it. Secondly, the transient stability becomes unstable when the main transmission line of the generator complex trips. To stabilize this, the generator trips by SPS or constraint can be imposed. Finally, the voltage stability may be due to the breakdown of the voltage of the power system when the main transmission line trips. New measures need to be taken for the conversion of the energy paradigm such as the difficulty of establishing and expanding the power transmission and substation facilities. Recently, the commercialization of the energy storage system (ESS) in KEPCO grid has been actively promoted, and a system for revitalizing the market has been established. Among the various ESS functions in Korea, there is a high interest in frequency regulation (F/R) service, which corresponds to the power system frequency in place of existing thermal power plants. This paper is intended to redefine ESS to utilize it as a power system stabilization scheme, and shows the role and effect of ESS for each stability improvement application.

KEYWORDS

ESS (Energy Storage System), Frequency Stability, Voltage Stability, Transient Stability, Rotor Angle Stability, Generation Constraint

I. INTRODUCTION

In Korea, the demand for electric power is continuously increasing due to the expansion of the economy scale and the improvement of the living standard. The load is concentrated in the metropolitan area, and the power plants are being built mainly in the super large power generation complexes which are near coastal area far away from cities In the case of delays in the construction of the ultra-high voltage transmission grid of the large power generation complex, the constraints of the corresponding power generation complex are being applied as general measures to secure the stability of the power grid. The South Korean government presented the vision of a new and renewable 3020. It planned to achieve the goal to reduce the dependence on nuclear power plants and coal fired power plants.t The renewable energy will account for 20% of total power generation by 2030. The difficulty of establishing

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and expanding such power transmission and substation facilities and expanding the renewable power supply can deteriorate the stability of the power system[1].

As shown in Fig. 1.1, the stability of the power system is classified into three types such as frequency stability, transient stability (rotor angle stability), and voltage stability. Firstly, the stability of the frequency requires a balance between supply and demand, securing reserves to maintain it, and costing reserve power. Secondly, the transient stability becomes unstable in the event of failure to the main transmission line of the power plant, and as a method to stabilize it, there is a generator trip by SPS or constraint, which also causes a cost. Finally, the voltage stability may cause the power system to collapse when the main transmission line trips, so that there is a load cut-off by SPS or constraint, which also causes a cost. New measures need to be taken for the conversion of the energy paradigm such as the difficulty of establishing and expanding the transmission and substation facilites[1].

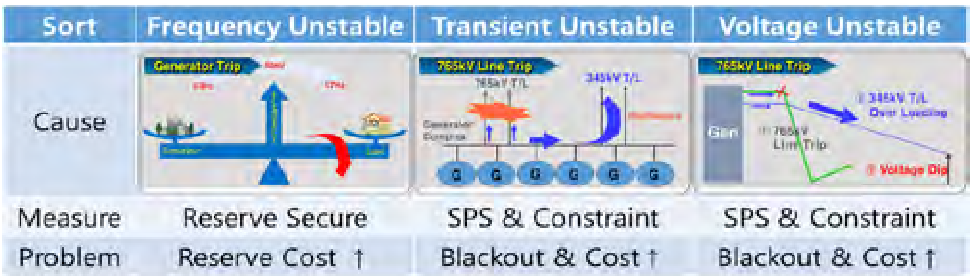

Fig. 1.1 Types of power system stability and existing countermeasurse

Recently, the commercialization of the energy storage system (ESS) in KEPCO grid has been actively promoted, and a system for revitalizing the market has been established. Among the various ESS functions in Korea, there is a high interest in frequency regulation (F/R) service, which corresponds to the power system frequency in place of existing thermal power plants. Among the various ESS application methods, application methods for improving the transient and voltage stability have been examined in the case of ESS having rapid response characteristics. There are technological alternatives that can minimize constraints that are expected in power system by improving system stability with ESS, and it is feasible to examine various technical applicability of ESS in terms of utilization of power system such as transient stability, voltage stability and frequency reduction prevention. This paper redefines ESS to utilize ESS as a power system stabilization scheme, and shows the role and effect of ESS for each stability improvement application[1].

II. STABILITY PROMOTION THROUGH INTRODUCTION OF NEW CONCEPT KG-ESS

2.1 Overview of KG-ESS

KG-ESS (KEPCO Grid ESS) refers to ESS used in order to improve the stability of power system such as frequency stability, transient stability, and voltage stability in connection with KEPCO Grid. As shown in Figure 2.1, the classification system of KG-ESS was redefined for each use. FC-ESS (Frequency statbility Control ESS) to improve frequency stability, TC-ESS (Transient statbility Control ESS) to improve transient stability, and VC-ESS (Voltage statbility Control ESS) to improve voltage stability. In addition, FC-ESS is divided into FR-ESS (Frequency Ragulation ESS) replacing G/F of existing generator, CM-ESS (Constraint Mitigation ESS) improving frequency bottom point, and VM-ESS (Variability Mitigation ESS) mitigating renewable energy variability.

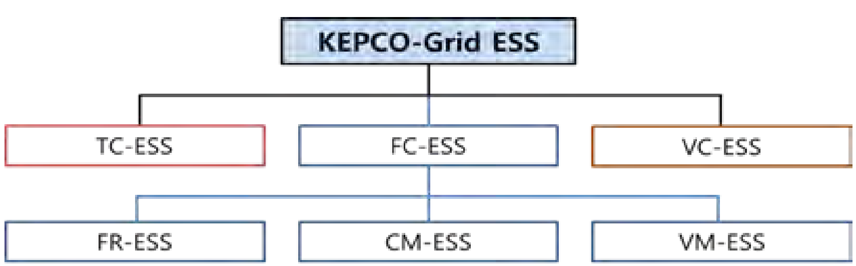

Fig. 2.1 Functional classification system of KG-ESS

KEPCO is also pursuing research projects to develop ESS for over 154kV level as shown in Fig. 2.2 in order to increase utilization of ESS for power system stability. Due to the voltage limit of the battery, KEPCO is enhancing the voltage level by developing PCS as MMC type.

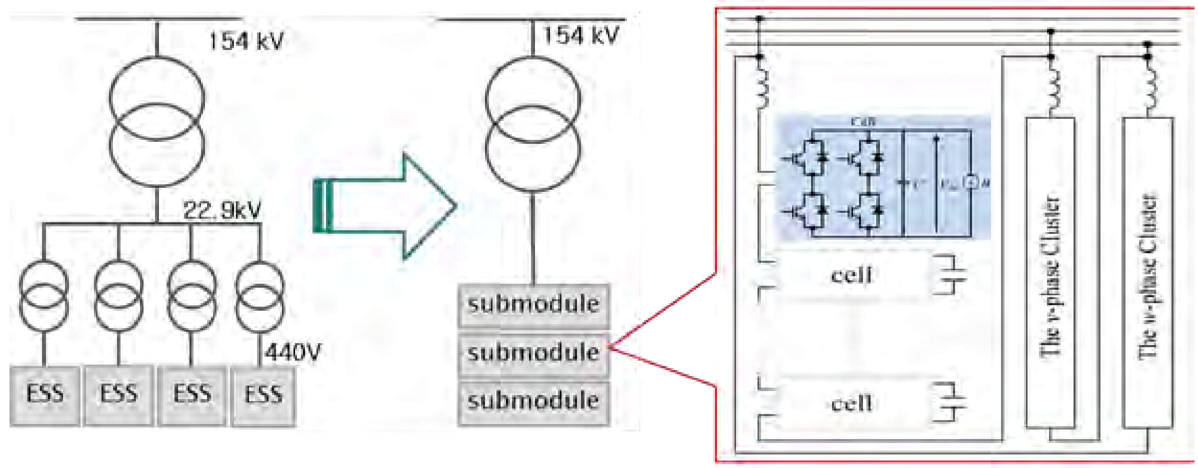

Fig. 2.2 Concept of MMC type ESS for over 154kv level

2.2 Roles and Effects of KG-ESS

A. FR-ESS (Frequency Ragulation ESS)

The FR-ESS discharges when the frequency falls, or charges when the frequency rises, and controls the frequency by balancing the supply and demand of the power system. As shown in Figure 2.3, the FR-ESS replaces the G/F portion of the thermal power generator. As the FR-ESS is installed, the utilization rate of coal-fired power generators with costs can be increased, thereby improving the economics of power system operation. KEPCO is currently operating a 376MW FR-ESS.

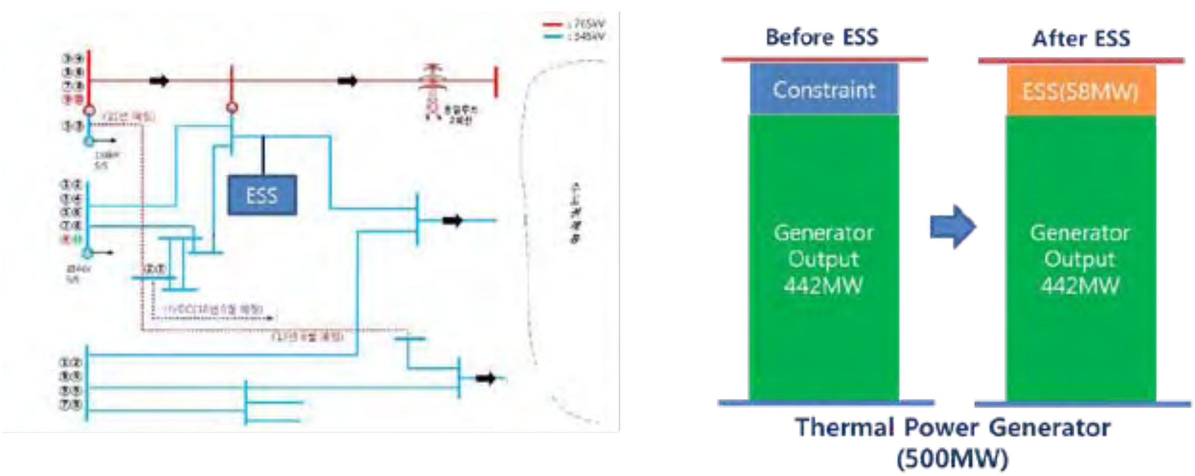

Fig. 2.3 Concept of FR-ESS

B. CM-ESS (Constraint Mitigation ESS)

CM-ESS refers to the ESS that is installed and operated to alleviate constraints. KEPCO installs SPS (Special Protection Scheme) to trip the generator in order to secure the transient stability in case of a failure of 765kV transmission lines. At this time, if the trip amount of the generator exceeds 2.4GW, the frequency may be lowered to 59HZ or less, and the load may be cut off by the UFR, resulting in a wide-scale power outage. In order to prevent such a wide-scale power outage, the ESS discharges fast when 765kV transmission lines trip, and improves the lowest point of the frequency to keep the frequency higher than 59Hz. Figure 2.4 is a graph showing that the frequency drop is improved by the fast discharge characteristic of the ESS.

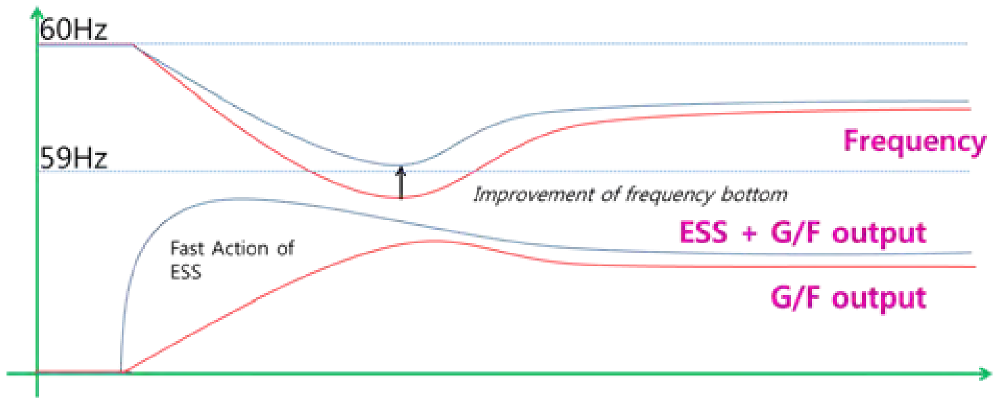

Fig. 2.4 Graph showing the effect of improving the lowest point of frequency by ESS

C. VM-ESS (Variability Mitigation ESS)

VM-ESS is an ESS aimed at mitigating the volatility of renewable energy. As shown in Fig. 2.5, PV or wind power generators have high output volatility. Such volatility leads to supply-demand imbalance and deteriorates frequency stability. In addition, PV and winds can reduce the inertia of the power system and deteriorate the frequency stability when replacing the conventional turbine generators.

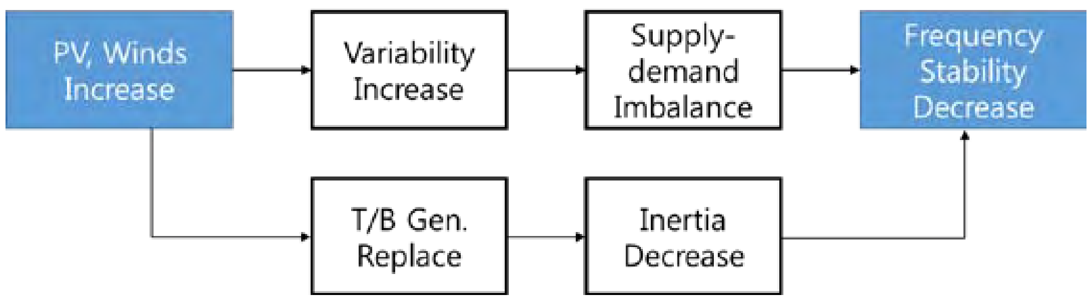

Fig. 2.5 Impact of Volatile Renewable Energy on Power System

Since the variability of renewable energy is rapid, ESS can be used as a backup facility to supplement this. As shown in Fig. 2.6, it will be possible to secure frequency reserve as well as stable system operation by introducing a renewable energy monitoring system and VM-ESS, as much as output of solar and wind power.

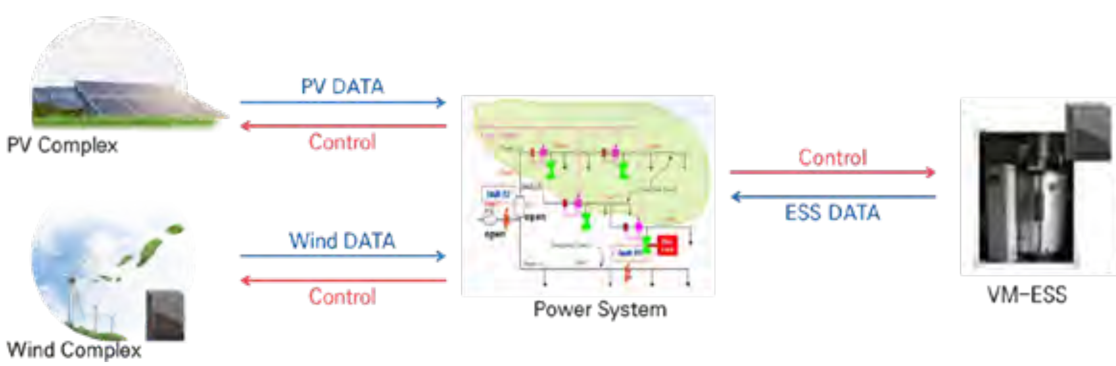

Fig. 2.6 Concept of renewable energy monitoring system and application of VM-ESS

D. TC-ESS (Transient statbility Control ESS)

TC-ESS is installed in a large-scale power generation plant as shown in Figure 2.7, and absorbs surplus generation power momentarily when a main transmission line fails, such as 765kV transmission lines, to improve transient stability of the power generation complex.

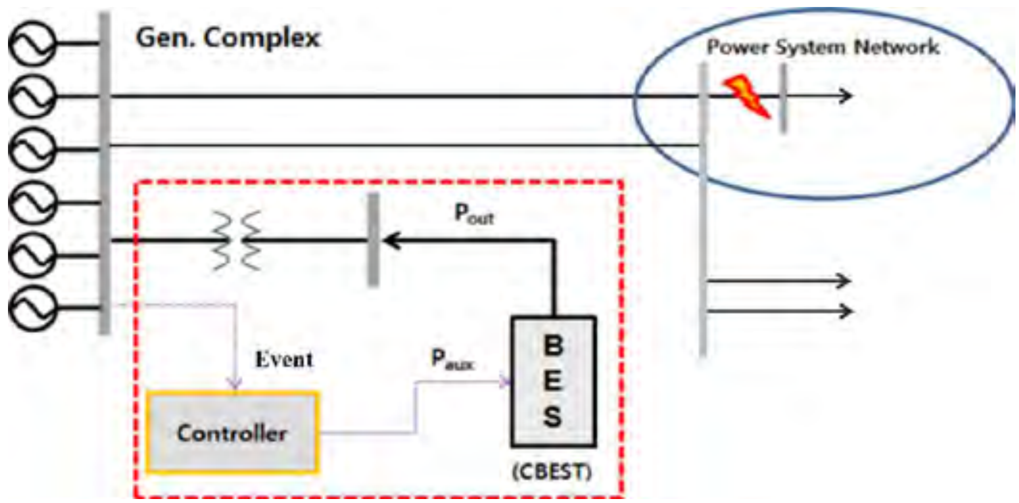

Fig. 2.7 Concept of TC-ESS applied to power system

The TC-ESS control strategy can consist of constant power charge control and frequency control as shown in Fig. 2.8. Firstly, when receiving a fault signal on the transmission line, full charge is made for 1 second through P control of ①, and frequency control is performed through f control of ② after 1 second.

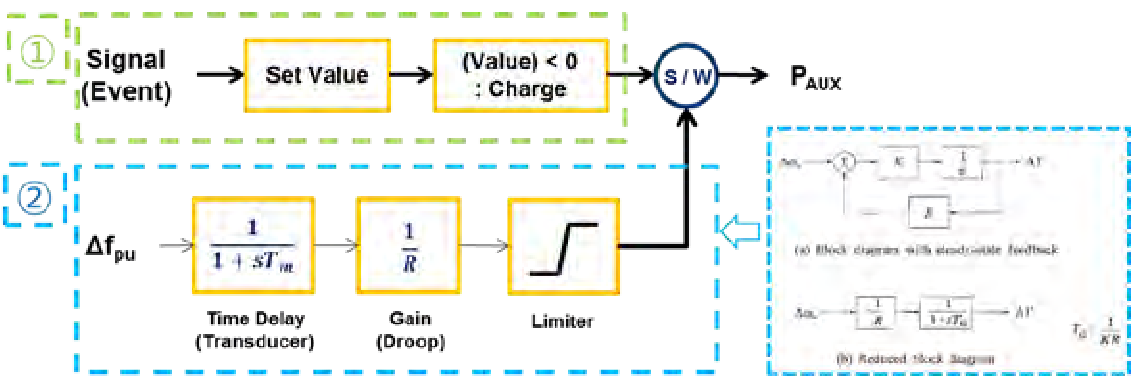

Fig. 2.8 TC-ESS control block concept

Fig. 2.9 is a graph showing that transient stability is improved through this control strategy. The p-f control strategy, which is used in combination rather than controlling the two modes, shows the best for improving transient stability.

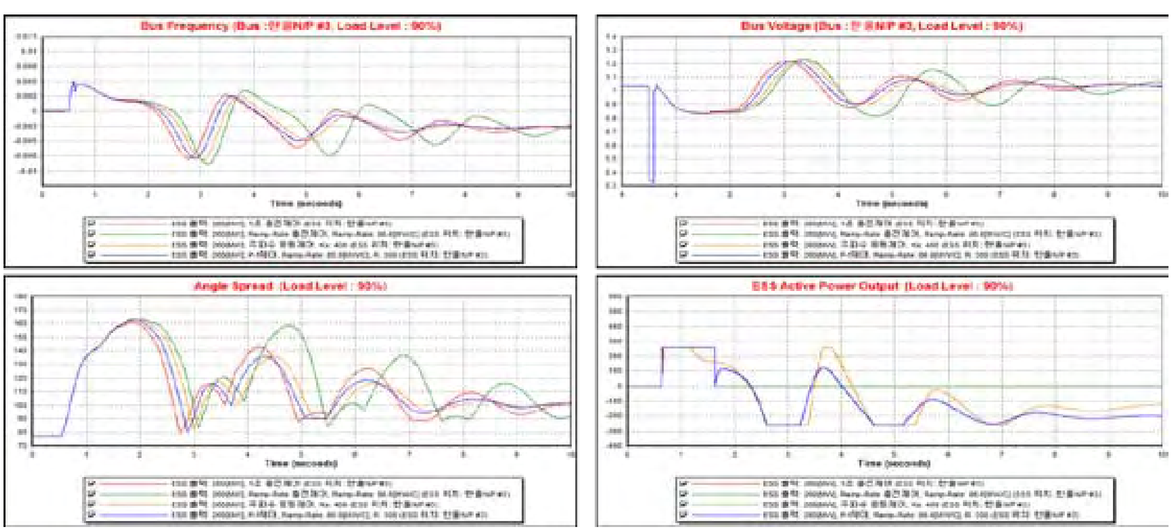

Fig. 2.9 Result Graphs showing TC-ESS application effect

E. VC-ESS (Voltage statbility Control ESS)

VC-ESS refers to ESS which is installed on the load side as shown in Figure 2.10 and secures the voltage stability by discharging the output when the transmission line fails in order to improve the voltage drop. In the event of a transmission line failure, the discharge of the ESS can absorb the active power of the load and raise the substation bus voltage by lowering the load factor of other transmission lines supplying power to the substation. With these improvements, VC-ESS can replace the existing load-sharing SPS.

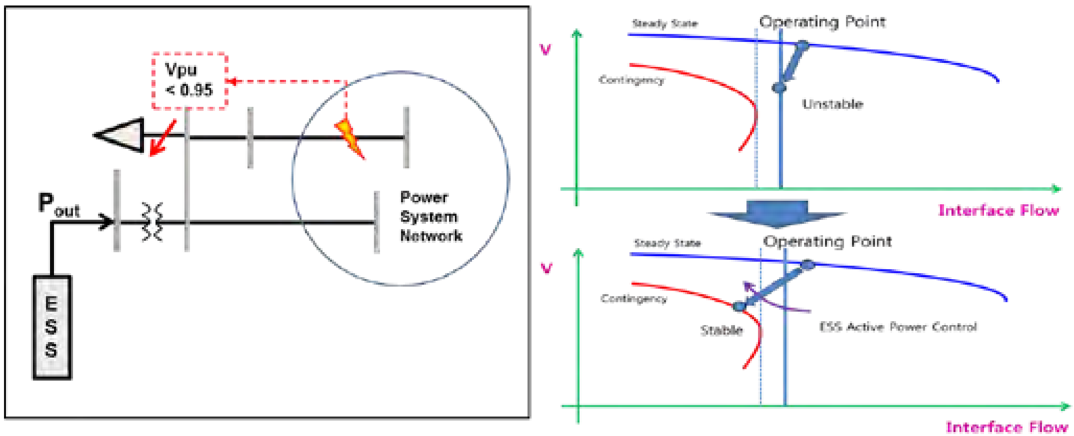

Fig. 2.10 Concept of VC-ESS application and improvement of voltage stability

III. CONCLUSION

This paper redefines the function classification system of KG-ESS, ESS for power system stability, and shows the roles and effects for each application. KG-ESS can improve the frequency stability, transient stability, and voltage stability by adapting it to its characteristics in order to improve the stability of the power system. In order to overcome these limitations, the application of ESS for stability of the grid has been applied to increase the reliability of the power system and to improve the efficiency of existing facilities It is expected to be a new solution to improve the economic feasibility through efficiency increase. However, in order for the ESS to expand to a large scale for the power system stability, the pirce of ESS should be lowered, and the technology of ESS should develop as well.

IV. APPENDIX

[1] H.P.Bang, H.C.Song, Y.G.Ha, G.H.Kim,T.O.Kim “ESS Operation Strategy to Secure Power System” In KIEE Conference, July 2017, pp. 200-201

[2] P. Kundur, et al. “Definition and classification of power system stability IEEE/GIGRE joint task force on stability terms and definitions”, IEEE Trans. Power Systems, vol. 19, no. 3, 2004.

[3] P. Kundur, Power System Stability and Control, McGraw-Hill, 1994.

[4] S.K. Kim, H. Song, T.W. Yoon, "Damping Improvement and Voltage Regulation for a Synchronous Machine Using an Energy Storage Device," Int'l Journal of Electronics, vol. 102, no. 4, pp.582-598, 2015.

Use of Large Rating Generators as Synchronous Condenser to Support Regional Grids

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TOPICS

- Background
- Understanding Reactive Power and its Role
- Where to Inject Reactive Power
- How much Reactive Power to Inject
- Concern for future Reactive Power Management
- Available Solutions
- Use of Large Rating Generators as Synchronous Condenser

Definition of Reactive Power

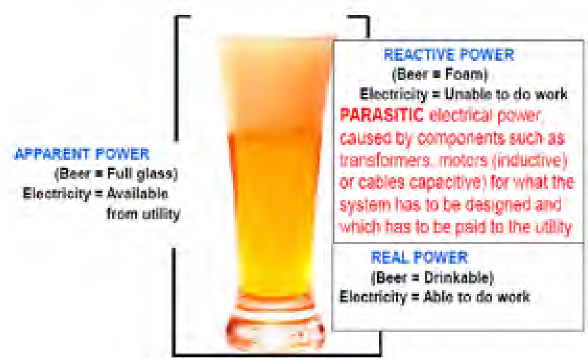
- Reactive Power has been defined by U.S. Department of Energy as
- " the portion of electricity that establishes and sustains the electric and magnetic fields of alternating current equipment. Reactive power, which must be supplied to most types of magnetic equipment, such as motor and transformers, is provided by generators, synchronous condensers, or electrostatic equipment such as capacitor."

  It further states that "The reactive power also supports the flow of real power throughout the grid."
- REACTIVE POWER IS CARRIER OF REAL POWER TO REACH CONSUMER FROM GENERATOR THRO ELECTRIC SYSTEM.

Background

- Renewable Generation of 175GW is planned by 2022- will have large variation in generation every day
- Transport sector will see a big change by switching to Electric Vehicles, resulting in cyclic loading on network.
- Old inefficient plants in urban areas will retire depriving the local network of Reactive Power support

Above three will impose a great challenge to manage grid.

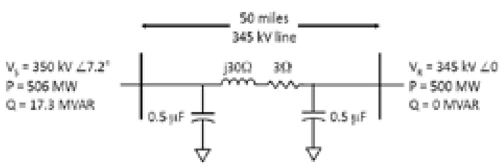


Understanding Reactive Power and its Role

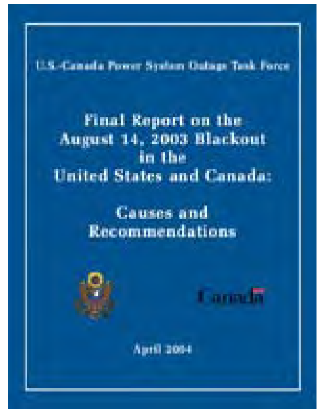
Some facts about Reactive Power

- Reactive Power generated by synchronous machines and Capacitors.
- Machines with high Short Circuit Ratio contribute more in Reactive power support.
- Reactive power is consumed by transformer and motor
- Reactive power is also consumed in transporting electricity.
- Thus Reactive Power generated and consumed only by electrical equipments in system. Its origin and end both are in electrical system.

MVAR Consumed –Example in GE Study



- Voltage amplitude and phase changes with distance.
- Available MW and MVAR changes with distance.
- Thus MVAR plays a vital role in transporting MW.



- Subsequent to grid collapse in 2003, a guideline was issued to take necessary steps to avoid any blackout in future.
- The report suggest to inject Reactive power close to its demand locations.

Reactive Power Delivery/ Absorption

Reactive Power Delivery

- **Synch. Generator or Condenser in under excitation mode**
- **Capacitor**
- **Transmission line loading below SIL**

Reactive Power Delivery

- **Synch. Generator or Condenser in over excitation mode**
- **Reactor**
- **Transformer**
- **Motors**
- **Transmission line loading above SIL**

Recommendations to Prevent or Minimize the Scope of Future Blackouts

The blackout on August 14, 2003, was preventable. It had several direct causes and contributing factors, including:

- **Failure to maintain adequate reactive power support**

- Failure to ensure operation within secure limits
- Inadequate vegetation management
- Inadequate operator training
- Failure to identify emergency conditions and communicate that status to neighboring systems
- Inadequate regional-scale visibility over the bulk power system.

Where to Inject Reactive Power ?

MVAR Generation right at point of demand

- Report on August 14, 2003 blackout in US and Canada states:
- *“Reactive power does not travel far, especially under heavy load conditions and so must be generated to its point of consumption”.*
- It also states “Control Areas must continually, monitor and evaluate system conditions, examining reactive reserves and voltages, and adjust the system as necessary for secure operation.”
- **Thus besides compensation at thermal generation end, it is necessary to provide MVAR generators (FACTS devices) near load points or where system demand.**

How Much Reactive Power to Inject ?

Concern for Future Reactive Power Management

2000MW Largest wind Farms In U.S. Planned For Oklahoma Panhandle, Texas USA

Retiring Old Plant- Urban area Deprived of Reactive power

- In order to meet stringent GHG emission target set in India, inefficient plants of urban areas are getting retired and therefore adversely affecting the Reactive Power compensation.
- New generation at far off location do not support MVAR requirement to load centres.
- Two issues needs to be addressed while retiring old plants:
  - Where from the MW will come?
  - Where from the MVAR support will Come?

Synchronous Condenser Size for 2000MW Wind Farm in Texas

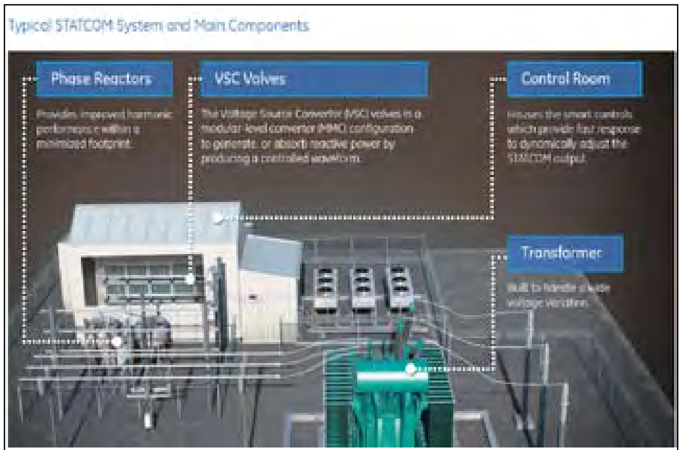
- 2000MW rating wind farms will be completed by Electric Reliability Council of Texas (ERCOT) Grid by 2020 at Panhandle. 800 number of turbine of 2.5MW.
- In 2015 ERCOT grid ordered two (2) number of 150MVAR synchronous condenser to be located at two nearest sub station within 50 km of wind farm.
- 15% of MW rating has been considered for Wind Farms.

Wind and Solar addition

- Wind and solar addition also requires adequate Reactive Power support to transport power to load centre.
- Also, whenever any cloud movement takes place in region, electricity generation falls suddenly, demanding Reactive Power compensation.

Addition of E-Vehicle

- The switching to electrical vehicles will introduce a new pattern of load cycles.
- The introduction of E-Vehicles will create new Reactive Power demand varying in nature.



AVAILABLE SOLUTIONS

Advantages of STATCOM

- The STATCOM has faster response and good to handle transients requirement
- It has efficiency higher than 99% excluding the transformer.
- Low O&M cost

Managing VAR (Reactive Power) demand - FACTS Devices

The Solution includes provision of FACTS devices:

- Static Synchronous Compensator STATCOM
- Static VAR Compensator SVC
- Synchronous Condenser.

Synchronous Condenser

Advantages of Synchronous Condenser

- It can very well meet the system Reactive Power demand expected in future as discussed above,
- Available for very large range (e.g. +720/-360) rating
- Low voltage ride thro capability during peak condition
- Fast dynamic compensation
- Perform well during low grid voltage
- Good overload capability and
- Maintains power quality acts as sink for harmonics originating from static devices.
- Efficiency more than 98%.

Performance Comparison of FACTS Devices

Sl. No.	Parameter	STATCOM	Synchronous Condenser
1	Short Circuit Current	Poor	Good
2	Overload	Poor	Good
3	Response time	Excellent	Good
4	Inertia	Poor	Good
5	Handling Transient – fault condition	Excellent	Good
6	Handling Dynamic condition	Good	Good
7	Efficiency	99.2%	98.5%
	Approx. Cost per KVAR in Rupees (large ratings)	3000/-	1500/-

Suggested Solution to Meet Future MVAR Requirements

- One of techno-economic solution could be combination of STATCOM, SVC and Synchronous condenser.
- Whereas the transients requirement will be met by fast acting Power electronics devices, the Synchronous Condenser will help in meeting the day to day dynamic Reactive Power demand due to Renewable Generation and E-Vehicle load.

Use of Generators As synchronous Condenser

Why Synchronous Condenser for Wind/Solar generation

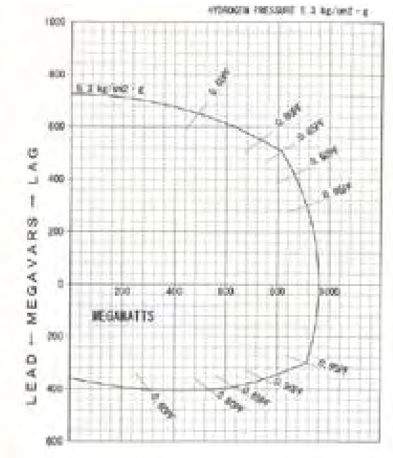
The wind and solar generation has following limitation as they are connected to Grid by Static Frequency Converter:

- Limited Short Circuit Current
- Limited Voltage Support
- Limited Overload capacity
- Limited Inertia of machine.

The Synchronous Condenser performance is much superior meeting above requirements.

Use of Generators as Synchronous Condenser

- This paper suggest to use generator as synchronous condenser to augment requirement of MVAR in different regional grids.
- It is suggested to build and operate these plants by generation company and financial impact could be taken care either in electricity generation price or transmission charges.
- It is suggested to locate these MVAR generators preferably near load centres or as per system requirements.

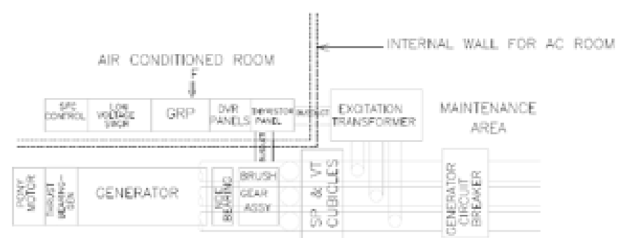


Annexure-II			
Estimated Price of Synchronous Condenser Scheme			
Description	**Price for 400kV & 800MW**	**Price for 765kV system & 800MW**	**Price for 400kV and 660MW**
Generator Transformer bank	**15 Crores**	**18 Crores**	**15 Crores**
Generator Circuit Breaker	**11 Crores**	**11 Crores**	**11 Crores**
Static Excitation System	**20 Crores**	**20 Crores**	**20 Crores**
Civil foundation and building	**12 Crores**	**12 Crores**	**12 Crores**
EHV bay	**5 Crore**	**8 Crore**	**5 Crore**
Drive motor with VFD	**5 Crores**	**5 Crores**	**5 Crores**
Generator Busduct	**3 Crore**	**3 Crore**	**3 Crore**
Generator Auxiliary system	**5 Crore**	**5 Crore**	**5 Crore**
HV and LV System, Air conditioning and Misc.	**6 Crore**	**6 Crore**	**6 Crore**
Total Price	**82 Crores**	**88 Crores**	**82 Crores**
Note: **1.Transformer MVA rating as per Synch Condenser MVAR.** **2.SEE is considered as imported.** **3.Spare Generator cost is not included. Transportation is part of misc.**			

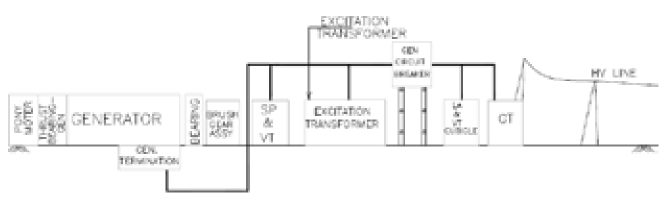
Generator need lesser modification

- 500MW/200MW Spare Generator (available due to plant closure) needs to be accessed for healthiness of insulation system by conducting Residual Life Assessment (RLA) study prior to use as Synchronous Condenser.
- The main generator bearing has to be changed to thrust bearing. The new bearing should be same as used in the test bed, when machine is not coupled to the turbine and run using Variable Frequency Drive (VFD) driven motor.
- The excitation system is to be static type to meet fast ramp rate requirements.
- The drive motor coupled to synchronous condenser will be fed from VFD.

Synchronous Condenser Building – Equipment Layout



Synchronous Condenser Building Equipments



CIGRE- AORC Technical Meeting 2018 – International Conference on Global Energy Transition – Issues and Challenges, 24-25 May 2018, Gangtok, Sikkim, India

Application of Remote Accessibility System & Automated Fault Analysis System for fault analysis in Power System- An Experience

Sunil Agarwal, P.K. Srivastav, Sunil Kumar, A.K. Singh, K.Muruganantham and Vikas Bishnoi
Power Grid Corporation of India Limited

SUMMARY

The Indian electric power system is on a high growth phase and has expanded manifold. As on March 2018, POWERGRID have 148,838 ckm Transmission Lines, 236 Sub-Stations and 332,163 MVA Transformation Capacity.

There is a noticeable trend of utilities implementing Centralised Control Centers for Remote Operation of transmission system to improve the operational efficiency with reduced equipment downtime and to make utility more competitive. The centralised remote operation provides real time visibility and control of the transmission system, aiding quick restoration after a fault in comparison to the local operation being carried out from substation control room. Also, the comprehensive analysis and historical information helps in better asset management of the transmission system.

Faults in power systems are inevitable. Faults interrupt the power flow leading to economic loss and may also cause physical damage to the power system equipment. For precision in isolation of the fault, Numerical protection relays are being configured for various types of protection function like distance, differential, earth fault, over current, restricted earth fault etc for power system element i.e. Transmission line, Transformers & Reactors. These relays continuously monitor the system parameters and ensure the fast & precise isolation of the faulted element from the grid to ensure operational reliability and safety of the equipment. During the fault, the numerical relays also generate the disturbance record with pre fault & post fault values for the analysis of the incident.

Traditionally, protection engineers in a substation download the disturbance records (DR) & events from relays for manual analysis of the fault. These details are also sent to main office for broader analysis. The acquisition of disturbance records and its analysis for restoration of power system elements requires certain exposure as well as it is a time consuming process and also, it prohibits the fast decision making by operators at remote control centre. Thus, the need for development of a system was envisaged in POWERGRID.

Tools to analyse system conditions during fault and immediate transfer of DR files & events from various make & model of relays was a formidable challenge. This paper describes the application of Remote Accessibility System (RAS) & Automated Fault Analysis System (AFAS) for fault analysis in Power System which is implemented at POWERGRID for the first time globally. RAS-AFAS uses the communication capabilities of relays to share the DR files with identified devices over certain protocol. It provides the fault details to substation operators at remote control centres to take quick decision for restoration or otherwise of a transmission element in comparison to the traditional methodology of manual download of disturbance record file & manual analysis of fault by an expert. Thus, RAS-AFAS reduces the no. of experts placed at every station for local analysis, as expertise can be polled at centralised control centre only. The DR files of relays at substations is transmitted to the RAS server at remote control centre and the AFAS server analyses the incident based on the DR file shared by RAS server. In order to expedite the spread of information regarding the tripping of the power system element, the RAS-AFAS has been configured with the capability to send the email & SMS alerts to the concerned. Also, the appreciable features of remote access of relays from control centre and more precise fault location based on cumulative DR files from both ends of transmission line are available with RAS-AFAS system.

KEYWORDS

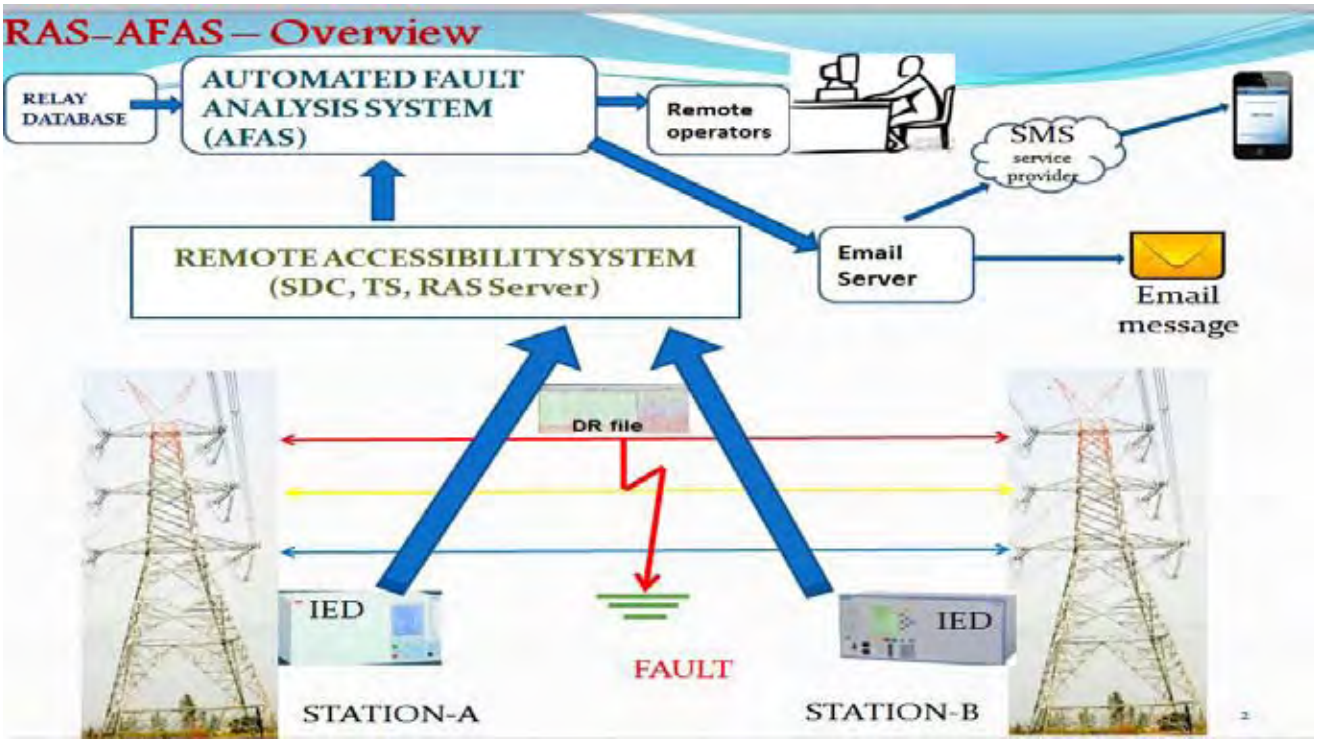
Remote Accessibility System-RAS, Automated Fault Analysis System-AFAS, Disturbance Record files-DR, automatic fault analysis reports, System Operation from remote control centre, Visualization of fault, Quick decision, Reduced outage time, Numerical protection relay, COMTRADE

1. BACKGROUND & MOTIVATION FOR RAS-AFAS

To overcome the challenging requirement of immediate availability of fault information at remote control centre, RAS-AFAS system was designed and broad comparison of fault analysis with traditional methodology is as follows:

Fault analysis with RAS-AFAS system	Traditional methodology of analysis
Automatically acquires the DR files from the substations numerical relays and transmits it to the remote servers located at control centre (In general, within 5 min after generation of DR file in the relay)	Usage of multiple relay specific configuration tools by substation Engineer to manually download the required DR files after connection to the relays individually.
Immediate availability of DR files and automated analysis report containing type of faults, distance of fault location, breaker operation analysis etc with operator at remote control centre for quick decision	Time consuming process of sharing the DR files and manual analysis report with operator
Immediate receipt of email as well as SMS alerts regarding the fault information to the concerned	Limited or delayed access of fault information
Automated analysis report gets generated based on predefined expert rules and template	Requirement of certain exposure to manually analyse the DR files
Availability of double end fault location based on cumulative DR files from both ends of the transmission line along with the single end fault locations.	Only single end fault location from both sides of transmission line is available

Other appreciable functionalities of RAS-AFAS system include the remote access of relays for reading relay logs & other parameters from control centre. Also, it avoids the possibility of loss of DR files from relay due to flushing of files because of limited storage in the relays. RAS-AFAS overview:



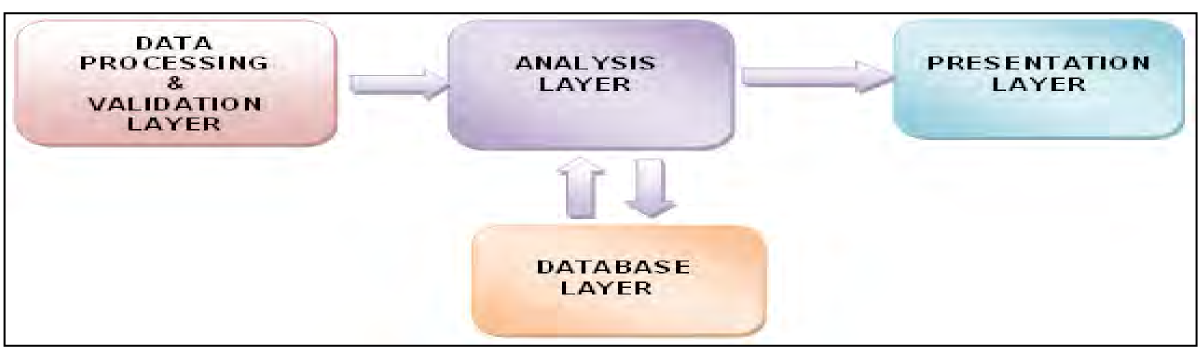
2. **IMPLEMENTATION OF RAS-AFAS**

Hardware used for RAS-AFAS implementation:

i. RAS-AFAS Server: Installed at main & backup control centres
ii. Substation Date Concentrator: Installed at each substation
iii. Media & protocol converters: Installed at each substation
iv. Ethernet switches & Serial Port Splitter: Installed at each substation for redundancy
v. RAS-AFAS PC: Installed at each substation for local view at each substation & control centre

Redundancy of hardware & ports has been ensured at substation as well as control centre level.

System Architecture:



For integration of a substation with RAS-AFAS system, following activities are involved:

a) Communication is to be established with various make & model of relays (IEC61850, IEC103, Courier, SPA & SEL) for auto collection of DR files.
b) The collected DR files from relays are to be converted to COMTRADE format (if it is in proprietary format eg .areva, SPA etc).
c) The COMTRADE format DR file is to be renamed with predefined naming convention and is to be forwarded to remote server at control centre.
d) Protection relay database population & development is to be done at database server of control centre.
e) Application server is to be configured with predefined expert rules to analyse the collected DR files based on developed database.
f) Email addresses are to be configured to send the fault analysis report and similarly the groups of mobile no. are to be defined to SMS the fault summary in standard template.
g) Configuration of application server for broader analysis (double end report, station level report) related to particular system event and to publish the report on web client.
h) Configuration of RAS server to be done for remote access of relays for reading relay logs & other parameters from control centre.

Implementation challenges:

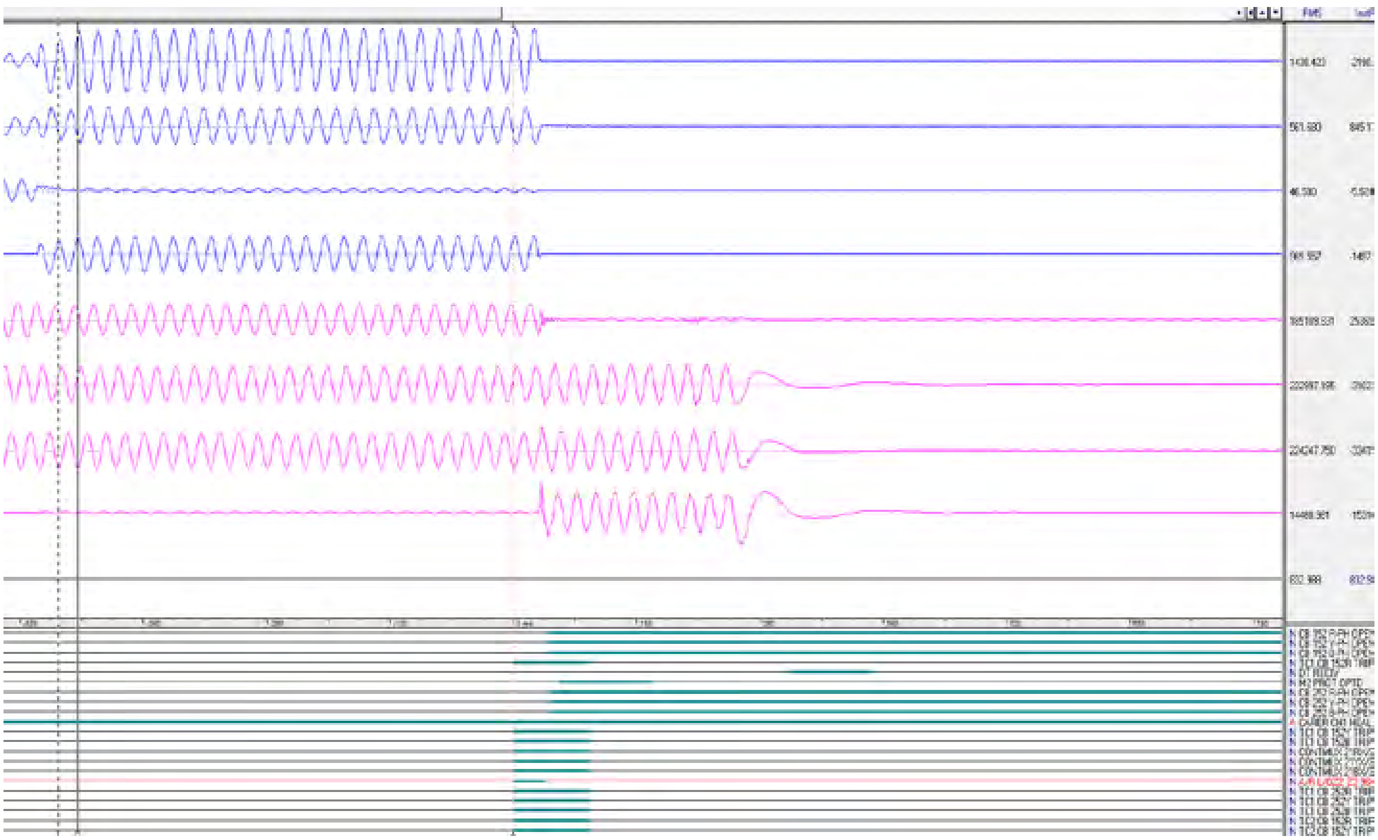
i. Unique & customised design of software & hardware
ii. First time implementation on large scale (~ 6500 no. relays of various make & model and protocol support) which results in multiple patches & fine tuning
iii. Non-uniformity in signal names and type of Disturbance recorders
iv. Choosing the right Algorithm depending upon the fault detected
v. Management of multiple versions of relay specific configuration tool and restriction of multiple access of a particular relay
vi. Partial configuration of relay communication port for data exchange on supported protocol

3. **CASE STUDY OF APPLICATION OF RAS-AFAS DURING TRIPPING**

RAS-AFAS system fulfils the requirement of operator at remote control centre and overcomes the possible issues with traditional fault analysis methodology. It also enhances the transparency, accuracy and reduces the requirement of trained manpower at multiple locations.

Following are the practical cases where application of RAS-AFAS at remote control centre during system fault may be appreciated:

1) **Zone-2 tripping case: Subhasgram-Sagardighi line dated 02.05.2018 11:05**
The fault was in zone-2 for Subhasgram end. Since no carrier is received from other end, zone-2 three phase trip was given after 500 msec (Z2 time). The remote operator got the DR file as well as report and executes successful manual charging attempt.



MiAFAS™ Automated Fault Analysis System

File Name : 180502,110524864,IST,P163,4011,ER02

REPORT FOR :

पावरग्रिड

EVENT ANALYZED

Report Type	Operator Report
Report ID	3231241
Region Name	ER02
Station Name	SUBHASHGRAM 400KV
Equipment	Transmission Line-400KV SUBHASHGRAM-SAGARDIGHI
Analysis Type	Single End
Relay Code	Main-1[ISTP1634011ER02]
Make and Model	AREVA MICOMP442
Trigger Date and Time	02/05/2018 11:05:24.864424
Fault Severity	Moderate

MiAFAS Analysis Summary

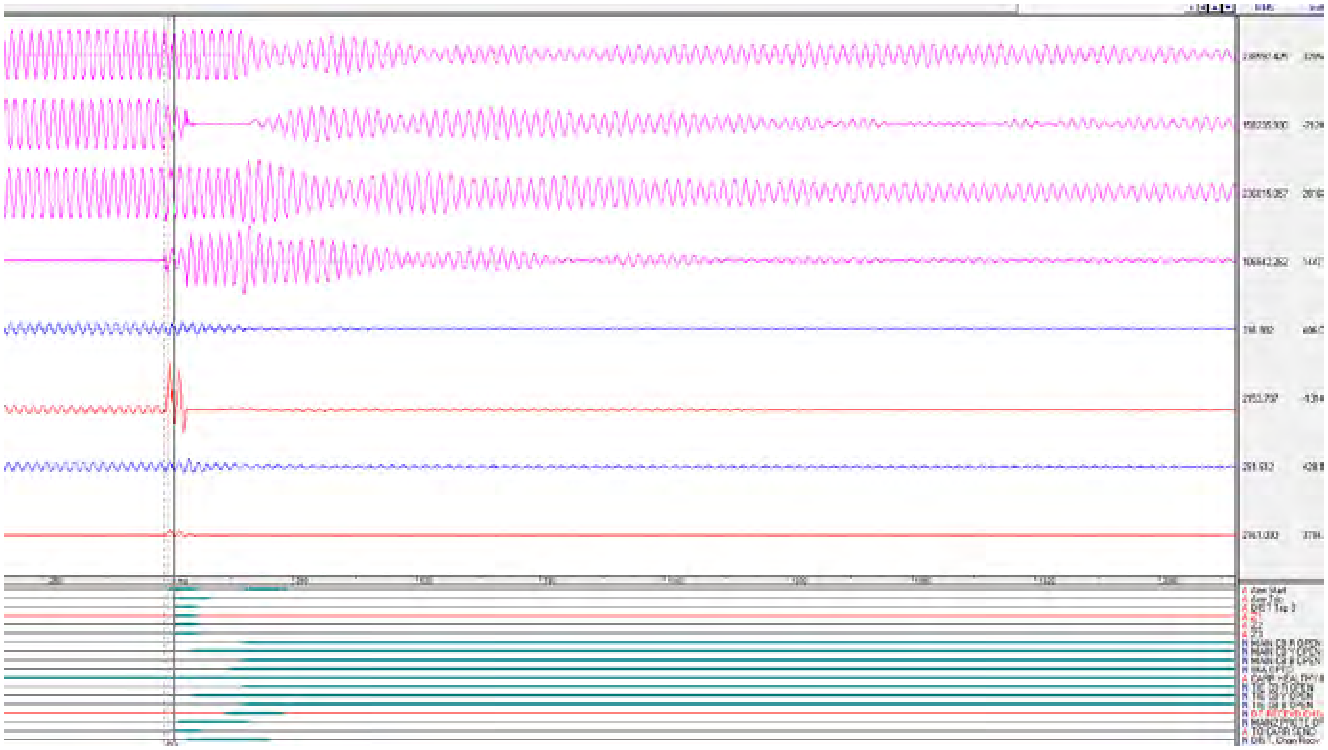
1. Fault Information
   a. R Phase to Ground Fault detected at 11:05:24.864424 Hrs (Dt: 02/05/2018) on 400kV 400KV SUBHASHGRAM-SAGARDIGHI
   b. The fault is calculated to be located at around 220.387 km from SUBHASHGRAM 400KV.
   c. During the incidence, maximum fault current of 1.73 kA and voltage dip of around 199 kV (0.86 pu) was recorded.
2. Line Trip / Auto Reclose Information
   a. DT was received at 11:05:25.156333 Hrs (799 ms after fault detection), on receipt of Direct Trip (DT) signal.
   b. No auto reclose action was detected.
   c. Opening of all three poles was recorded at 11:05:24.912167 Hrs (555 ms after fault detection).
   d. The line tripped at 11:05:25.106333 Hrs (749 ms after fault detection).
3. Relay Operation Information
   a. Zone 2 Trip was Obtained from Analog Zone Operation Analysis

Fault Details

Variable Name	Value
Fault Trigger Time	02/05/2018 11:05:24.864424
Fault Type	R Phase to Ground Fault
Fault Location (km)	220.387
Fault Current (kA)	1.725
Fault Voltage (kV)	199.510
Fault Impedance (Ohms)	12.779
Auto Reclosure	Not Attempted.
Fault Clearance Time (ms)	555.000
A/R Dead Time (ms)	NA
System Disturbance Time (ms)	749.166

2) Auto reclose not attempted case: Silchar-Azara line dated 02.05.2018 1:26

Line got tripped 3-phase at Silchar end on receipt of DT signal from other end. The remote operator got the DR file as well as report and executes successful manual charging attempt.



MiAFAS™ Automated Fault Analysis System

File Name : 180502,012527922,IST,P191,4031,NER1

REPORT FOR :

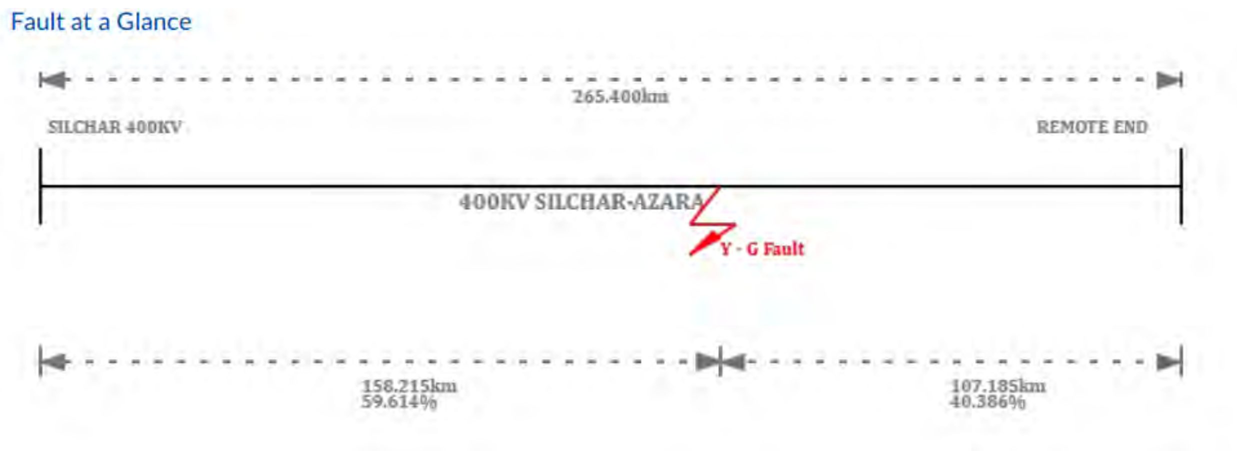
पावरग्रिड

EVENT ANALYZED

Report Type	Operator Report
Report ID	3229089
Region Name	NER1
Station Name	SILCHAR 400KV
Equipment	Transmission Line-400KV SILCHAR-AZARA
Analysis Type	Single End
Relay Code	Main-1[ISTP1914031NER1]
Make and Model	AREVA MICOMP444
Trigger Date and Time	02/05/2018 01:25:27.922000
Fault Severity	Moderate

MiAFAS Analysis Summary

1. Fault Information
   a. Y Phase to Ground Fault detected at 01:25:27.922000 Hrs (Dt: 02/05/2018) on 400kV 400KV SILCHAR-AZARA
   b. The fault is calculated to be located at around 158.215 km from SILCHAR 400KV.
   c. During the incidence, maximum fault current of 2.19 kA and voltage dip of around 155 kV (0.68 pu) was recorded.
2. Line Trip / Auto Reclose Information
   a. Line Tripped at 01:25:28.041667 Hrs (128 ms after fault detection), on receipt of Direct Trip (DT) signal.
   b. No auto reclose action was detected.



Additionally, following benefits from RAS-AFAS are also obtained:

a) Availability of collected DR files, events & statistical reports at control centre in a systematic manner & stored in hierarchical form.
b) Better accuracy of Fault location based on cumulative DR files from both ends of transmission line (double end analysis)
c) Web client access over VPN to substation and all control centre for accessing the data & reports in a secure manner
d) Cumulative fault current for decision on breaker health
e) Monitoring the pole open discrepancy of the breakers
f) Monitoring of CVT errors & CT saturation

4. SCOPE FOR FUTURE ENHANCEMENT OF RAS-AFAS

System operators have had the first-hand experience of the benefits of RAS-AFAS with deployment done at 175 no. POWERGRID substations. The following enhancement may be considered as scope for future:

1. Fault signature analysis
2. Auto update of AFAS database from relay (similar to DR files) subject to standardization of relay setting template by each OEM
3. Relay setting proposal based on pre-fault & post-fault condition of grid and regularity of fault occurrence.
4. Since relay DR file sampling rate is generally 1000 samples per sec, the analysis accuracy (say fault location) may be increased with high sampling rate DR file.
5. Integration of AFAS with PMU data.
6. Update of actual details of fault in AFAS database by substation maintenance team for record & further fine tuning.
7. Automatic reading of relay event logs & transfer to server at control centre
8. Integration of RAS-AFAS with ERP for broader access

5. CONCLUSION

The paper has shared the POWERGRID experience of application of Remote Accessibility System & Automated Fault Analysis System for fault analysis in Power System. Other than the benefits outlined above in the paper, RAS-AFAS expedites the decision making to reduce the outage time of power system equipment. Thus, the implementation cost seems to be recovered within one year with full utilization of the system. Further, RAS-AFAS seems the next technological change to fulfill the requirement of rapidly growing power systems.

BIBLIOGRAPHY

[1] Approved DRS of RAS-AFAS under NTAMC project
[2] Working experience during the development, deployment & operation of RAS-AFAS from remote control centre under NTAMC project

CIGRE-AORC Technical Meeting 2018 – International Conference on Global Energy Transition – Issues and Challenges, 24-25 May 2018, Gangtok, Sikkim, India

Load and RE Forecasting -Utilization and Impact on System Operation

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Western Regional Load Despatch Centre, POSOCO, Mumbai

***Abstract*— Two important variable parameters of the grid are Load and Renewable Energy (RE). Management of complex synchronous grid of India thus requires appropriate measures to preclude and counter the variability of these two parameters. Forecasting is the tool to preclude the effects of variability of these two parameters to a great extent and thus facilitating system operator to just deal with variability in forecasting by the means of flexibility available in the generating sources. The limited availability of flexibility in the grid further strengthens the need of accurate forecasting.**

Further RE Forecasting is extremely important for system operator for integration of available green power without compromising the security and reliability of the grid. The ambitious target of 175GW of Renewable generation capacity by 2022 thus keeps forth the challenge of integration of RE which will be almost three times to the current RE installed capacity of the country. The penetration of Renewable Energy in WR is presently around 23%. As of now the variability is being countered with thermal generation that meets 70-80% of demand in the Western Region (WR). This paper presents the characteristics of demand and RES in the Western Regional grid and the efforts being made towards forecasting demand and injection from RES at the grid level for balancing.

Keywords—Load; Forecasting; Variability; Statistic; Impact; Error

I. Introduction

Western Region is the largest region of country in terms of generation capacity. It is also the highest power exporting region in the country [Figure 1]. The country is witnessing higher growth rate in integration of RE compared to growth of overall power system. The variation in system parameters like load, generation, RE generation variation, export to other regions, Voltage, Frequency as well as elements operation is to be monitored simultaneously by System Operator. With all these factors, the system operation is becoming complex day by day.

Figure 1. Plot of Consumption and Inter Regional Flow

The demand in Western Region varies with hours of the day, weeks and seasons, festivals and special events etc. Demand during the day varies due to diurnal nature of human activities. It also depends upon the customer types (i.e. domestic, agricultural, commercial and industrial) and atmospheric temperature [1]. The time of peak demand in different regions in India varies due to the diversity in weather, timing of sunrise-sunset, composition of demand, diversity in agricultural seasons, religious festivals/holidays etc. [Figure 2].

The demand in Northern Region is high during July-September due to high temperature while in Western region demand is less during July-September due to heavy rains.

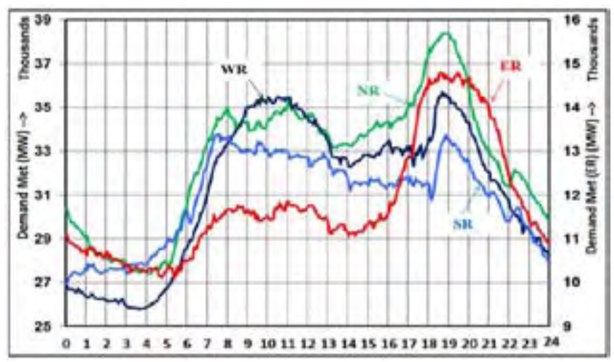

Figure 2. Demand Pattern of Northern, Western, Eastern and Southern region.[1]

The increasing penetration of variable RES has added to the existing uncertainties. Since these resources are generally embedded in the Distribution Companies (Discom) grid, its effect is reflected as Net load in the regional/national grid. This poses as a new challenge in balancing load and generation and calls for better tools for system operators for operational planning.

India has a vibrant day-ahead energy market operated by the two Power Exchanges. The day-ahead Market Clearing Prices provide a strong signal for the anticipated "trend" of Net load on the next day. Rate of energy in Exchange also depends on availability of generation.

Forecasting of the demand is being used for a long time for long term planning of energy purchases and generation outages. Forecasting is also an essential tool for short term planning for real time management of large electrical systems. The sanctity of forecasting depends on its accuracy which ensures the support it can render for maintaining the load generation balance with minimized constraints and violations in the grid.

II. Characteristics of Demand in Western Region

Demand is a rate at which the energy is being consumed by all defined loads in the area. Demand varies hourly during the day [Figure 3]. It has two cardinal points over a day.

i. Night Lean

ii. Morning Peak

iii. Day Lean

iv. Evening Peak

Size and magnitude of these points vary with season, type of load and temperature [1].

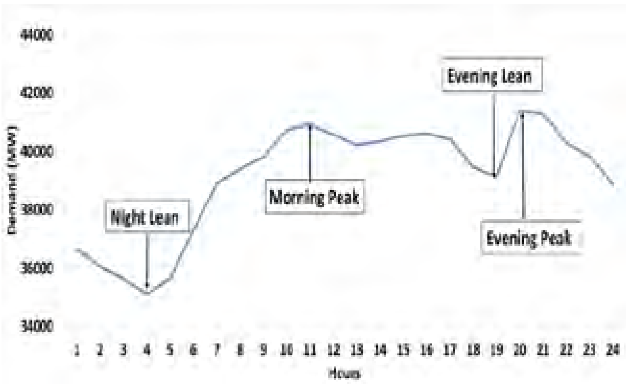

Figure 3. Western Regional Demand curve on typical day showing hourly variation

In WR, the hourly change in demand is in the range of -3000MW to 5000MW. It is changing with season and has high deviation in winters as shown in Figure 4. It means the schedule of generation to be changed frequently. The spinning reserves in real time should be available to handle imbalances in system. The hourly deviation in demand is increasing over the time. For optimum scheduling of the reserves the demand in next time of hour is to be known with high accuracy.

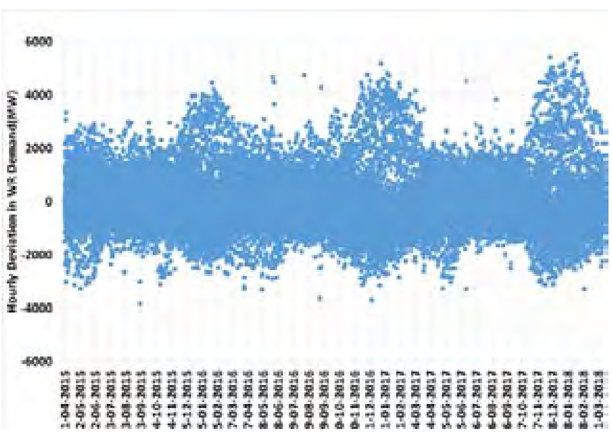

Figure 4. Plot of Hourly Deviation in WR demand since 2015

The difference in daily peak and lean demand is also a big challenge and it also varies with season. In WR max. difference in daily Peak to Lean reaches maximum value during winter season [Figure 5].

The highest value of the difference observed in Western region is 15103MW that means generation schedule is to be changed mostly in thermal generator as demand is being catered mostly by thermal generation. Difference has increased by 2.4 times over a decade it's increasing with growth in load [Figure 6] .

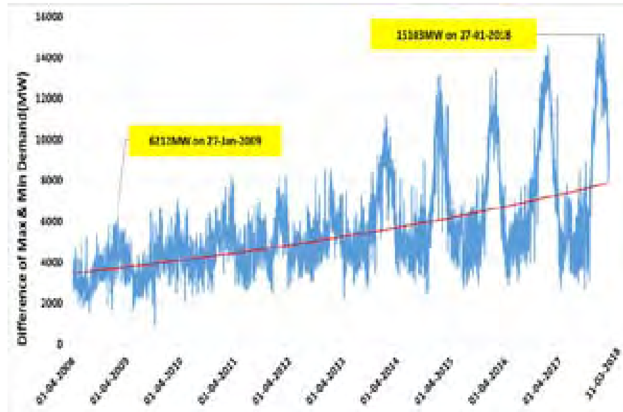

Figure 5. Plot of difference in daily maximum and minimum demand of WR

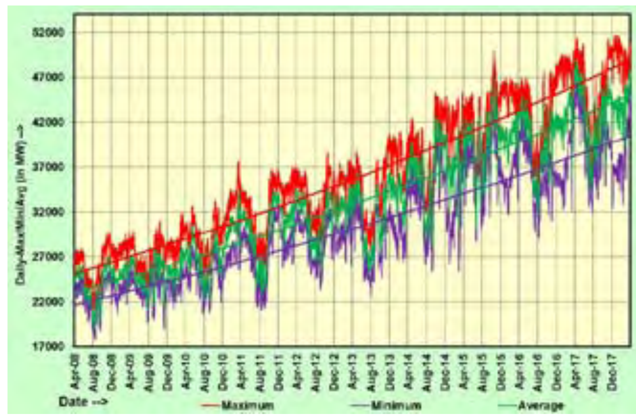

Figure 6. Plot of daily Maximum, Minimum and Average demand of WR

Seasonal variation has been shown in Figure 7, WR demand during Q1 (Apr-Jun) has peak during 15-16 hours and less difference in daily peak and lean. During Q2 (July-Sept), demand reduces due to heavy monsoon. But variation in demand during monsoon is high and has different pattern on each day. The peak demand occurs at 20:00Hrs.

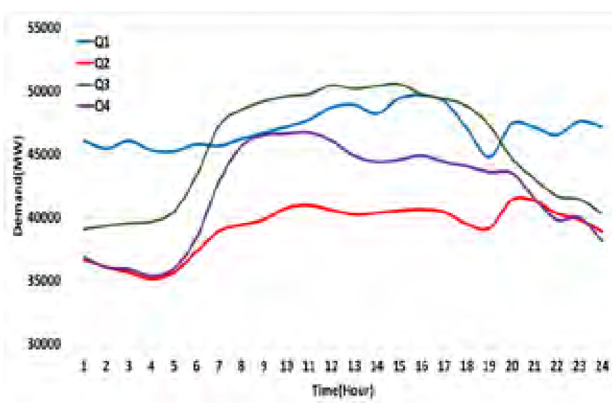

Figure 7. Seasonal Load Curve of WR on typical days during Q1 (Apr-Jun), Q2 (Jul-Sep), Q3 (Oct-Dec) and Q4 (Jan-Mar)

In Q3 (Oct-Dec) the demand increases due to onset of Rabi season when agricultural demand is predominant with many pump sets operating. This quarter, also being the festival season, commercial and residential demands are on the higher trajectory. Jan-Mar is high demand period similar to that of previous quarter due to continuation of agricultural activities. The industrial demand is at its peak as this is the last quarter of the financial year. The difference of peak and lean is high during this quarter and has the peak in morning at about 10:00Hrs.

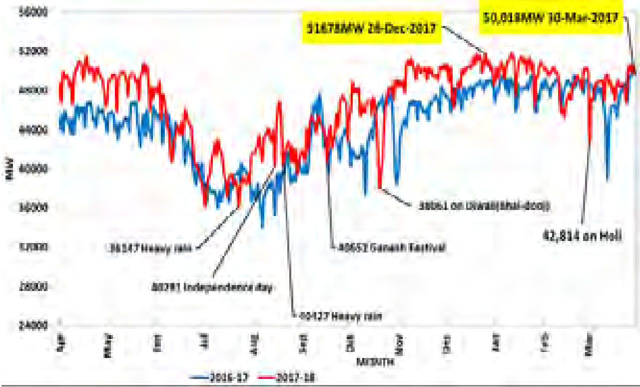

Figure 8. Demand variation due to season and festivals in WR for last two years

Variation in peak demand of WR has high fluctuation over the days and sudden drop in demand occurs due to different festivals and bad weather conditions [Figure 8]. WR demand has the peak during March to May month and drops to the minimum during monsoon months of June-Sept. System operator is simultaneously managing large variation in demand and countering the high variability of wind during the monsoon.

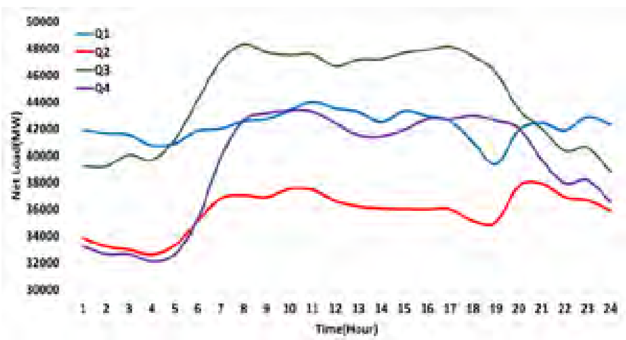

Figure 9. Seasonal variation in Net Load of WR on typical days during Q1 (Apr-Jun), Q2 (Jul-Sep), Q3 (Oct-Dec) and Q4 (Jan-Mar)

Variation in Net load plays an important role in grid as the thermal generation cannot be switched frequently and it takes time to ramp the output of it. Seasonal variation in WR net load on typical days are shown in Figure 9. There is high variation during Q3 (Oct-Dec) and Q4 (Jan-Mar). Variability in net load would increase with increase in RE generation.

The WR demand has peak during evening most of the time but it is observed to be peaking at 10:00-12:00Hrs and at 15:00-16:00Hrs in recent years as shown in Figure 10. It shows high variability in WR demand.

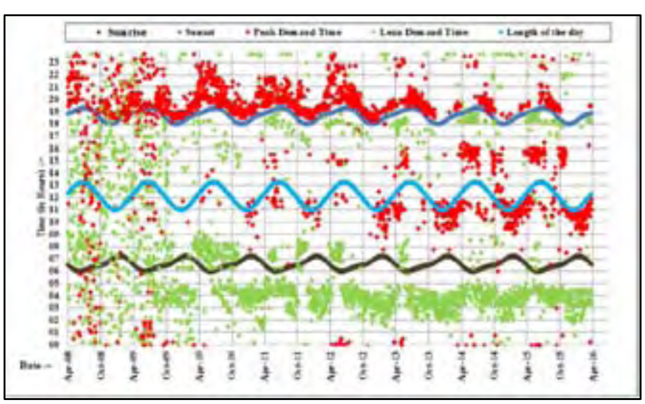

Figure 10. Time of daily sunset, sunrise with occurrences of peak and lean demand met of WR.

III. Characterisctics of VRE Generation in Western Region

Wind and Solar are the clean sources of energy. RE generation is alternate to generation from fossil fuels and building the green future free from greenhouse gases. Country is going to have more green power in future and the day is not far when India will become dependent on RE sources for its power requirements. Government has planned to increase the RE capacity to 175GW by 2022 in India. As on 31.03.2018, WR has achieved the installed capacity target of 56% and 44% is going to be added in the system by 2022[Table 1].

Table 1.Wind Power Installed Capacity and target by 2022 for WR Constituents

Constituents	As on 31.03.2018 (A)	Target by Year 2022 (B)	Balance (C=B-A)	% balance target capacity
Gujarat	5574	8800	3226	36
Maharashtra	4775	7600	2825	37
Madhya Pradesh	2428	6200	3772	61
Total	12777	22600	9872	44

Table 2.Solar Power Installed Capacity and target by 2022 for WR constituents

Constituents	As on 31.03.2018 (A)	Target by Year 2022 (B)	Balance (C=B-A)	% balance target capacity
Gujarat	1493	8020	6527	81
Maharashtra	1082	11926	10844	91
Madhya Pradesh	1247	5675	4401	78
Chhattisgarh	76	1783	1707	96
DD	10	199	189	95
DNH	4.1	449	445	99
Goa		358	358	100
Total	3939	28410	24471	86

Increase in RE generation and variability is the concern about how to accommodate the large scale of variation into the system. Solar generation has lesser uncertainty and has peak during the Peak Load time. Solar generation follows the demand pattern for most of the time. Wind generation is having large variations compared to solar. Short-term fluctuations in wind power are stochastic in nature, but distinctive patterns exist for longer-term fluctuations [Figure11].One way to overcome the issue of uncertainty is to have the spinning reserves in thermal power generation or hydel power to increase or decrease the generation in case of deviation in RE generation.

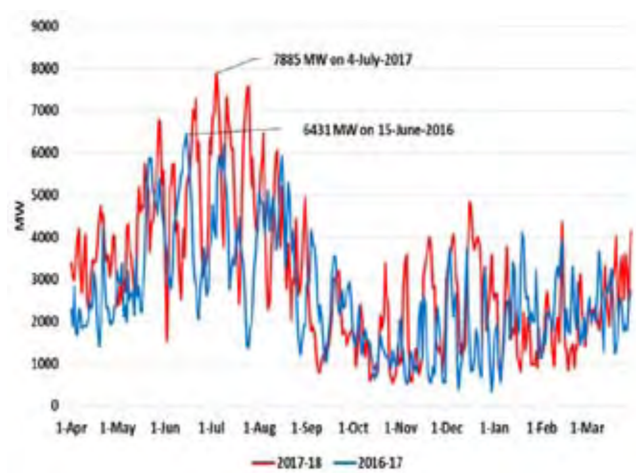

Figure 11. Plot of daily Max wind power generation in WR for FY 2017-18 and 2016-17

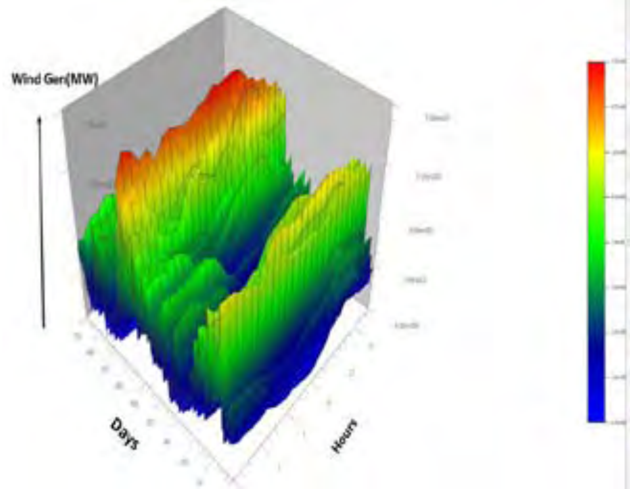

Figure 12. 3-D plot of hourly wind generation in WR from Apr'2016 to Mar'2018

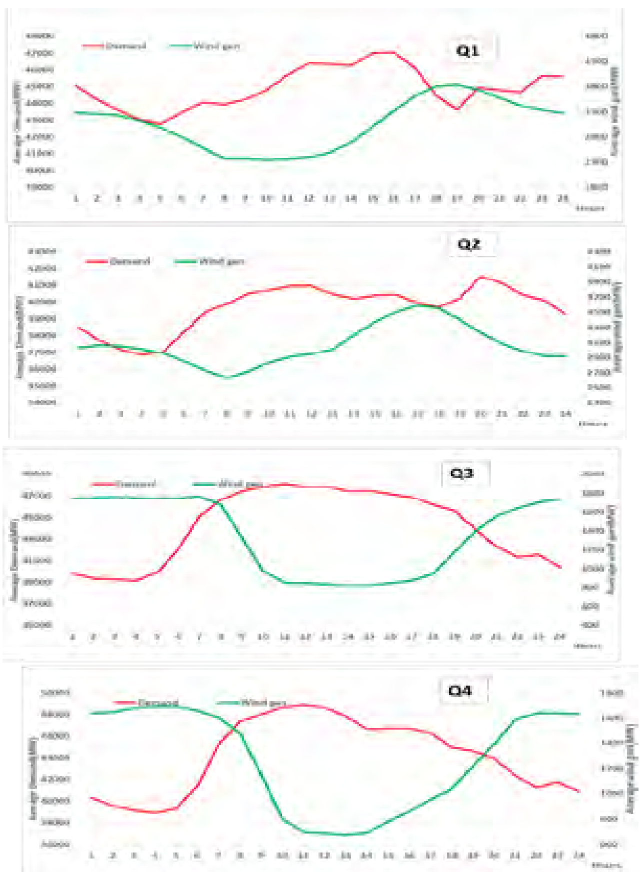

Figure 13. Plot of average Wind generation Vs Demand for Q1(Apr-Jun),Q2(Jul-Sep),Q3(Oct-Dec) and Q4(Jan-Mar) 2017-18

Wind power generation in Western Region is high during monsoon period [Figure 12] and it has high variability for full year. The intraday change in wind generation is about 3000-4000MW in monsoon season and reduces up to 2000-2500MW. Wind power generation increased in 2017-18 with the rate of 23% w.r.t. 2016-17.

As per Figure 13, During Q1 (April-June), WR Wind generation is supporting the demand by ramping down during night up to 05:00Hrs. It is increasing when the demand is high during the day time. During Q2 (July-September), wind generation is supporting the WR demand by ramping up in the morning and ramping down in the evening. During Q3 (October-December) and Q4 (January-March) wind generation opposes the demand of the region. Wind is high when demand is low during night hours and ramps down when demand increases. Similarly wind generation is low when demand is high and it ramps up when demand starts ramping down.

It shows the high variability of wind generation over the season and it needs to be planned for countering the uncertainty.

IV. Reserves for Balancing the Grid

CERC mandated as given below to keep the spinning reserves available for control the frequency and maintain the grid secure.

Quote-

"Each region should maintain secondary reserves corresponding to the largest unit size in the region and tertiary reserves should be maintained in a decentralized fashion by each state control area for at least 50% of the largest generating unit available in the state control area. This would mean secondary reserves of 1000 MW in Southern region; 800 MW in Western regions; 800 MW in Northern region; 660 MW in Eastern region and 363MW in North-Eastern region (total approx. 3600 MW on an All India basis). Primary reserves of 4000 MW should be maintained on an All India basis considering 4000 MW generation outage as a credible contingency. The same should be provided by generating units in line with the IEGC provisions".

Unquote

Spinning reserves in WR [Figure 14] reduces to minimum and it remains almost zero during the peak demand time. System operator are having Reserves Regulations Ancillary Services (RRAS) as a tool to control the Reserves in central generating stations (CGS) and regulation UP or DOWN can be implemented when demand increases/drops to control the frequency. It is also being used for congestion management to increase or decrease the generation to maintain the tie line flow under ATC.

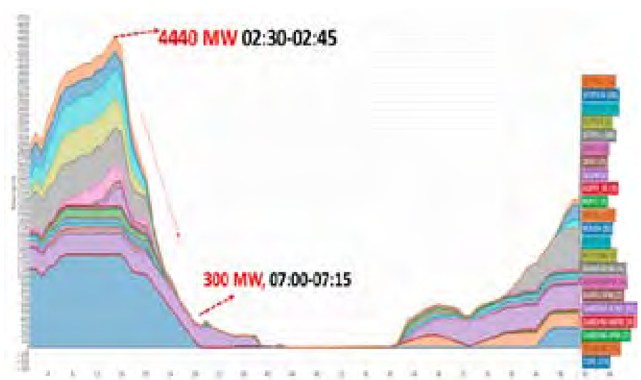

Figure 14. Plot of spinning reserves available in WR on typical day

When generation is higher than load and frequency increases above 50Hz, constituents reduce their internal generation to maintain the balance with load and if required RRAS DOWN is being implemented in thermal CGS up to the technical minimum of 55% of installed capacity to maintain the load generation balance in real time.

When generation is lower than the load and frequency reduces below 50Hz, constituents increase their internal generation to maintain the balance with load. Also adjudging the requirement of support, RRAS UP is being implemented in CGS thermal generators where spinning reserves are available. The situation is critical when no spinning reserves are available as shown in Figure 6 and constituents are not having sufficient generation. In such cases, the constituents are to purchase power which takes at least 6 time blocks through contingency procurement. It is also non-economical to procure the power without knowing the requirement in advance and it leads to more financial burden as DSM charges has to be paid extra.

V. Need for Forecasting Load and Variable Renewable Energy(VRE)

After the targeted RE capacity addition, the contribution of RE will significant improve and in such scenario, RE generation will determine the prices in Energy Exchanges. Out of the two variable RE sources of Wind and Solar, solar is more predictable and less variable. However wind RE shows high level of uncertainty and variations. Therefore, Wind Forecasting plays the key role in balancing the supply and demand in the grid. Accurate wind power forecasting reduces the need for additional reserves to integrate wind power and better scheduling of thermal, Gas and Hydro generators.

It is very challenging to implement schedules at appropriate time when load pattern in the region is changing with different parameters like weather, season, special events and festivals and to keep appropriate generation available from thermal power to counter the uncertainty in the grid due to RE generation with high penetration. Therefore, in real time, it is needed to have the forecast to maintain the load generation balance for secure grid operation and for being prepared with required optimum reserves.

Forecasting is a sort of planning. It's a process which involves estimation of the future of load and the ways load can be met. Generating units are scheduled to meet the requirement of the load. Optimum utilization and scheduling of generators is carried out for economic dispatch. Due to the fact that large thermal units often have long start-up times, the unit commitment decisions (i.e. whether a unit will be on or off during the specified period) have traditionally been performed in the day ahead timeframe. Because load is variable and uncertain, day ahead forecasts are required to ensure that sufficient generating capacity is available to meet the expected load. This forecast can be a critical factor in ensuring near-optimal system operations. For example, if the load forecast is significantly lower than the realized load, too little baseload capacity may be operational at the needed time, and fast starting, more expensive units will be required to fulfill the load. The economic cost of this deviation from the optimal dispatch stack can be directly attributed to the inaccurate load forecast. The main cause of additional costs in the day-ahead timeframe is the commitment or de-commitment of large thermal units. This fact, along with the ability of the economic dispatch process to handle smaller forecast errors, means that large magnitude, but relatively rare, forecasting errors are the most important for system operation [4].

VI. Regulations for Demand Estimation and RE Forecasting

Regulation has been issued by CERC on Forecasting of Load and RE generation. For Load Forecasting ,as per clause 5.3(b), (c) and (d) of IEGC,

Quote-

"The demand estimation is to be done on daily/weekly/monthly /yearly basis for current year for load - generation balance planning. The SLDC shall carry out system studies for operational planning purposes using this demand estimate.

Each SLDC shall develop methodologies/mechanisms for daily/ weekly/monthly/yearly demand estimation (MW, MVAr and MWh) for operational purposes. Based on this demand estimate and the estimated availability from different sources, SLDC shall plan demand management measures like load shedding, power cuts, etc. and shall ensure that the same is implemented by the SEB/distribution licensees. SLDCs. All SEBs/distribution licensees shall abide by the demand management measures of the SLDCs and shall also maintain historical database for demand estimation.

Each SLDC shall carry out its own demand estimation from the historical data and weather forecast data from time to time. All distribution licensees and other concerned persons shall provide relevant data and other information as required by SLDC for demand estimate."

Unquote

For RE forecasting, as per clause 6.5.23(ii) of IEGC:

Quote

"Forecasting shall be done by wind and solar generators which are regional entities as well as the concerned RLDC. The concerned RLDC may engage forecasting agency(ies) and prepare a schedule for such generating stations. The forecast by the concerned RLDC shall be with the objective of ensuring secure grid operation. The forecast by the wind and solar generator shall be generator centric. The wind and solar generators which are regional entities will have the option of accepting the concerned RLDC's forecast for preparing its schedule or provide the concerned RLDC with a schedule based on its own forecast. Any commercial impact on account of deviation from schedule based on the forecast chosen by the wind and solar generator shall be borne by it."

Unquote

For implementation of RRAS to schedule the spinning reserves, As per CERC approved Detailed Procedure for Ancillary Services Operation:

Quote-

"The Nodal Agency shall forecast the daily region-wise and All India demand on day-ahead basis generally by aggregating demand forecast by the State Load Despatch Center (SLDC) and BBMB, DVC, SSP, etc. If required, the aggregated demand forecast may be moderated by the Nodal Agency. Each SLDC shall prepare the block wise daily forecast of demand (Format AS4) on day-ahead basis by 1500 hrs of current day for next day taking into account various factors such as historical data, weather forecast data, outage plan of units / transmission elements, etc."

Unquote

Generating units also taken out due to less demand on reserve shutdown. It can be taken into the service only after the three days of shutdown. For countering the variability in the system it's required to keep the unit in service if appropriate reserves are not available. The unit can only be in service if the schedule of generation in that unit is given not less than 55% of the capacity. To meet the requirement in real time, it is required to know if schedule is to be given to the unit or it should be taken out of the service. For optimization of the generation, it requires to have better forecast of demand and RE with high accuracy. Hence, for the security of the grid, to maintain the discipline and control over frequency, it's desired to forecast the demand and RE generation.

VII. METHODOLOGY ADOPTED FOR LOAD FORECASTING

There are many modules developed for forecasting and being used by different users. Analysis of forecast error is to be done for the accuracy and suitable method may be adopted for correction in forecast of demand and RE. In forecasting, some events are certain like festivals, holidays etc. and can easily be tracked with historical data. Load forecasting during monsoon is also possible to be done accurately with help of weather prediction like temperature, humidity, wind speed, cloud cover etc.. For better accuracy, aggregation of forecast of individual small areas shall be done with weather prediction.

Errors in any type of forecasting method is certain but error prediction by historical data also gives good idea of possible deviation from forecasted demand so that operator can have better and optimized band of generation to be kept available for the load.

In WR, Forecast Service Provider (FSP) are forecasting the load and Wind generation for the individual states. Forecast for load is also being done internally at Western Regional Load Dispatch Centre (WRLDC). For forecasting of 15 minutes time block-wise load at regional level, following algorithm for Load Forecast has been developed after analyzing the historical demand pattern of the region.

$$\boldsymbol{D_{F_{n+1}i} = (1+\mathcal{E}) * D_{A_{n-1}i}}$$

$$\boldsymbol{\mathcal{E} = \frac{\sum_{x=1}^{3} \mathcal{E}_x}{3}}$$

$$\boldsymbol{\mathcal{E}_1 = \frac{D_{A_{n-6}i} - D_{A_{n-1}i}}{D_{A_{n-1}i}}}$$

$$\boldsymbol{\mathcal{E}_2 = \frac{D_{A_{n-6}i} - D_{A_{n-8}i}}{D_{A_{n-8}i}}}$$

$$\boldsymbol{\mathcal{E}_3 = \frac{D_{A_{n-13}i} - D_{A_{n-8}i}}{D_{A_{n-8}i}}}$$

Where,

n = day of preparation of forecast
i = Time Block starting from 1 to n
$\boldsymbol{D_{Fi}}$= Forecasted Demand in $\boldsymbol{i^{th}}$ time block
$\boldsymbol{D_{Ai}}$= Actual Demand in $\boldsymbol{i^{th}}$ time block
$\boldsymbol{\mathcal{E}}$= variation in demand w.r.t. day of week

It is been used to forecast the load on day ahead basis and to plan the generation accordingly. Although it's not have any weather parameter incorporated but gives good idea how the load will vary on the forecasted day. In case of special event like festivals, holidays etc., a variability is being measured with historical data for the same event and incorporated in the forecast for better accuracy.

VIII. CASE STUDIES - LOAD FORECAST ERROR

Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) are calculated for evaluation of accuracy in forecast as per the formulae given below-

Root Mean Square Error, RMSE (MW)= $\sqrt{\frac{\sum_{i=1}^{y}(D_{Fi}-D_{Ai})^2}{y}}$

RMSE (%)= $RMSE(MW) * \frac{y*100}{\sum_{i=1}^{y} D_{Ai}}$

Mean Absolute Error, MAE (MW)= $\frac{\sum_{i=1}^{y} Abs(D_{Fi}-D_{Ai})}{y}$

MAE (%)= $\frac{100*\sum_{i=1}^{y} Abs(\frac{D_{Fi}-D_{Ai}}{D_{Ai}})}{y}$

Where,

y = No of Time Block in a day (96)
i = Time Block starting from 1 to y
D_{Fi}= Forecasted Demand in i^{th} time block
D_{Ai}= Actual Demand in i^{th} time block

The variation in block wise percentage error in day ahead load forecast from July'17 to April'18 is shown in Figure 15. Block-wise error is less than +/-5% for more than 90% of time as shown in figure 16.

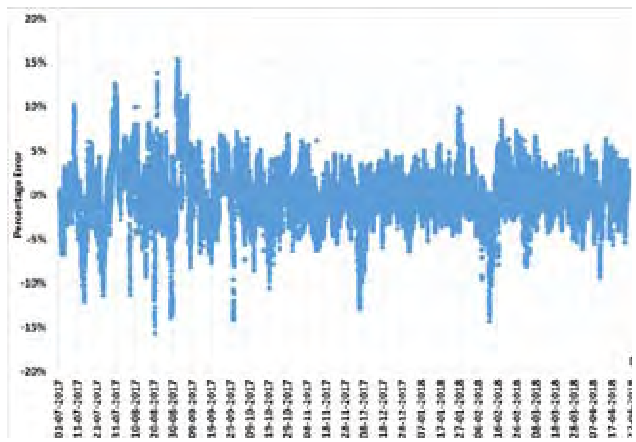

Figure 15. Plot of time block wise percentage error in Load Forecast

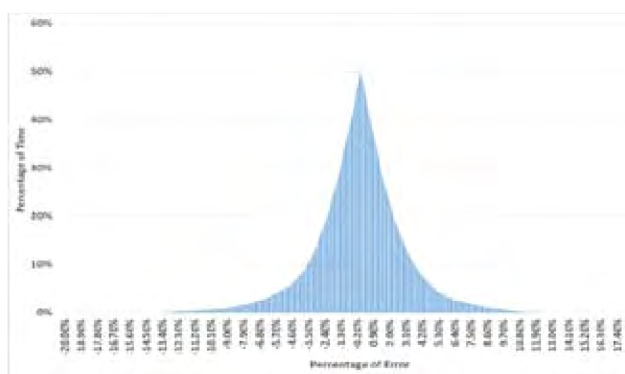

Figure 16. Density curve of Block wise percentage error in Load Forecast

RMSE and MAPE in day ahead load forecast is being calculated on daily basis and for most of the time it's less than 5% except during monsoon due to uncertainty in rains as shown in Figure 17. During the rains when forecast has high MAPE and RMSE up to 8-10%, the real time deviations from schedules increases resulting in over-drawl or under-drawl by constituents. The schedule of generators during this time has to be increases or decrease accordingly that results in frequent ramping up/ramping down of generating units.

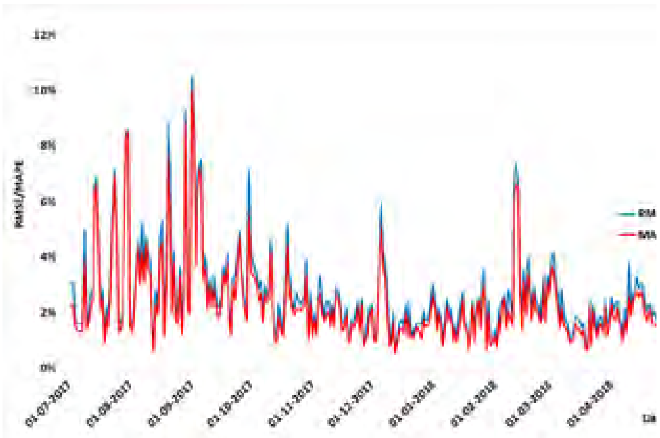

Figure 17. Plot of day-wise RMSE and MAPE in Load Forecast

Case 1. When MAPE=10% on 01-09-2017-

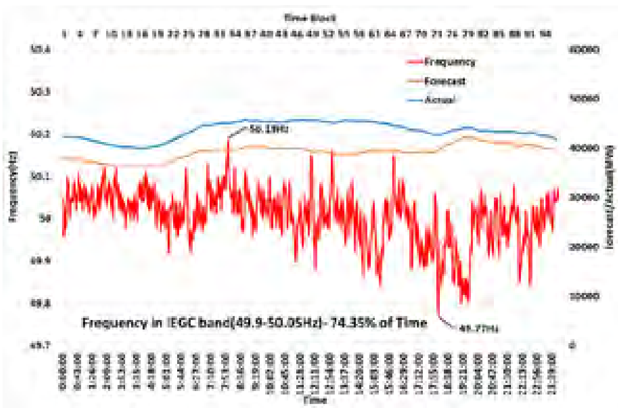

Figure 18. Plot of Frequency, Load Forecast and Actual on 01-09-2017

On 01.09.2017, MAPE of 10% was observed in Load Forecasting. Large variation in frequency observed due to high error in forecasted load and thus in scheduled generation. Due to over-drawl and under-drawl, frequency rose up to 50.19Hz and fell down to 49.78Hz. On the day frequency observed to be in IEGC band for 74.35% of time as shown in Figure 18.

Case 2. When MAPE=2% on 17-07-2017(Average error day)-

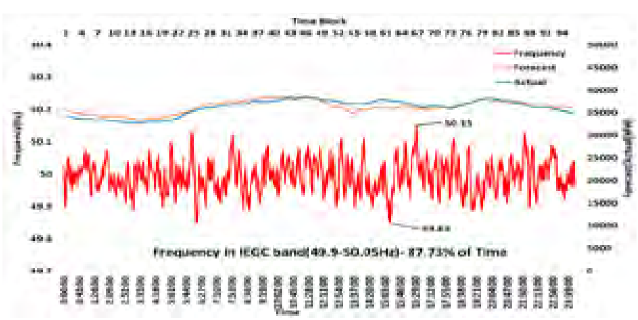

Figure 19. Plot of Frequency, Load Forecast and Actual on 17-07-2017

When forecast has good accuracy, it’s easy to plan the generation in real time and revisions in schedule are less. On 17-07-2017 frequency was observed to be in IEGC band for 87.73% as shown in Figure 19.

IX. Load Forecast by Forecast Service Provider

Forecast Service Provider (FSP) are also providing the forecast of Western Region as a pilot project under the non-commercial MoU signed with WRLDC. FSP also use the weather data for load forecasting and various models are being considered for adoption of suitable one for considering in real time. Analysis of error and various issues in forecast provided by FSP is being done and based on the feedback, the model is being modified from time to time. Variation of Absolute Percentage Error in FSP and Internal Forecast is plotted as shown in Figure 20. Earlier the error was high and sometimes it’s higher than error in internal forecast but over the time it’s improved.

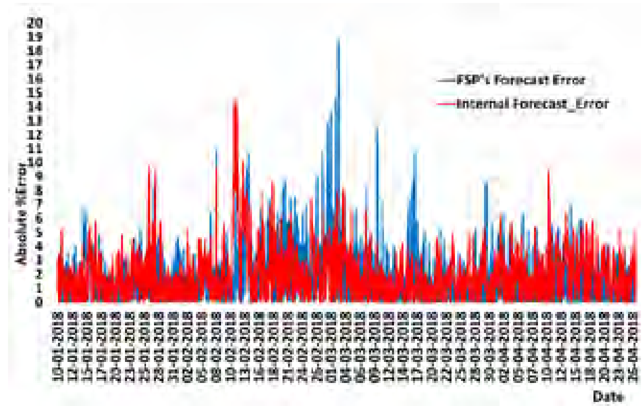

Figure 20. Plot of Absolute Percentage Error in FSP load forecast vs Internal Forecast

In forecasting, correct historic data and information regarding the event is also important due to its significant weightage in deriving the forecast. Spurious non-validated historical data can result totally wrong forecast. On the day of Holi festival on 02-03-2018, demand forecasted wrongly based on historical data of one day advance of holi. Demand drop on Holi is incorporated one day before and on Holi day forecast was higher than actual as shown in Figure 21.

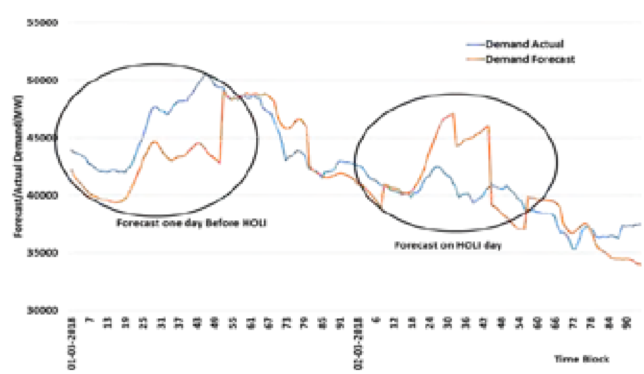

Figure 21. Plot of FSP’s load forecast vs Actual for previous day and day of Holi

X. Wind Forecast and Experiences

Forecasting of wind power plays an important role for system operation to balance load and generation. It has high variation due to which the accuracy of forecast is lesser than the load forecast. For large integration of Wind power, it’s essential to improve accuracy of wind power forecasting for better system operation and economic dispatch.

Different FSPs are providing forecast of wind power for different constituents of WR on commercial or pilot project basis. The forecasts are being done on week ahead, day ahead and real time basis. Aggregation of day ahead wind power forecasts of all constituents is being done at WRLDC for system operation. The accuracy of day ahead to intraday forecast has been evaluated on basis of RMSE and MAPE as shown in Figure 22 and 23. These errors are normalized with respect to installed capacity/ capacity telemetered for the state for which the forecast is issued.

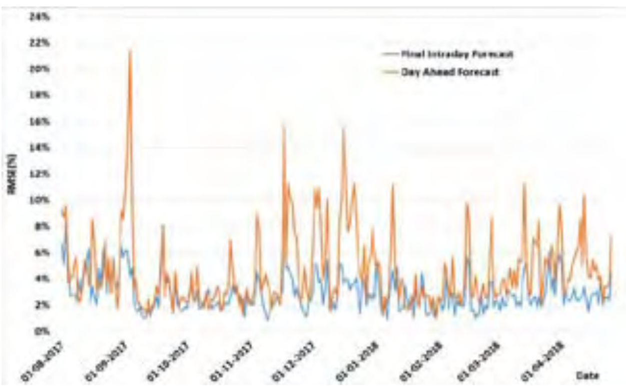

Figure 22. Plot of RMSE of Intraday Wind Forecast and Day Ahead Forecast

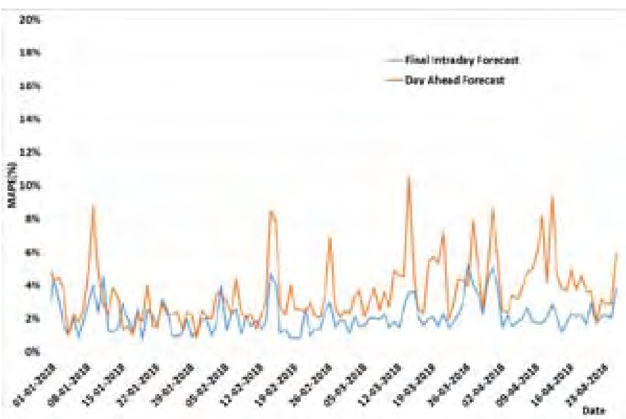

Figure 23. Plot of MAPE of Intraday wind forecast and day ahead forecast

RMSE and MAPE in final intraday forecast issued in real time is up to max 5% as shown in Figure 22 and 23. The error in day ahead forecast is high that's around 10% which means 800-1000MW in Western region and required the reserves of same capacity. Therefore, high accuracy of day ahead forecast is also required to plan for availability of spinning reserves and to start the cold machines if required for countering the wind variability in real time.

The block-wise percentage error in intraday wind forecast is concentrated between -5% to +5% for more than 90% of time and error in day ahead forecast is on higher side as shown in figure 24. The forecast is continuously being improved and has been utilized in real time for taking the decision to maintain the load generation balance and controlling the frequency deviations.

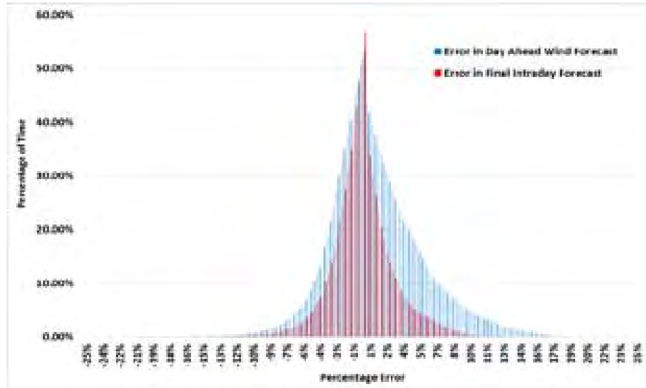

Figure 24. Plot of time block-wise percentage error in intraday wind forecast and day ahead forecast

XI. Conclusion

The paper has illustrated the experiences of WRLDC in load and RE forecasting. The algorithm used for forecasting of load at WRLDC is also elaborated in the paper that is being used for proper planning and optimization of generation. The variability of RE generation helps to meet the demand pattern of WR in some of the seasons hence the variability can be used in support of system operation also. Various cases of demand and RE (Wind) variability has been evaluated to describe the need of forecasting for real time operation. The reserve availability of WR for handing the RE and load variability is detailed and in such prevailing scenario of low availability of wind, the importance of accurate forecasting is further strengthens. Calculation of errors and analysis done is shown which gives fair idea about accuracy band of the forecast.

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References

[1]. POSOCO, Electricity Demand Pattern Analysis, report, 2016.

[2]. "Examining the Variability of Wind Power Output in the Regulation Time Frame" Bri-Mathias Hodge, Sandra Shedd, and Anthony Florita National Renewable Energy Laboratory Conference Paper NREL/CP-5500-55967

[3]. Bri-Mathias Hodge, Anthony Florita, Kirsten Orwig, Debra Lew, and Michael Milligan, "A Comparison of Wind Power and Load Forecasting Error Distributions" World Renewable Energy Forum Denver, Colorado May 13-17, 2012NERC,

[4]. Armstrong, J.S. Selecting Forecasting Methods. In Principles of Forecasting: A Handbook for Researchers and Practitioners (Ed. J. Scott Armstrong). Kluwer, 2001.

[5]. Chang, W.-Y. (2014) A Literature Review of Wind Forecasting Methods. Journal of Power and Energy Engineering, 2, 161-168. http://dx.doi.org/10.4236/jpee.2014.24023

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Synchrophasor: Key Insight into the Power System Dynamic Monitoring

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SUMMARY

Synchrophasor technology has brought a paradigm change in the real-time operation in the grid control center across the world. This has become a medium to have an insight into the power system dynamic phenomena during various events that could earlier be observed only through offline simulation. This paper explores how the Synchrophasor technology integration into the control room environment has helped in improving the grid reliability. Specifically, this paper considers how System Operators can use Phasor Measurement Unit (PMU) data and Synchrophasor-based application outputs to monitor the power system, detect any events and other dynamic phenomenon, assessing the small signal, frequency and angular stability during the Real-time Operations Horizon.

KEYWORDS

Synchrophasor, Power System Monitoring, Power System Dynamic, Low Frequency Oscillation, Indian Grid, Synchronization, Islanding, Power System Stabiliser, Asset Management

1. Introduction and Background

Synchrophasor data and their various applications are valuable tools for ensuring security and reliability of any power system. It provides an unprecedented insight into the wide area dynamics of the power system at a very high resolution to the grid operators. The information from Synchrophasor data can be processed and utilized with the help of various online and offline applications for predicting, detecting and taking corrective action for a power system event or condition to ensure the adequate reliability and security.

The Indian Power System has adopted this technology in an enormous way in the form of Unified Real-Time Dynamic Measurement System (URTDSM) [1]. This paper describes the various key benefits that have been derived and extracted by the Indian Grid operator from the Synchrophasor technology since its inception.

2. Overview of Synchrophasor Technology

Phasor Measurement Units (PMUs) measure the voltage and current parameters of individual phases and with these measurements, it derives frequency, the rate of change of frequency and phase angle. The key benefit lies in the fact all PMUs utilize the same GPS reference and time stamp their measurements, thus providing a true snapshot of the entire grid in real time for any particular instant. This time synchronized data with sub-second resolution has provided the dynamic view of the entire power system and has added a new dimension in the operator visualization from the existing conventional Supervisory Control and Data Acquisition (SCADA) display. Further, the common reference with time stamp helps in measuring the relative angles among voltage/currents in the entire grid during real time, which could only be estimated through the state estimator; thus shifting the course from state estimation to state measurement [2]. Synchrophasor data reporting rates are typically 25 records per second and can be increased depending upon the usage, requirements and applications.

3. Application of Synchrophasor in Indian Power System

Indian Power System has been utilizing the Synchrophasor data for real-time operation since its inception in the year 2010 [3-4]. Presently more than 600 PMUs are installed in the Indian Power system and the count will increase to more than 1700 to cover the entire 400 and 765 kV networks [1]. The various utilization of synchrophasor data by the Indian System Operator at present can be categorized as under:

1. Power System Monitoring
2. Power System Islanding Detection and Synchronization
3. Power System Oscillation Detection and PSS Tuning Assessment
4. Power System Fault Monitoring and Analysis
5. Short Circuit Test Assessment
6. Power System Asset Management
7. System Protection Scheme (SPS) Improvement
8. Power System Event Analysis

The above usage of Synchrophasor has been described in the next few sections with various case studies. The case studies will show how they have benefitted the operator in increasing their situational awareness, decision-making capability and remedial action planning.

4. Power System Monitoring

Monitoring of any power system involves awareness about the voltage, active and reactive power and frequency and their limits. The most direct way of utilizing Synchrophasor data for power system monitoring is to display phasor information for operators to increase situational awareness. Examples of such monitoring include simple monitoring of voltage/frequency over the geographical display or through display dials or charts as shown in figure 1. Further, geographical display of wide area angular separation provides a global overview of power system stability for the entire grid as shown in figure 2. Further, based on PMU measurements, various alarms have been developed to alert the operator in case of a large change in frequency and rate of change of frequency (ROCOF) indicating sudden loss of generation or load. Apart from these, voltage alarms have also been integrated in order to alert the operator under high voltage and low voltage condition to respond appropriately.

Figure 1: Geospatial display, Dial display and trends of voltage and frequency for System Operator.

Figure 2: Wide area angular Separation plot

5. Power System Islanding Detection and Synchronization

The Synchrophasor is quite helpful in detection of islanding in the system and alerting the operator. Further, it also helps system operator in synchronizing the two islands. For any islanding detection, there is need of monitoring angular separation and frequencies in the different parts of the system. The section of the system, which gets islanded from the rest of the system, will have different frequency and due to which its angular separation with respect to any node in the rest of the synchronized system will be varying as observed in conventional synchroscope.

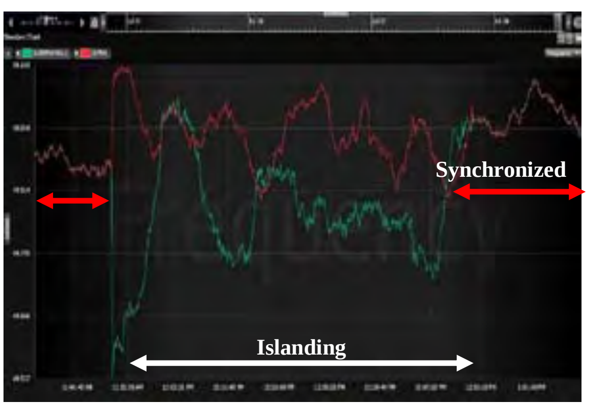

Figure 3: Frequency of the two systems when in synchronization and when separated from each other. (Red: NEW Grid, Green SR Grid)

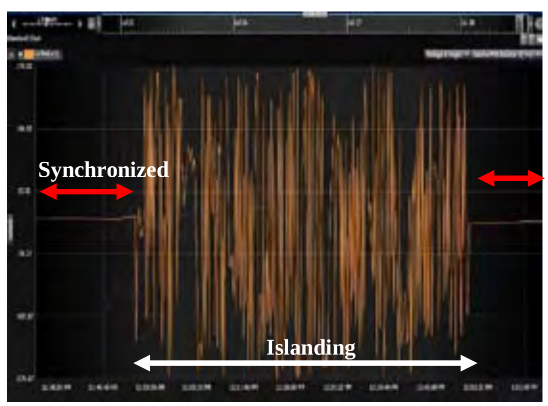

Figure 4: Angular separation between two systems during synchronized condition and during separation. (Angle of Sholapur Bus of NEW Grid with respect to Raichur bus in SR grid)

One Example of synchronization and islanding monitoring can be observed from figure 3 and 4 where frequency and angular separation has been plotted for NEW (North-East-West-North

Eastern Grid) with respect to Southern Grid using PMUs in both the grids [5-8]. In the synchronized condition, frequencies of both grids are same and angular separation is the standing phase angle difference between the corresponding buses. However, under the islanded condition, the frequency of both grids are different and resulting in large deviation in angular separation depending on the frequency difference indicating system separation. Several such use cases like islanding of north-eastern grid, part of the north-eastern grid, islanding of UMPP etc. have been monitored using Synchrophasor in the Indian power system and has alerted the system operators [3,9].

One Further usage of Synchrophasor is the controlled synchronization of the two large systems by using it for Coarse correction. Synchrophasor data under such condition help operators in bringing frequencies of the two systems closer to each other by manual action and when it is within the range of auto-synchronization/synchro check relay, the system operator can provide instruction to the field operator for closing the breaker of the tie line through which synchronization is being done. The system operator has extensively used this application of Synchrophasor during the synchronization of NEW Grid and SR grid in the Indian power system [5-8].

6. Power System Oscillation Detection and PSS Tuning Assessment

Low Frequency Electromechanical Oscillations (LFOs) are inherent to the power system and are of less concern if their damping is positive. These oscillations are not observable to system operator until their damping become low or negative. The frequency range of such oscillations mainly varies from 0.1 Hz to 4 Hz and can have an adverse effect to one generating unit to the entire electrical grid. Hence, it is essential to monitor them and take preventive action like Power System Stabiliser (PSS) tuning in order to improve their damping.

Indian grid operator has been extensively using Synchrophasor to monitor LFOs and has taken several leap steps in order to improve the damping [10,11]. Two case studies of LFOs are described below in order to emphasize the importance of their monitoring and assessing the PSS tuning which was done thereafter to improve the damping.

6.1 Local Mode of Oscillation at Power Plant

Local mode of oscillation in a power plant can result in the hunting of machines in the power plant with respect to the rest of the system. Such oscillation arises due to either lack of power system stabilizer (PSS) or its ill tuning. One such case of the local mode of oscillation occurred in one of the power plants where the PSS was kept out of service. During a fault on its evacuation line and its tripping, the power plant started oscillating at 0.86 Hz, which persisted for a duration of 5 minutes [12].

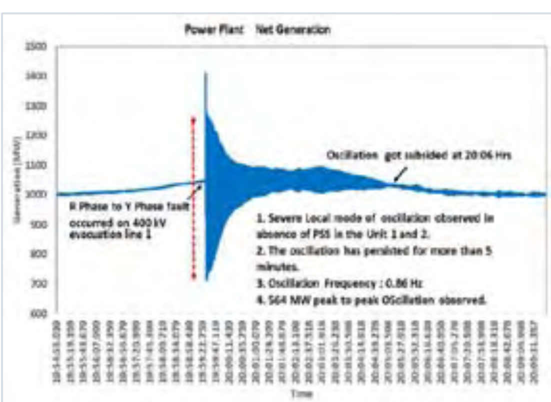

Figure 5: LFO and its damping observed in Power Plant Output when PSS is out due to the absence of proper tuning.

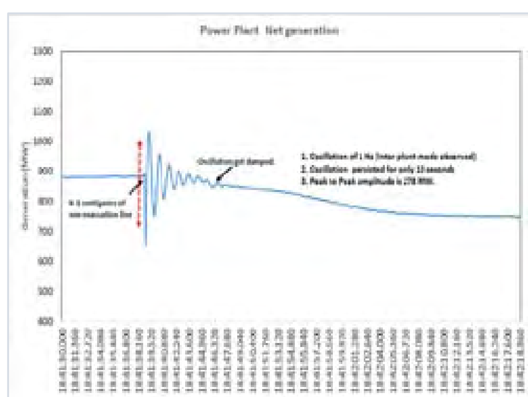

Figure 6: LFO and its damping observed in Power Plant Output at the Power Plant with Properly tuned PSS.

After an investigation by the system operator, it was found that PSS of the generating units in the power plant was kept out of service as they were not properly tuned during commissioning. Immediately after providing suggestion and feedback from System operator, the PSS was tuned and taken in service by the plant. After this, again a similar kind of event has occurred at the plant, however, this time oscillation was found to be well damped as can be seen in figure 6 due to the tuning of PSS.

6.2 Group of Power Plant with Low Damping

In the previous case, local mode of oscillation has been discussed at one power plant. However, when several large power plants are located in a close electrical vicinity with ill-tuned PSS, then they together can cause inter-plant oscillation where a group of power plants starts oscillating with the rest of the grid [13]. Once such case of LFO was observed where three power plants located in the close vicinity severely oscillated during a fault followed by tripping of evacuation line. It was found that the LFO was due to the ill-tuned PSS in the plants while one more power plant located near to these plants with robust PSS tuning has not oscillated. The power plants where inadequate damping were observed during this event is shown in figure 6. The oscillation frequency observed during this was 0.78 Hz and it can be observed in figure 6 that the magnitude of oscillation was severe.

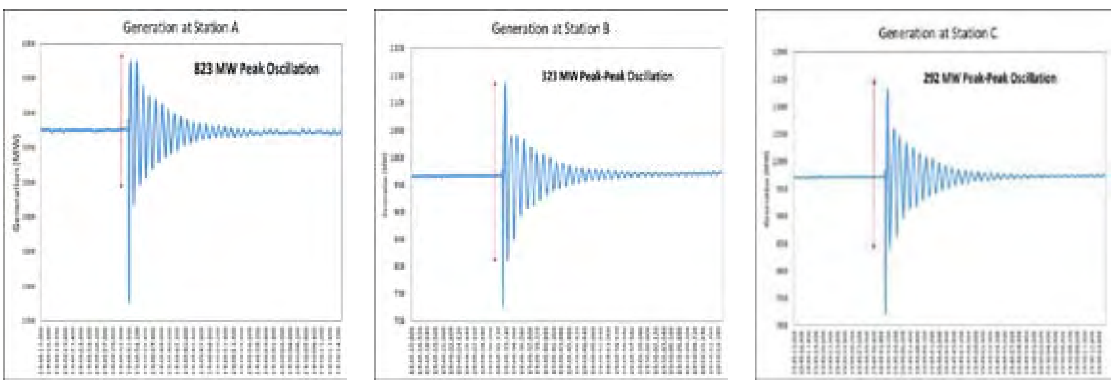

Figure 6: LFO of 0.78 Hz and its low damping observed in Group of plants (Plant A 6 X660 MW, B =2 X500 MW, C=2 X 500 MW) where PSS was not adequately tuning.

After monitoring of the LFO and its analysis, System Operator immediately advised the power plants to tune their PSS considering the present network. The PSS of generating units in all the three generating plants were then tuned to improve the damping in the system.

7. Power System Fault Monitoring and Analysis

One of the key aspects of Synchrophasor data is helping system operator in detection and analysis of power system fault during real-time and offline using various signatures. Each fault in power system has its own signature and if the same is generalized then it can help the operator in deciding reliability, dependability and efficiency of the operation of protection system to clear the fault. Various issues related to protection system have been corrected after its real-time analysis from PMU data. Among them, the important one is auto-reclosure on the transmission line. With the availability of feeder wise three phase time synchronized voltage as well as the current phasors, the system operator can confidently conclude whether the auto-reclosure operation was satisfactory or otherwise [14,15]. The current phasor from the transmission line CT provides the key insight on the state of auto-reclosure i.e. successful/unsuccessful and no auto-reclosure as can be seen from figure 7 and 8. The voltage phasors are taken from the bus CVT in the Pilot project PMUs as can be seen in figure 7 and 8. Therefore, largely, they provide a good indication of the auto-reclosure action. In the URTDSM project, the voltage input to PMU has been taken from the line CVT which like the line CT will provide the actual information and will be more fruitful. In a similar way, any delay in envisaged protection action can also be easily monitored using synchrophasor. This insight on the protection and fault analysis has helped the operator in providing immediate feedback to utilities to correct any issue in their protection setting, protection logic or protection device to ensure that its operation is reliable, accurate and dependent.

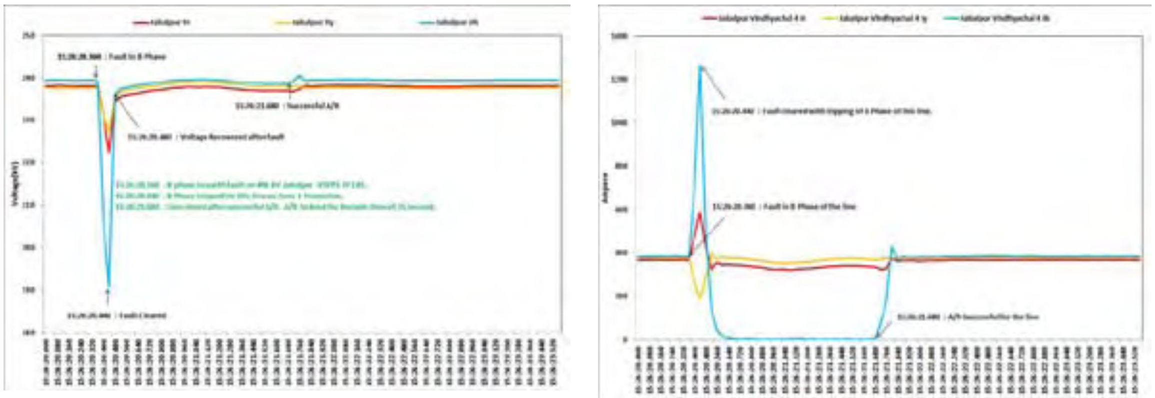

Figure 7: Voltage of 400 kV Jabalpur bus and Current of 400 kV Vindhyachal-Jabalpur circuit 4 at Jabalpur end from Synchrophasor data during single phase to the ground fault indicating successful Auto-reclosure attempt.

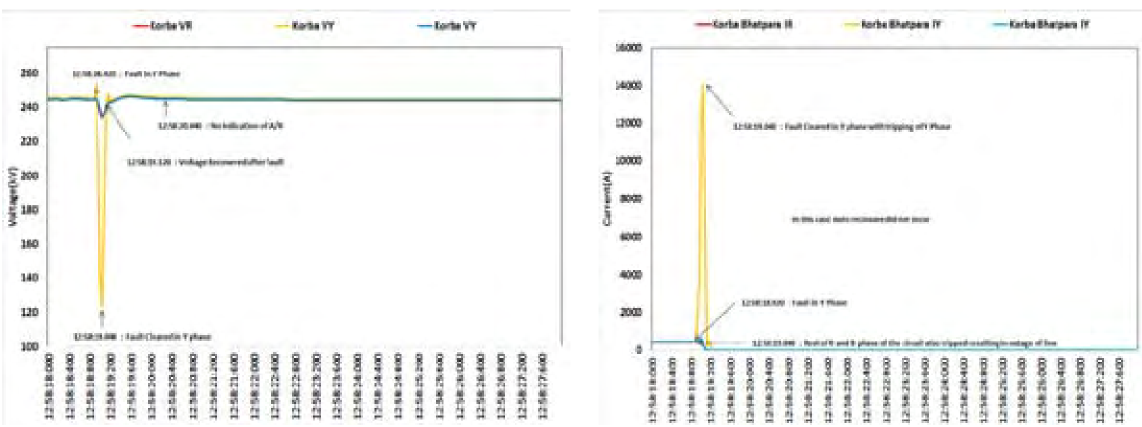

Figure 8: Voltage of 400 kV Korba bus and Current of 400 kV Korba-Bhatpara at Korba end from Synchrophasor data during single phase to the ground fault indicating no Auto-reclosure attempt.

8. Short Circuit Test Assessment

In India, National High Power Testing laboratory (NHPTL) has been established at Bina in Madhya Pradesh. This is first of its kind grid connected high voltage short circuit test facility in the continent. NHPTL has been conducting short-circuit testing of large power transformers of 132 kV, 220 kV and 400 kV class. NHPTL is connected to 765/400/220 kV Bina substation from where it draws required short-circuit currents for testing. In order to ensure the proper monitoring of each short-circuit test and to ensure system reliability, PMU has been installed there to monitor the performance. These short-circuit tests are basically Phase to phase fault of 250 ms duration which is higher compared to the fault clearance time of 100 ms defined for 400 kV and above transmission system in India. This emphasizes the need for monitoring of test and evaluation of the performance.

In general, the impact of fault on the grid is evaluated through the location of the fault, duration of the fault and dip and unbalance in voltage during the fault. In similar terms to evaluate the impact of short circuit testing on the grid, parameters like duration of short circuit, asymmetrical and symmetrical currents drawn from the grid, % voltage dip and % unbalance in voltage are monitored. Based on the PMU data, the voltage dip at Bina and Short circuit MVA drawn from the grid for several numbers tests has been shown in figure 9. While a comparative analysis of fault current of a line-to-line fault of 100 ms and short circuit test of 250 ms is shown in figure 10.

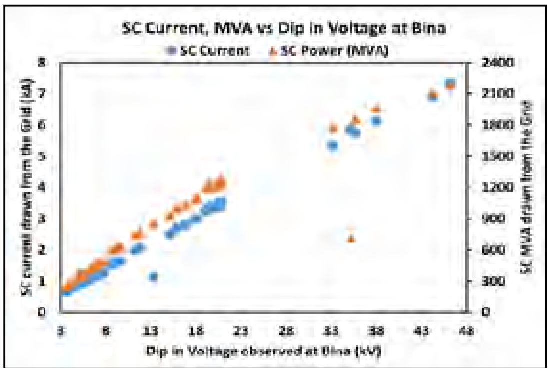

Figure 9: Voltage Dip in Bina versus current and MVA drew from the grid during testing

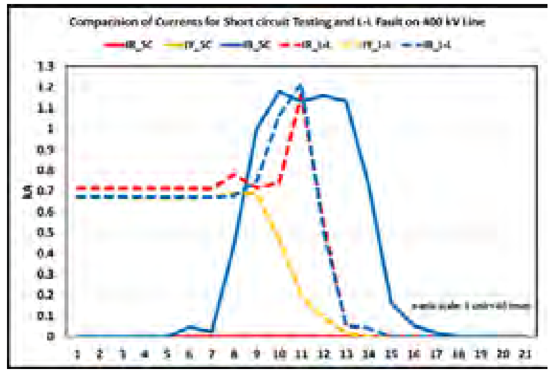

Figure 10: Comparison of currents drawn from the grid during short circuit testing of the transformer on Y-B phases and R-B phase fault on 400 kV line observed from PMU

9. Power System Asset Management

The voltage and current data from PMU also provide the signature of the healthiness of the measurement instrument i.e. Current and voltage transformer. Any problem in these devices starts appearing in terms of measurement issue prior to their failure. If such changes can be determined and timely action can be taken by resolving the issue or replacing the instrument, it will help in averting major event in the grid due to equipment failure [16].

One such example of determining the ill health of instrument transformer for Y phase CVT of 400 kV Bus 1 in an EHV substation is shown here in figure 11 where 400 kV Bus 1 voltage measured by the PMU at the substation is provided. In this case, system operator was able to identify the bad CVT before it failed and the utility was able to take the bus out of service and replace the faulty instrument transformer to avert any major event.

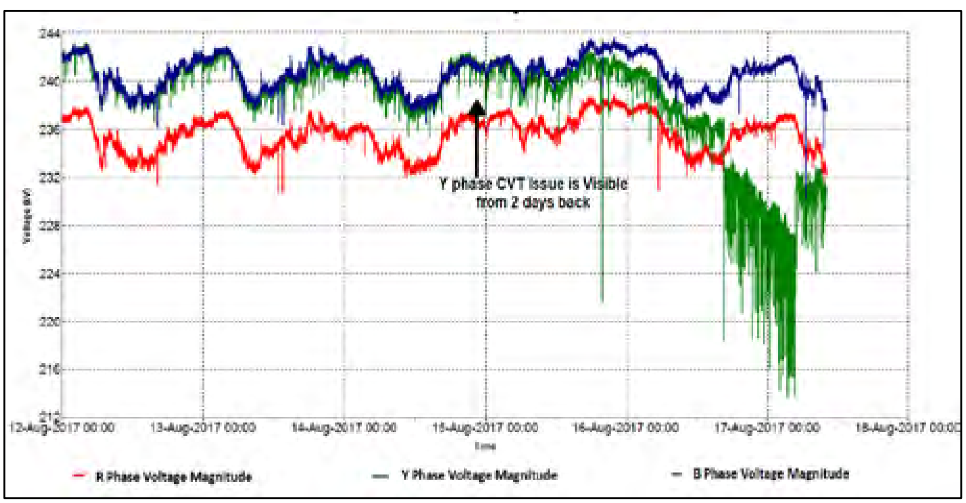

Figure 11: Bhadrawati Bus 1 voltage measurement from PMU indicating problem with Y phase CVT

10. System Protection Scheme (SPS) Improvement

SPS is designed to detect the emergent/contingent conditions in the system and take pre-planned, corrective actions to ensure system security [17]. After detection of such deviation from normal system conditions, the SPS actions take place in sub-seconds. Monitoring of SPS actions and its performance evaluation using conventional SCADA having a long scan time of 2-10 seconds is a major concern. Synchrophasor measurements can be considered as a perfect instrument for monitoring SPS actions and evaluating its performance as they monitor Power System states in a fraction of a second. Even though the number of PMUs is limited, the synchrophasor measurements from them have helped in monitoring the performance of the deployed SPS in the Indian grid. In addition, for several cases, modifications in the SPSs have been done to improve its performance based on the insight provided by the evaluation based on synchrophasor data. More than 400 numbers of SPS operations in the Western regional grid of India have been analyzed using Synchrophasor data until 2017 [18].

Similar to protection system performance, the performance of SPS can be evaluated in terms of its characteristics like Dependability, Security, Selectivity, effectiveness and Robustness. One case study of Indian power system is illustrated below which evaluates the dependability, effectiveness and unwanted operation rate (UOR) of the SPS using Synchrophasor measurements.

The case study illustrates the application of Synchrophasor in assessing the performance of a wide impact SPS [17]. Initially, the two grids were connected through single 765 kV transmission line. Grid 1 was of size 100 GW and Grid 2 was of 35 GW. Later on the network between Grid 1 and Grid 2 augmented with one more 765 kV transmission line as shown in figure 12.

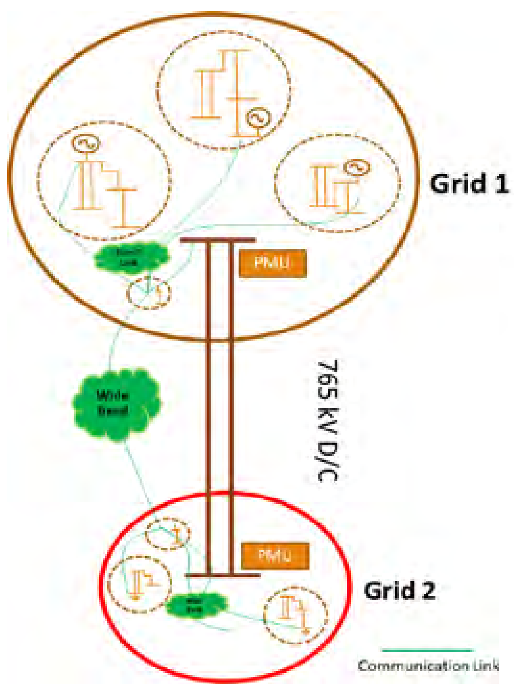

Figure 12: Wide Impact SPS scheme on the inter-regional tie lines between Grid 1 and Grid 2

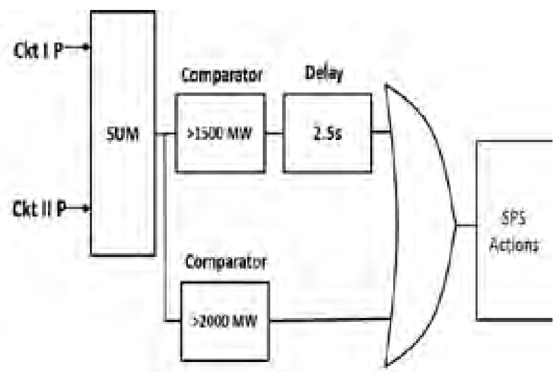

Figure 13: Wide impact SPS logic 1

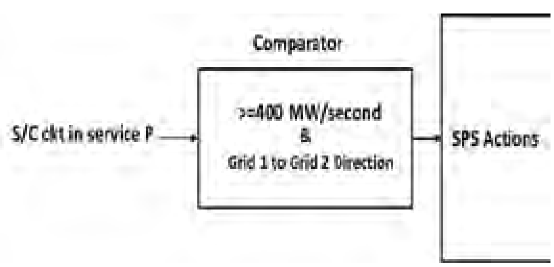

Figure 14: Wide impact SPS logic 2.

Several SPS logics were designed to handle contingencies in either Grid 1 or Grid 2 for secure and reliable operation under various operating condition. Among the several numbers of SPS logics, two logics have been illustrated here for measuring their performance using Synchrophasor data. SPS logic 1 is illustrated in figure 13 which would trigger if flow on D/C is greater than or equal to 1500 MW for more than 2.5 sec or if flow on D/C is greater than 2000 MW. The SPS logic 1 actions comprise of generation rejection in several generating stations located in Grid 1 and load rejection in Grid 2 to ensure the reliability.

Figure 15 shows active power measurements of D/C from PMU when SPS logic 1 has triggered. Upon exceeding 1500 MW for 2.5 sec, the SPS has operated and which led to generation rejection in Grid 1 and load rejection Grid 2 due to which the power flow on the circuits has reduced below the safe limit as decided by the system operator. The delay of 2.5s helped in preventing frequent operation of SPS during any transient phenomenon. This SPS has operated with 100% dependability based on the analysis of PMU data. There has been no unwanted operation or insecure operation of this SPS that has led to its high effectiveness index.

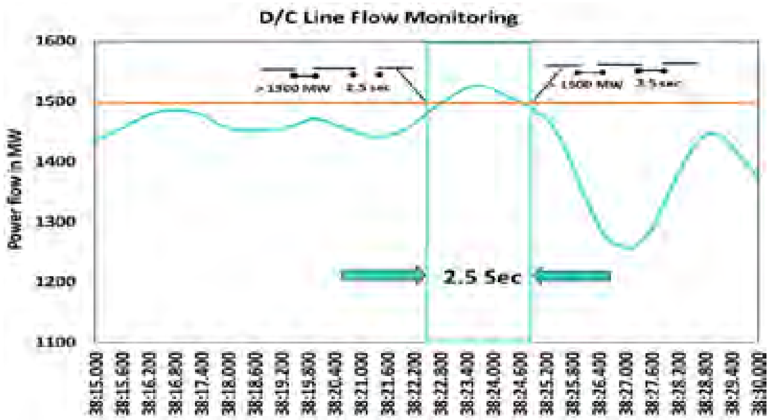

Figure 15: Plot of power flow on the tie line showing the dependability of the SPS Logic 1.

The SPS Logic 2 is for the condition when a single tie line is in service between Grid 1 and Grid 2. This condition appears during planned/forced outage on one circuit. SPS logic 2 will operate when there is huge power flow from Grid 1 to Grid 2 during contingencies happening in either Grid 1 or Grid 2. The implemented scheme is shown in figure 14 and it would operate only when the rate of change of power (dp/dt) on the circuit exceeds 400 MW/sec in Grid 1 to Grid 2 direction. The desirable SPS operation is shown in figure 16. SPS got triggered correctly and was effective in damping the oscillations that seem to be growing in amplitude.

It was observed that out of 24 operations, this SPS logic has operated successfully for 21 times. While on two occasion's directionality condition was not satisfied and on one occasion the ramp rate condition was not satisfied as shown in figure 17. Due to triggering of SPS irrespective of the direction of power flow and error in ramp rate calculation at occasions, it was disarmed.

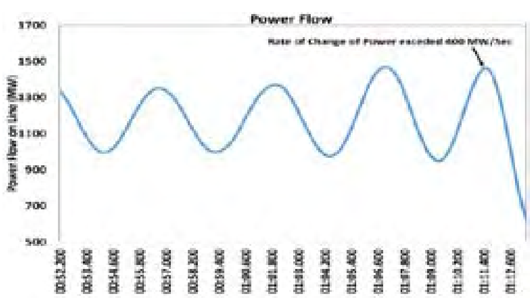

Figure 16: Plot of power flow on the tie line indicating the correct operation of SPS Logic 2.

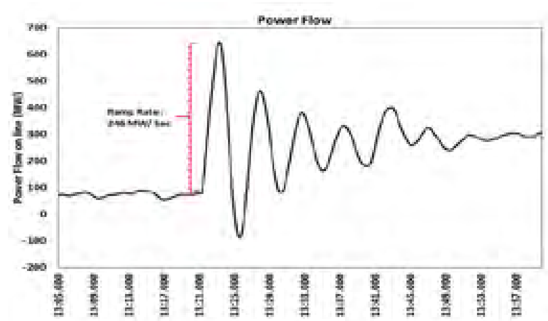

Figure 17: Plot of power flow on the tie line indicating the undesirable operation of SPS Logic 2.

11. Power System Event Analysis

Since its inception, the Synchrophasor data has helped system operators in the Indian power system in analyzing the various power system events in a rapid way with greater insight. In addition to this, it has also helped in providing feedback to utilities in correcting the time synchronization of the recording facilities like DR, event logger etc. Several use cases of the utilization can be observed in the literature available [3,4,19,20]. These use case has helped the operator in operating and managing the grid with better situational awareness.

Conclusion

Overall, the paper has illustrated the various key insights that the Synchrophasor has provided to the Indian Grid operator in the monitoring of power system dynamic phenomenon. The case studies illustrated in the paper explore the utilization of the technology as of now in control center and provide a course how it can be made more useful to the grid operator. It can be concluded that Synchrophasor has provided a new channel for interaction between the offline and online simulations for improving the grid reliability.

BIBLIOGRAPHY

[1]. PGCIL, "Unified Real-Time Dynamic State Measurement (URTDSM) -A Report", New Deli, Feb 2012, [Online]: http://www.cea.nic.in/reports/committee/scm/allindia/agenda_note/1st.pdf

[2]. A. G. Phadke, "PMU Memories: Looking Back Over 40 Years [in my view]," IEEE Power and Energy Magazine, vol. 13, no. 5, pp. 96-94, September/October 2015,

[3]. POSOCO, "Synchrophasors Initiative in India", New Delhi, Tech.Rep. December 2013.

[4]. POSOCO, "Synchrophasors Initiative in India", New Delhi, Tech.Rep. June 2012.

[5]. S.R. Narasimhan., Nallarasan, Mohit Joshi, Pradeep Reddy,"One Nation-One Grid-One Frequency, Grid Tech 2015, 5th International Exhibition and Conference, New Delhi, April-8-10,2015.

[6]. Vivek Pandey, Chandan Kumar, Srinivas Chitturi, "Utilization of Synchrophasors during Synchronization and Operation of Large Grids - Experience of Indian Grid Operator", NASPI, WG Meet, 14-15 Oct 2015.

[7]. P. Mukhopadhyay, P. Seshadri, C. Gangrekar, C. Kumar, A. B. Rai and N. M. Reddy, "WAMS and synchrophasor experience during synchronization of large grids in India," 2015 IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems (SPICES), Kozhikode, 2015, pp. 1-5.

[8]. P. Mukhopadhyay et al., "Islanding detection of interconnected grids based on synchrophasor measurements (PMU)," 2014 6th IEEE Power India International Conference (PIICON), Delhi, 2014, pp. 1-6.

[9]. WRPC, "Report on Blackout at CGPL Mundra (UMPP) at 19:22 hrs, 12-March-2014", Mumbai, April 2014, [Online] : http://www.wrpc.gov.in/pcm/cgpl_report.pdf

[10]. POSOCO, "Report on Power System oscillations experienced in Indian Grid on 9th , 10th ,11th and 12th August 2014", New Delhi, Tech.Rep. September 2014.

[11]. POSOCO, "Low Frequency Oscillation in Indian Power System", POSOCO, New Delhi, Tech.Rep. March 2016.

[12]. WRPC, "SPS for JP Nigrie, MB Power and for High Loading of Sugen-Vapi S/C", Mumbai, Sept 2017, [Online]: http://wrpc.nic.in/PCM/sps_m23.08.2017.pdf

[13]. WRPC. "Agenda notes of 503 Operational Committee Meeting of Western Region", Mumbai, Jan 2018, [Online]: http://www.wrpc.nic.in/occ/503OCC_AGENDA.pdf

[14]. P. Mukhopadhyay, R. Anumasula, A. Gartia, C. Kumar, P. Seshadri and S. Patil, "Case study on fault analysis using PMU," 2014 Eighteenth National Power Systems Conference (NPSC), Guwahati, 2014, pp. 1-6.

[15]. P.Mukhopadhyay, S.R.Narasimhan, S. K. Saha, Rajkumar Anumasula, Chandan Kumar, Sunil Patil, Srinivas Chitturi, "Automated Fault Analysis Using Synchrophasor Measurements", Grid Tech 2015, 5th International Exhibition and Conference, New Delhi, April-8-10,2015. https://www.researchgate.net/publication/324978001_Automated_Fault_Analysis_Using_Synchrophasor_Measurements

[16]. NASPI Technical Report, "Diagnosing Equipment Health and Mis-operations with PMU Data", May 2015, [Online]: https://www.naspi.org/sites/default/files/reference_documents/14.pdf?fileID=1530

[17]. CIGRE 38.02.19, "System protection schemes in power networks",June 2001

[18]. P. Mukhopadhyay, V. Pandey, C. Kumar, P. Seshadri and S. Chitturi, "Performance evaluation and review of system protection schemes using synchrophasor measurement," 2016 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia), Melbourne, VIC, 2016, pp. 856-861.

[19]. Pandey Vivek, Seshadri Pushpa, Kumar Chandanm, Prabhakaran, Selvamani, "Reliability Coordination of Power Stations Connected Radially to Grid through EHV Pooling Stations", 7th International Conference on Power Systems Protection and Automation-2018, Feb 2018, New Delhi, India

[20]. R. Shukla, A. Singh, C. Kumar, N. L. Jain, S. R. Narasimhan and K. V. S. Baba, "Impact of delayed fault clearance on the load in Indian Power System," 2016 National Power Systems Conference (NPSC), Bhubaneswar, 2016, pp. 1-6.

Distributuion System, Power Quality, Cyber Security, Electricity Markets, Smart Grid

CIGRE- AORC Technical Meeting 2018 – International Conference on Global Energy Transition – Issues and Challenges, 24-25 May 2018, Gangtok, Sikkim, India

Cybersecurity Threats to Thailand Smart Grid – Key Issues and Challenges

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SUMMARY

With ever-increasing of the energy consumption to continue along its path of aggressive economic growth, Thailand has approved a national smart grid plan to enhance the reliability, security, and availability of the country's grid. With its integration of advanced computing and communication technologies, Thailand Smart Grid (TSG) is greatly expected to enhance efficiency and reliability of future power grids infrastructure under renewable energy resources, as well as distributed intelligence and demand response. With the Smart Grid applications, wireless communication networks, and millions of the electronic devices, cybersecurity emerges to be a critical issue and breaches on the reliability while sustaining critical energy delivery functions. The principal objectives of this paper are three-fold. First, the paper is to exemplify the key issues and challenges of cybersecurity for TSG. Second, this paper is to identify application requirements and technologies for smart grid system including information communication technology and wireless technology. Third, the security vulnerabilities and solutions in TSG development and the concurrent of demonstration projects in Thailand are highlighted. As a result, in order to shed the light on future research directions for Smart Grid security, the successful applications of smart grid systems are further discussed and presented.

KEYWORDS

Cybersecurity, Smart Grid, Thailand Smart Grid, Thailand

1. INTRODUCTION

As the next generation of power system with revolutionary and evolutionary regime of current power grids, so called Smart Grid, it is considered as integration of advanced computing and communication technologies with renewable energy resources, as well as distributed intelligence and demand response. Today's digitally enabled grid is more connected, intelligent, and flexible. Thus, the opening up vulnerabilities have been focused for the new coming challenges. In Thailand, with ever-increasing of the energy consumption to continue along its path of aggressive economic growth, Thailand has approved a national Smart Grid plan to enhance the reliability, security, and availability of the country's grid. In addition, Thailand is seemingly in the midst of test-bedding smart grids. This is taking place at a time when the world is seeing an increase in cybersecurity attacks specifically targeted at the power energy sector. Many incidents from the previous literature report that the threats of cyber-attacks on energy networks are no longer theoretical, then cyber-attackers across the world are focused on turning the risks into their realities. A wide range of potential attackers may have the direct effects from generation through to consumers. In Thailand, the cybersecurity laws and policy frameworks are recently launched in place, however, it remains uncertain whether these existing actions will be sufficient to lessen cybersecurity attacks aimed at smart grid upstream through consumer downstream.

With its integration of advanced computing and communication technologies, Thailand Smart Grid (TSG) is greatly expected to enhance efficiency and reliability of future power grids infrastructure under renewable energy resources. In accordance with the Smart Grid applications, wireless communication networks, and millions of the electronic devices, cybersecurity emerges to be a critical issue and breaches on the reliability while sustaining critical energy delivery functions. The power utilities and energy providers are also incorporating advance or newer technologies of generation, transmission, and distribution (i.e., meters, transformers, communication devices) available in the market. The principal objectives of this paper are three-fold. First, the paper is to exemplify the key issues and challenges of cybersecurity for TSG. Second, this paper is to identify application requirements and technologies for smart grid system including information communication technology and wireless technology. Third, the security vulnerabilities and solutions in TSG development and the concurrent of demonstration projects in Thailand are highlighted. As a result, in order to shed light on future research directions for Smart Grid security, the successful applications of smart grid systems are further discussed and presented. The subsequent section indicates the previous evidence relating various issues and challenges in cybersecurity threats.

2. PREVIOUS STUDIES

According to the past evidences, it was generally found that the issues and challenging in cybersecurity threats were vary in the energy sector (Banaseka, Kudjo, & Wornyo, 2017; Hawk & Kaushiva, 2014; Mo, Kim, Brancik, Dickinson, Lee, Perrig, & Sinopoli, 2012; Putra, 2015; Ricea & AlMajali, 2014). Smart Grids were known to be vulnerable to cyber securities due to the potentially high economic impacts and widespread social effects. Technology-based information communications systems i.e., smart grids or smart meters, while more reliable and efficient, were known to be threats to cybersecurity attacks. Information flowed to/from a smart meter including price information, control commands, meter data, etc. With this incidents, attackers were increasingly targeting in this energy sector.

2.1 Cybersecurity Threats vs Types of Smart Grid Threats

According cybersecurity threats, Symantec research (2018) reported from 157 countries and territories of Symantec's intelligence systems, the cybersecurity threat environment in Thailand ranked seventh-worst in Asia-Pacific as its dip from ninth in 2016. The major reasons were more connected devices and higher interest in cryptocurrencies and exchanges as depicted in Figure 1.

Figure 1: Top 10 Asia-Pacific and Japan Threat Rank in Cybersecurity Threats
Source: Symantec Internet Security Threat Report (2018)

Although cybersecurity threats were shown on the rise in Thailand, to date in Southeast Asia or in Thailand, there did not have report or solid evidence of hacktivists, terrorists or perpetrators of organized crime issuing any threat towards the fledgling smart grid industries in Southeast Asia (Hawk & Kaushiva, 2014). However, there were some cybersecurity-related incidents in other regions such as Puerto Rican power utility firm, the European Network and Information Security Agency, an EU agency. With this, Puerto Rican power utility firm suffered up to 400 million USD because hackers altered the data in its smart meters in 2013. The European Network warned that hackers used a “worm” to gain remote access to homes smart meters (Hawk & Kaushiva, 2014). Furthermore, some others cybersecurity threats have been found in 2013 such as Malaysian government websites were defaced by hackers, Cyber war was shown by Bangladesh Grey Hat Hackers and Indonesia’s Cyber Army, Traditional Chinese Medicine (TCM) in Singapore was defaced by hackers.

A global internet security corporation reported that smart grids could be attacked in many different scenarios and for various purposes (Banaseka et al., 2017; Hawk & Kaushiva, 2014; Mo, et al.; Putra, 2015). For instance, hackers could launch a denial-of-service attack by inserting corrupt data into the computer servers of the electricity retailers. They could manipulate power-grid data by intercepting communications between substations, grid operators, electricity consumers and suppliers. They could easily access to some of the grid components. They could access to the computer servers to malfunction and sent fake data to the grid network. They could manipulate the data exchanges in smart grids and influence the electricity market. They could modify the bills of smart meters end-users. They could carry out crimes like robbery and extortion for their best opportunity to commit burglary and theft. They could threaten their primary target to cut off the power supply via remote control. A cyber-attack on devices could result in power disruption or damaged equipment or interfere with critical energy delivery functions. To conclude, no single solution could prevent all cyber incidents.

2.2 Cybersecurity for the Power Grid vs Thailand Smart Grid

Many researchers revealed various approaches and solutions to secure the Power Grid System (Banaseka et al., 2017; Hawk & Kaushiva, 2014; Mo, et al., 2012; Ricea & AlMajali, 2014). Since the smart power grids system unavoidably were the exchange and interconnection of information flowed to/from a smart meter including price information, control commands, meter data, etc. Three primary security properties of confidentiality, integrity, and availability had been prominent. Handbook on Smart/Intelligent Grid Systems Development and Deployment was identified these properties as follows. Confidentiality prevented an unauthorized users from obtaining secret or private information. Integrity prevented an unauthorized user from modifying the information. Availability ensured that the resource can be used when requested. Furthermore, Hawk and Kaushiva (2014) recommended five phases of ongoing cybersecurity of Smart Grid technologies starting from design phase, procurement phase, installation phase, commissioning phase, and ongoing maintenance and support phase of the project. With this view, Ricea and AlMajali (2014) illustrated that the system design needed to include concepts drawn from cyber security, reliability, and fault tolerance design, integrated into a common methodology. Mo et al. (2012) deliberately outlined the most important requirement for protecting smart grids by starting from 1) the confidentiality of meter data; 2) integrity of data, commands, and software; and 3) availability against Denial-of Service (DoS)/ distributed DoS (DDoS) attacks.

As shown in Figure 2 for simple illustration of “A Cyber Security View of Smart Grid”, Banaseka et al. (2017) and Mo et al. (2012) correspondingly delineated cyber security approaches to smart grid security. Thus, power customers in the consumption components used electric devices (e.g., smart appliances, electric vehicles), and their usage of electricity were measured by an enhanced metering device, called a smart meter. The smart meter was one of the core components of the Advanced Metering Infrastructure (AMI). The meter connected and interacted with a gateway of a Home Area Network (HAN) or a Business Area Network (BAN). Banaseka et al. (2017) and Mo et al. (2012) then similarly denoted a smart meter as a gateway of a HAN. A Neighbor Area Network (NAN) was formed under one substation, where multiple HANs were hosted. With these consequences, a utility company could leverage a Wide Area Network (WAN) to connect distributed NANs.

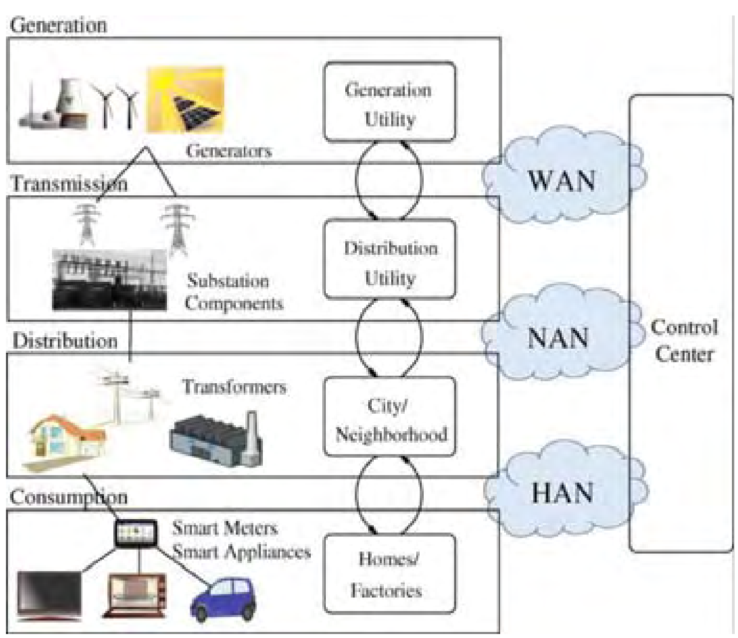

Figure 2: A Cyber Security View of Smart Grid

Source: Banaseka et al. (2017, p.6514) and Mo et al. (2012, p.3)

In addition to the above mentioned, other researchers advised such applications to the field of cyber security and the severity of cyber-attacks (Putra, 2015; Symantec, 2018). The designing cybersecurity into the smart grid at its foundation was prominent. Phasor measurement units brought unprecedented wide-area visibility of grid operations. Advanced Metering Infrastructure (AMI) enabled faster outage restoration. Distribution Automation (DA) enabled grid self-healing. Energy storage provided contingency reserves for grid stability. Demand Response (DR) technologies provided the utility a path to manage system load. Among others taken individually, these publications each told an incomplete story, but taken together, they each told a different piece of a larger story. The study of smart grid cyber security threats can gain more advantages from broader perspectives that tie each of these proposed solutions into a comprehensive system design. Such an innovated system design would not only provide the broader view of the studies like the mentioned above, but would also suggest various methods and solutions for evaluating them together against each other if adapting from each individual suggestions.

According to the external driving forces of Thailand Smart Grid Development and some researcher' arguments (Putra, 2015), of all the Southeast Asian stated with smart grid aspirations, Thailand seemed to be the least prepared and equipped with policy tools. Consequently, Thailand was released the master smart plan of Thailand smart grid development (2015-2036) by the Ministry of Energy so called "Thailand Smart Grid (TSG)". This plan was used for implementation guidelines and regulatory framework development and also be aligned with Thailand Integrated Energy Blueprint (TIEB) as the core of the long term energy development (TIEB). Thailand was developed the concrete mitigation and adaptation in respective sectors. Five strategies and objectives of Thailand smart grid master plan are outlined and executed in the following areas, (1) Power Reliability; (2) Energy Sustainability and Sufficiency; (3) Utility Operation and Service; (4) Integration and Interoperability; and (5) Economic and Industrial Competitiveness. In a successful smart grid system, today Thailand has launched and formulated smart grid development pilot projects in the various areas.

To secure the power grid network in Thailand, as most of the Thai utilities already had SCADA in their systems. SCADA enabled communication between the service providers and their customers and also allowed a transfer of gathered data between different authorities. Thai utilities could improve their services by providing advice to their customers for more efficient and more cost effective use of energy. Furthermore, the distribution management system processed real-time information of the grid conditions and promptly detected fault locations with the advanced sensors and meters. Power (2013) revealed various application areas and sub-technologies for Thailand Smart Grid Systems for short to mid-term prospects. These summarized as followings; 1) Substation and distribution automation; 2) Advanced metering infrastructure and communication; 3) Utility Enterprise Applications; 4) Micro-grid systems; 5) Electric vehicle charging stations. Likewise, Handbook on Smart/Intelligent Grid Systems Development and Deployment (2013) pointed out Thailand Smart Grid Technologies in Five primary components; as followed. 1) Smart Power Generation; 2) Smart Transmission Grid Applications; 3) Distribution Automation; 4) Customer Home Automation and Demand Response; 5) General Component. From these incidents, it could be summarized that most applications proposed in TSG focused the physical securities of the systems through the screening and assessment of contingencies.

According to TSG plan, Information Communication Technology and wireless technology was stated in short-to-medium action plan. These TSG infrastructures were developed including ICT Integration (G&T), Energy Management System (SCADA/EMS), Energy Storage System (G&T), SPP/VSPP Data Communication System (G&T), Substation Automation (G&T), Wide Area Monitoring System (WAMS)/Wide Area Protection and Control (WAPC), ICT Integration (Distr), Distribution Management System (SCADA/DMS), Distribution/Feeder Automation (DA/FA), Substation Automation (Distr), Smart Meter + AMR/AMI), Meter Data Management System (MDMS), SPP/VSPP Data Communication System (Distr), Intelligent Street Lights.

For long-term TSG action plan, in addition to the above mentioned, the implementation phase was employed in the various applications including Intelligent Charging System/V2G (G&T), Renewable Energy Forecast System, EHV/FACTS, Demand Response (DR)/Demand-Side Management (DSM) (G&T), Energy Storage System (Distr), Intelligent Charging System/V2G (Distr), Microgrid Development, Demand Response (DR)/Demand-Side Management (DSM) (Distr), respectively. As depicted in Figure 3, the following figure is the TSG demonstration project representing the Smart Grid Pilot Project, Mae Hong Son Province in Thailand.

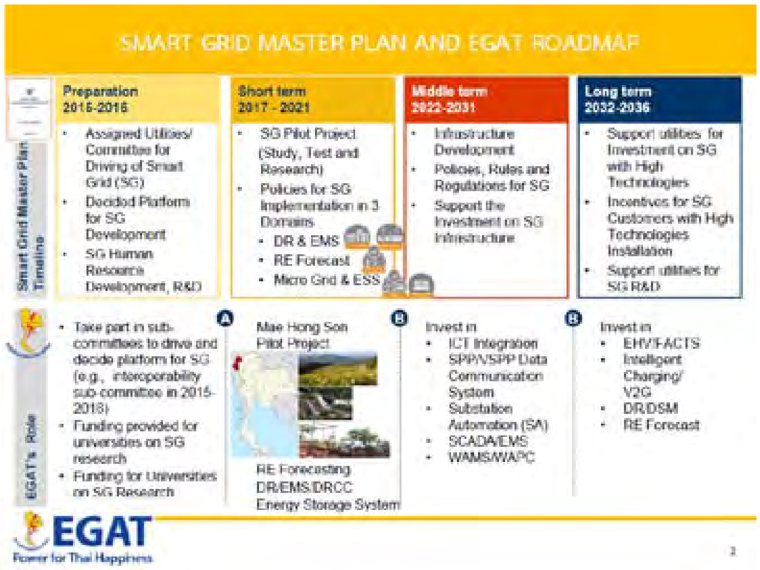

Figure 3: The Smart Grid Pilot Project, Mae Hong Son Province in Thailand.

Source: Takapong (2017, p.2)

To the extent practicable in TSG, Electricity Generating Authority of Thailand (EGAT), as a state-owned enterprise, needed to develop and applied new technologies as well as connecting the scattered power sources by the Information Communication Technology. With this, "Smart Grid" was to efficiently manage and control power generation, transmission, and distribution. To secure absolute all EGAT network securities, EGAT was able to identify and pin-point the areas of vulnerabilities in EGAT's network and mitigate them by annually conducting the Penetration Test. While annual tests helped to pinpoint these weak spots, EGAT awarded the external consultant to do the external penetration tests from (outside-in) and various developed cyber security protocols (inside-out). In practical use of all EGAT's Department, since 2016, EGAT had conducted assessments more frequently due to the fast-moving nature of technology. From this point forward, as the results of repeatedly testing, EGAT identified the cyber-threats by 1) removing all metadata on files before making them publicly available and disallowing the spidering of sensitive directories; 2) employing a finely-tuned email filtering solutions and properly configured firewall to block future phishing attacks; 3) restricting EGAT employees' email and internet access on the workstations; 4) continuously developing long-term strategic plan to prevent the unexpected incidents; 5) constantly updating software security programs, vulnerability protection, application controls; and 6) periodically training EGAT's employees to increase cyber-security awareness, respectively. Recently this month in May 2018, EGAT switched antivirus software internet & cloud security to a new smart protection network. This new software protection version claimed that the security leverages machine-learning capabilities with enhancements to all defenses. EGAT believed that the effective security program would help to minimize the risks from unexpected intruders. Furthermore, a vulnerability management program would help to rectify the issues of outdated software on the internal network and would proactively limit future exploitation. As an ideal target for hackers in the utilities sectors, it would be expected that TSG was not only proactive on the security, but also relying on automated data to make security decisions.

As a result, although TSG did not exactly state the issues of cybersecurity in the TSG Master Plan, the cybersecurity laws and policy frameworks were in place. Moreover, Thai government appeared to be focused instead on protecting the country's burgeoning digital economy and increasing electronic commerce activities for National Cybersecurity Bill (Putra, 2015). As it stands, none of TSG action plans specified that these short-term action plans were actively test-bedding smart grid technologies by 100 percent cybersecurity policies or strategies solely for smart grid protection. Meanwhile, the cybersecurity for the TSG also needed to further accommodate physical properties, requirements, and dependencies of power systems such as Intrusion Detection Systems (IDSs) and Firewalls. Two protocol strategies of "Detection and Protection" may warrant considerations by the TSG developers.

3. CONCLUSIONS AND RECCOMMENDATIONS

Nowadays, the recent increases in the rate and the severity of cyber-attacks on companies all over the world point out high risks to businesses and customers. Perfect protection for Smart Grid is practically impossible. Thus, putting smart grid cybersecurity will be critical for utility industries. This paper intends to exemplify the key issues and challenges of cybersecurity for TSG, to identify application requirements and technologies for smart grid system including information communication technology and wireless technology, and to reveal the security vulnerabilities and solutions in TSG development. Also, the concurrent of demonstration project in Thailand is enlightened, namely Mae Hong Son Smart Grid Project. However, various incidents reported that the issues of cybersecurity in the TSG did not found well prepared - processes, training and simulations in place. Smart Grid developers in Thailand launched various applications to secure their data following by the International Standard of Smart/ Intelligent Grid Systems development and deployment. Also, designing and building Smart Grid systems, in which security was embedded in the design requirements, was already as a primary key.

Thus, the following five practical guidelines for utility firms (Accenture, 2017, p.14-15) could possibly provide critical value here. First was to investigate the platform to cybersecurity capabilities. Second was to share cyber threats data with others. Third, utility firms needed to integrate resilience into asset and process design. Fourth was to employ security and emergency management governance models. Lastly, the utility companies needed to develop the relationship with regional security officials and with cyber response experts. At last, while the results of this work do not directly applicable to the protection of deployed TSG smart grid systems, this hope that various discussion here will provide some fruitful guidance in approaching the risks that utilities face with their TSG upgrades in the near future.

BIBLIOGRAPHY

Accenture Consulting. (2017). *Accenture executive review: Outsmart grid security threats POV*. Retrieved from https://www.accenture.com/us-en/insight-utilities-outsmart-grid-cybersecurity-threats

Banaseka, F. K., Kudjo, P. K., & Wornyo, D. K. (2017). A survey of new development in cyber security and networks. *Journal of Multidisciplinary Engineering Science and Technology*, *4*(1), 6513-6518. Retrieved from file:///C:/Users/Administrator/Downloads/FKB_Pub_5_JMEST.pdf

Energy Policy and Planning Office, Ministry of Energy, Thailand. (2017). *Thailand Smart Grid Action Plan (2560-2564)*. Retrieved from http://www.eppo.go.th/images/Power/pdf/smart_grid_actionplan.pdf

Energy Policy and Planning Office, Ministry of Energy, Thailand. (2015). *Thailand Smart Grid Master Plan (2558-2579).* Retrieved Retrieved from http://www.eppo.go.th/images/Power/pdf/smart_gridplan.pdf

Hawk, C. & Kaushiva, A. (2014). Cybersecurity and the smarter grid. *The Electricity Journal, 27*(8), 84-95. https://doi.org/10.1016/j.tej.2014.08.008

Mo, Y., Kim, T. H., Brancik, K., Dickinson, D., Lee, H., Perrig, A., & Sinopoli, B. (2012). Cyber–physical security of a smart grid infrastructure. *Proceedings of the IEEE, 100*(1), 1-15. Retrieved from https://www.researchgate.net/profile/Yilin_Mo/publication/224257991_Cyber-Physical_Security_of_a_Smart_Grid_Infrastructure/links/004635395d2f66a584000000.pdf

Power, A. (2013). *Market potential for smart grid technology in Thailand and Vietnam.* Retrieved from Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH: Germany website https://www.giz.de/fachexpertise/downloads/giz2013-en-market-potential-smart-grids-tha-vn.pdf

Putra, N.A. (2015). Mitigating cybersecurity threats to Southeast Asia’s Smart grids. *ESI Policy Brief*, *9*(11), 1-4. Retrieved from http://esi.nus.edu.sg/docs/default-source/esi-policy-briefs/Mitigating-Cybersecurity-Threats-To-Southeast-Asia's-Smart-Grids?sfvrsn=2

Ricea, E.B. & AlMajali, A. (2014). Mitigating the risk of cyber-attack on smart grid systems. *Procedia Computer Science*, 28, 575-582.

Symantec Corporation. (2018). *Executive summary: 2018 Internet security threat report*. Retrieved from ISTR website https://www.symantec.com/content/dam/symantec/docs/reports/istr-23-executive-summary-en.pdf.

Takapong, S. (2017). *Smart grid pilot project in mae hong son province.* Paper presented at the International Renewable Energy Asia Conference (REA 2017). Retrieved from http://www.thaiwater.com/Portals/3/conference/3.%20Presentation_Mr.%20Sawapop%20Takapong_Smart%20Grid%20Present%20MHS%2014_ENG_3.pdf

World Alliance for Thai Decentralized Energy Association. (2013). *Handbook on smart/intelligent grid systems development and deployment.* Retrieved from http://www.wadethai.org/docs/SMART_THAI_Handbook.pdf

CIGRE- AORC Technical Meeting 2018 – International Conference on Global Energy Transition – Issues and Challenges, 24-25 May 2018, Gangtok, Sikkim, India

Power Quality issues in Distribution System

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CESC Limited, Kolkata

Introduction:-

Power Quality (PQ) is recognised as an important issue in electricity distribution system across the globe. The issue is more pronounced with large scale use of electronic equipment. Majority of electronic equipment are causing PQ problems as well as being the victims of such problems. Without quality power, an electrical/electronic equipment may malfunction, fail or not operate at all.

Almost all the consumers suffer due to various PQ problems. But the fact remains, that the majority of consumers are not even aware of PQ problems – even the utilities do not possess adequate equipment to measure PQ. It is a must to educate and create awareness among the stake holders. In India, many parts of the country is struggling for creating electricity distribution infrastructure and providing 24x7 supply, PQ expectations will be generated at a later stage. But in the areas, where the network is robust and supply availability is reliable, PQ expectation is bound to arise.

Effect of poor PQ may cause:-

- Transformer, Cable, Capacitor bank overheating and thereby ageing of equipment and higher losses in the network
- High current on neutral which would cause increased losses and problem with protection system
- Problem with energy measurement equipment

Most common Power Quality (PQ) issues are:-

- Interruptions of supply – planned or unplanned
- Voltage Sag and Swell
- Voltage Spikes / Transients
- Voltage Regulation
- Harmonic Distortion
- Voltage unbalance

PQ issues:-

Interruptions of supply – planned or unplanned

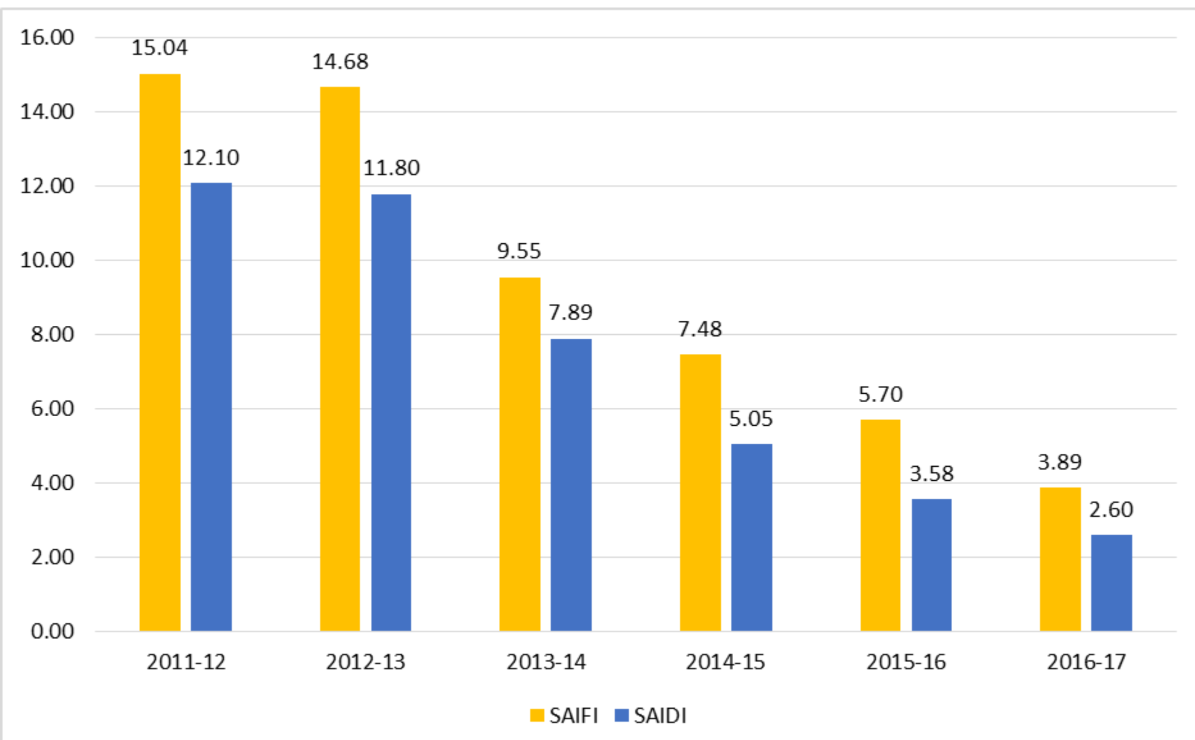
Outage of supply is generally due to non-availability of supply from sources and/or faults in the network. Network operators take planned outage of system due to planned maintenance of transformers, lines/cable, circuit breakers etc.

Interruptions are measured by Reliability Indices – SAIFI, SAIDI

SAIFI (System Average Interruption Frequency Index)
SAIFI is a measure of how often an average customer loses supply during one year. A SAIFI of 3 means that the average customers connected to the feeder or supply area being measured on average lost supply thrice during the past 12 months.
SAIDI (System Average Interruption Duration Index)
SAIDI is more commonly known as "average customer minutes off supply" and is generally reported over a one-year period. It is the total of interruption duration in minutes per year per customer experienced by customers for both planned and unplanned interruptions.

In the absence of data base at customer level, CEA suggested for such indices at 11kV feeder level supplying in town having population of more than 8 lakhs.

Reliability (HT Feeders) parameters (In line with data submitted to CEA):-

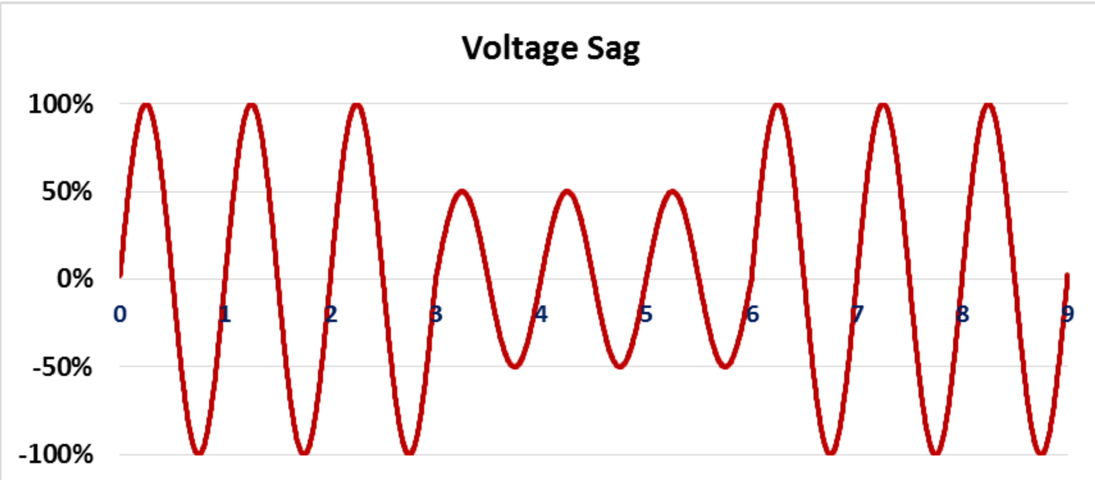


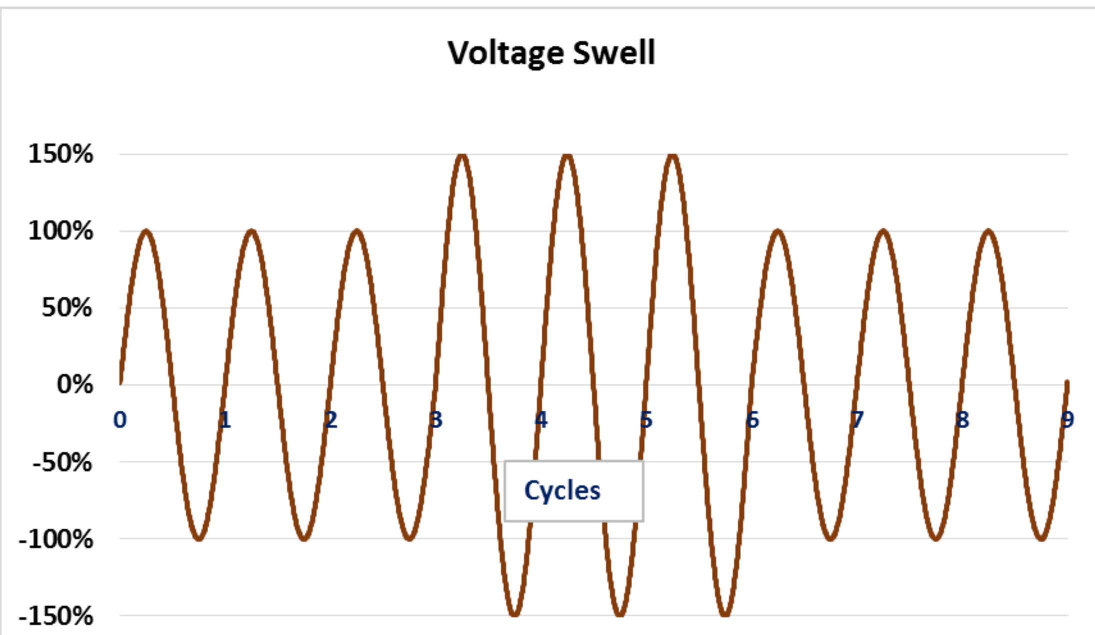
All outages due to load shedding, under frequency tripping, fault, work on faults and programme jobs included. Outage information are gathered from SCADA at EHV and HV level

Voltage Sag and Swell
Voltage sag relates to long-term reduction of voltage and swell is an increase in voltage.

Typical magnitude for voltage sag - 10% to 90% of nominal, at the power frequency for durations of ½ cycle to 1 minute.

Typical magnitude for voltage swell - 110% to 180% of nominal, at the power frequency for durations of ½ cycle to 1 minute.





Voltage sags are caused by abrupt increases in loads such as short circuits or faults, motors starting, or electric heaters turning on, or they are caused by abrupt increases in source impedance, typically caused by a loose connection.

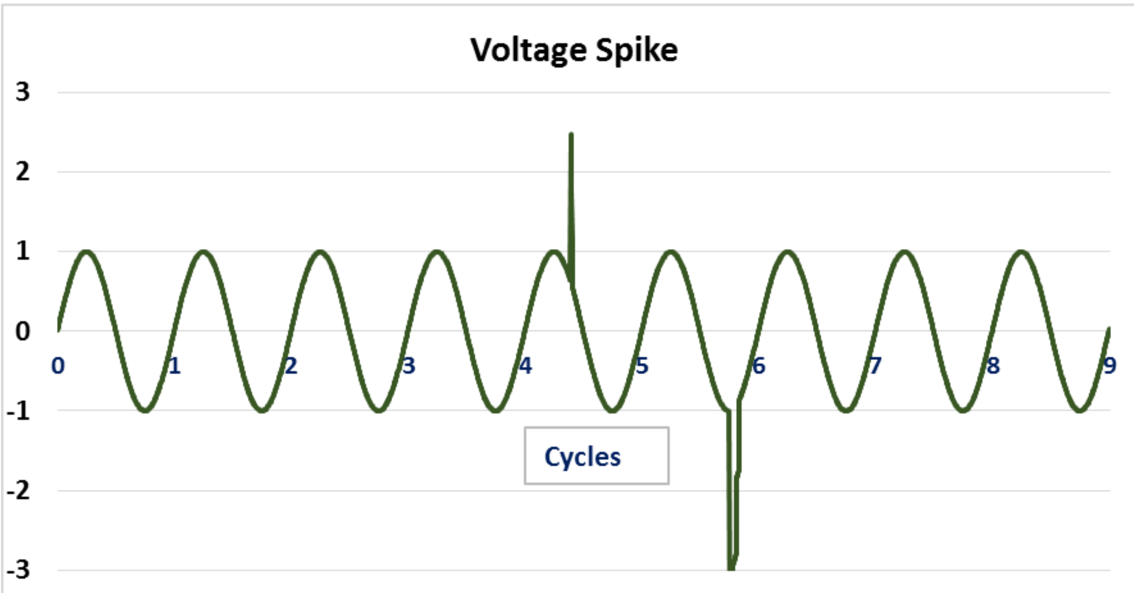
Voltage swells are almost always caused by an abrupt reduction in load on a circuit with a poor or damaged voltage regulator, although they can also be caused by a damaged or loose neutral connection.

Voltage Spikes /Transients

This is short term reduction for nanoseconds to milliseconds.

Voltage transients spikes are caused by lightning, switching of high reactive load (reactors or capacitors), Arc welding etc.

Generally, the reasons for voltage sag, swell and spikes are beyond control of licensee.



Voltage Regulation

There is a limit for voltage variations for a supplier, specified by Electricity Regulatory Commissions.

Voltage Regulation Limits:-

Voltage Level	Higher Side	Lower Side
EHV (Above 33kV)	10%	12.5%
HV (Above 650V and Upto 33kV)	6%	9%
LV (230 / 400V)	6%	6%

Sustained low voltage occurs in the system mainly due to overloading of the network, inadequate reactive power support at load end and incorrect position of the transformer tap. Over voltage may occur due to over compensation (capacitive loading) in the network, incorrect position of the transformer tap and underloading of the network.

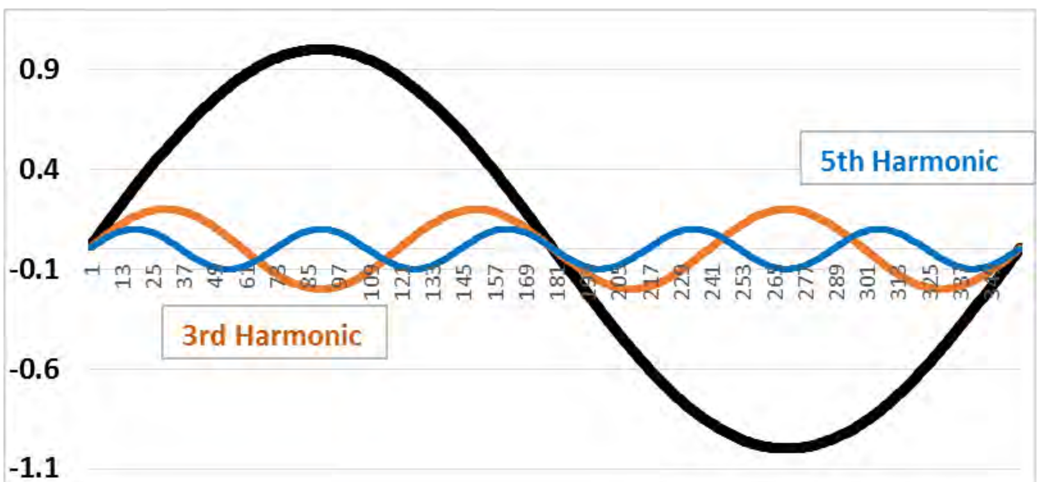
It is to be noted that there is high power factor rebate and surcharge on power factor, for HT consumers of CESC. Consumer can avail rebate of 5 to 8% on energy charge by maintaining power factor 0.99 and above. It is observed that majority of HT consumers avail high rebate by maintaining good power factor. However, as of now, there are no such provisions for LT consumers.

Harmonic Distortion

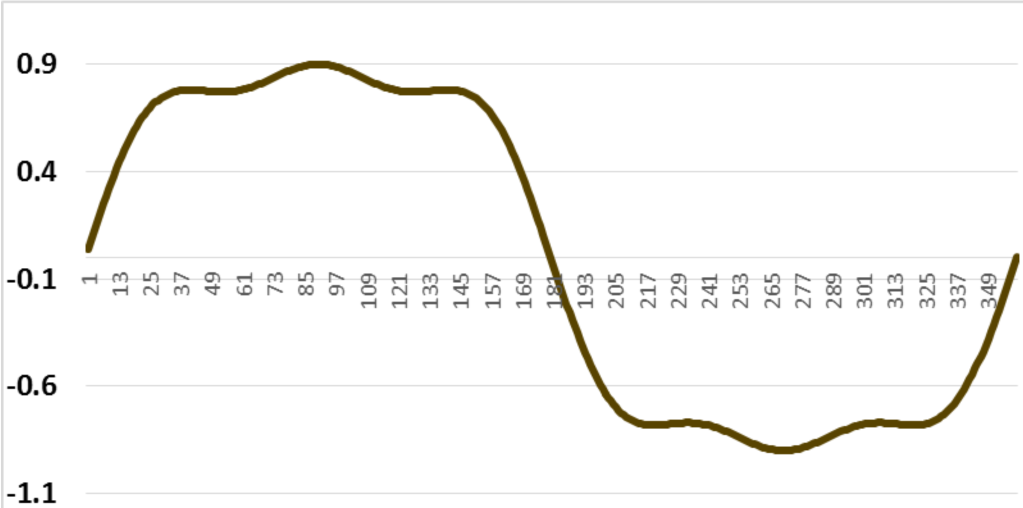
There is a saying :”**The utility owns the voltage,and the end-user owns the current**”-meaning that the utility is responsible for the generation , distribution , and regulation of the voltage at an end user’s meter, but the end users load is what characterises the shape of the electrical current. Whenever the current waveform is distorted to an extent, the supply voltage may get distorted. One of the main reason of current distortion is loads which are non-linear and generate harmonics e.g. UPS, Arc furnaces, Arc welders, Rectifiers/Inverters, speed-controlled drives, pumps, fans, and motors, and electronic equipment.

The fundamental frequency of the AC electric power distribution system is 50 Hz. A harmonic frequency is any sinusoidal frequency, which is a multiple of the fundamental frequency. Harmonic frequencies can be even or odd multiples of the sinusoidal fundamental frequency.

Voltage or current waveforms assume non-sinusoidal shape. The waveform corresponds to the sum of different sine-waveswith different magnitude and phase, having frequencies that are multiples of power-system frequency.



Fundamental with 20% 3^{rd} and 10% 5^{th} Harmonics



Composite wave form

Total Harmonic Distortion (THD)

THD is widely used to quantify the quality of power in transmission and distribution systems. It considers the contribution of every individual harmonic component on the signal and represented mathematically, as

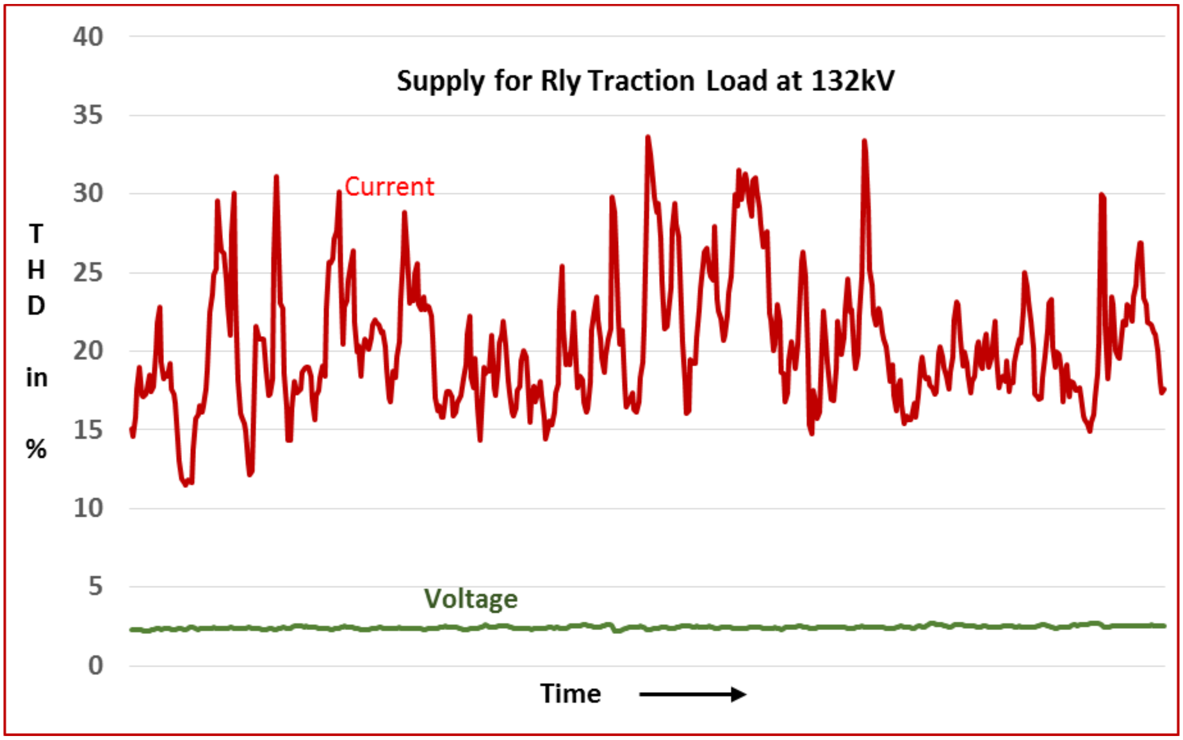
$$THD_V = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1}, \quad THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1}$$

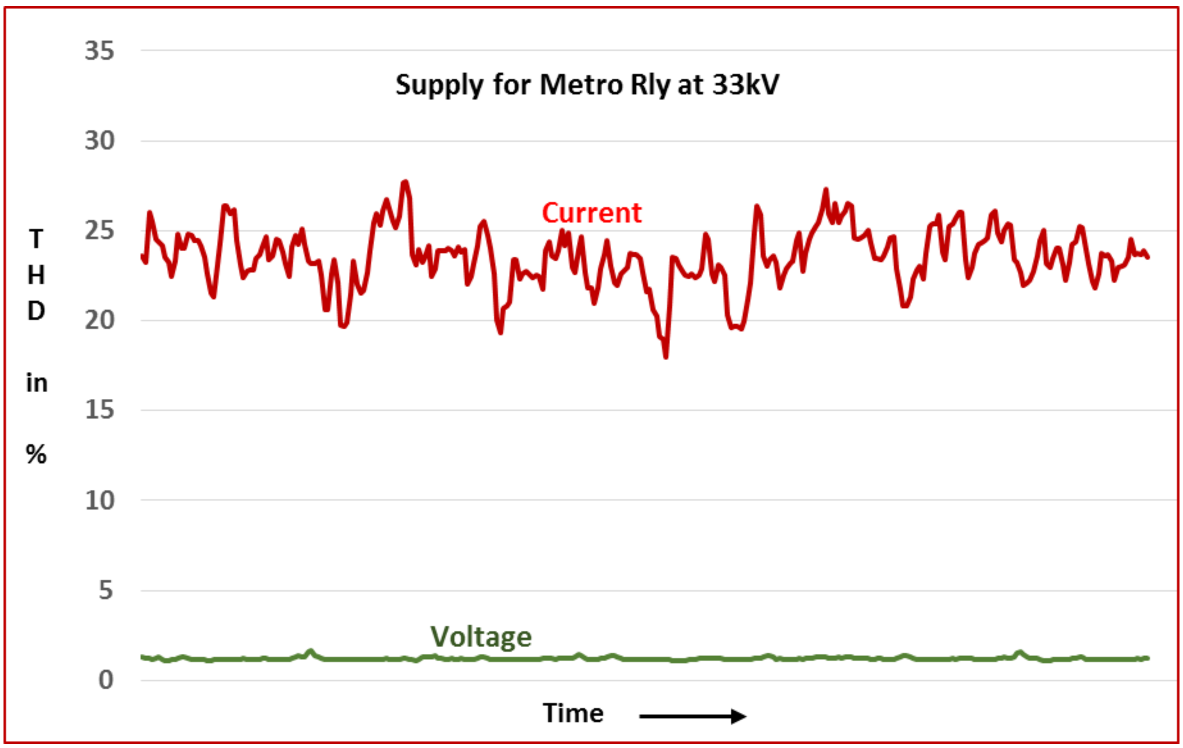
Consequences of high harmonics are many, some of which are listed below:-

- Overloading and overheating of Transformers/Cables/CBs
- Overloading of capacitors and fusing
- Increase in losses (skin effect)
- Rapid aging of insulation of electrical equipment and thus shortening their useful life
- Errors in measuring energy
- Malfunction of control equipment(tripping of circuit breakers)
- Loss of efficiency of motors
- Mechanical vibration, noise

Harmonic measurement

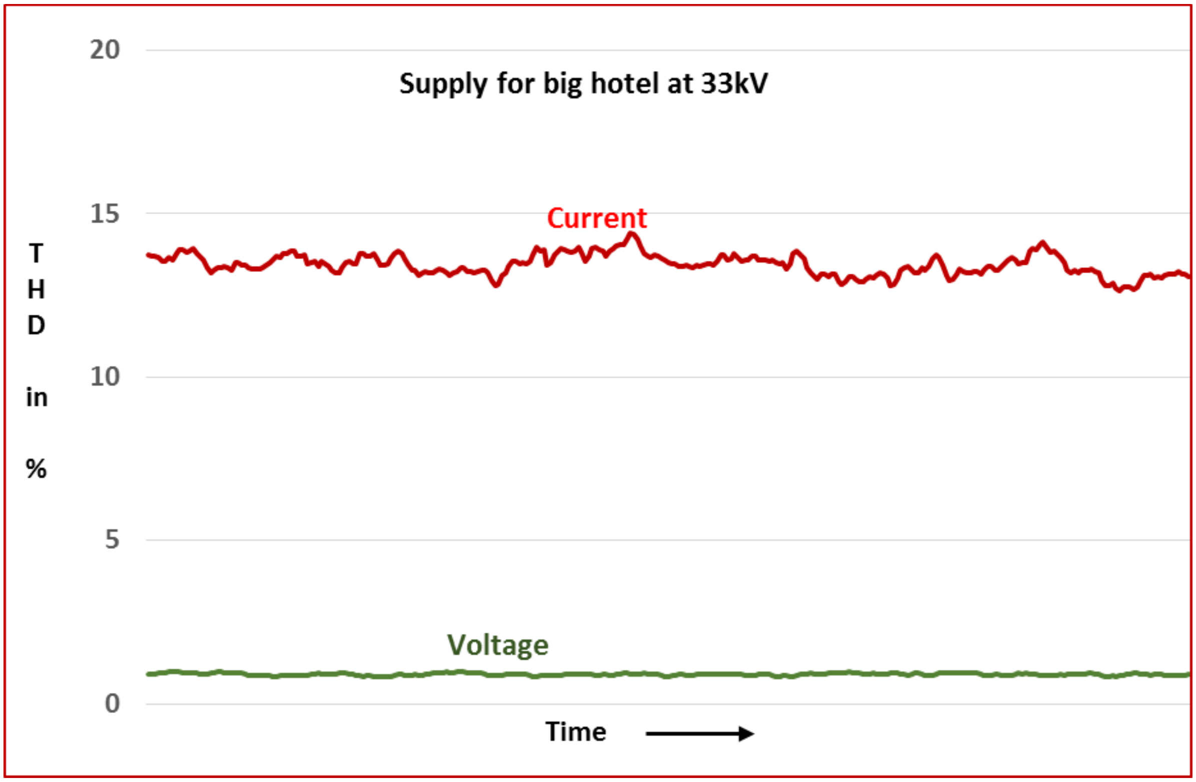
It is observed that Total Harmonic Distortion (THD) in current at the point of supply for High Tension (HT) consumers is varying widely. Often it is very high for traction loads.

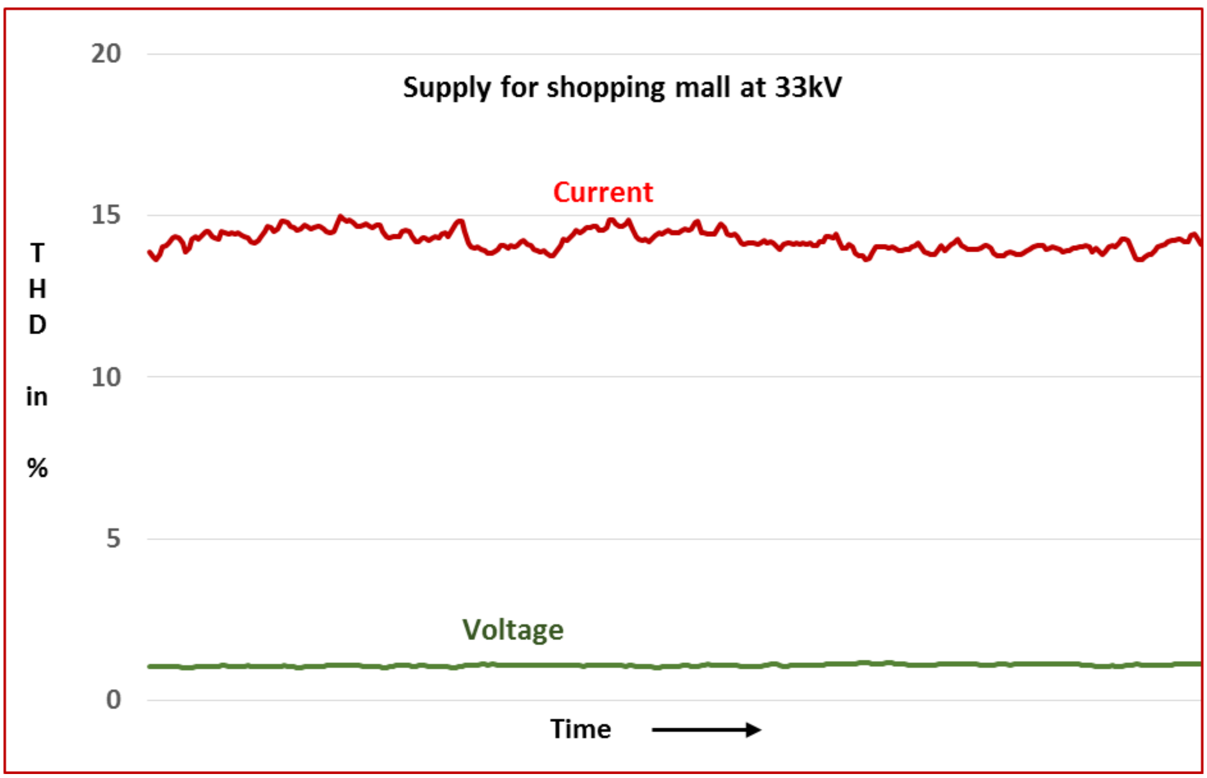




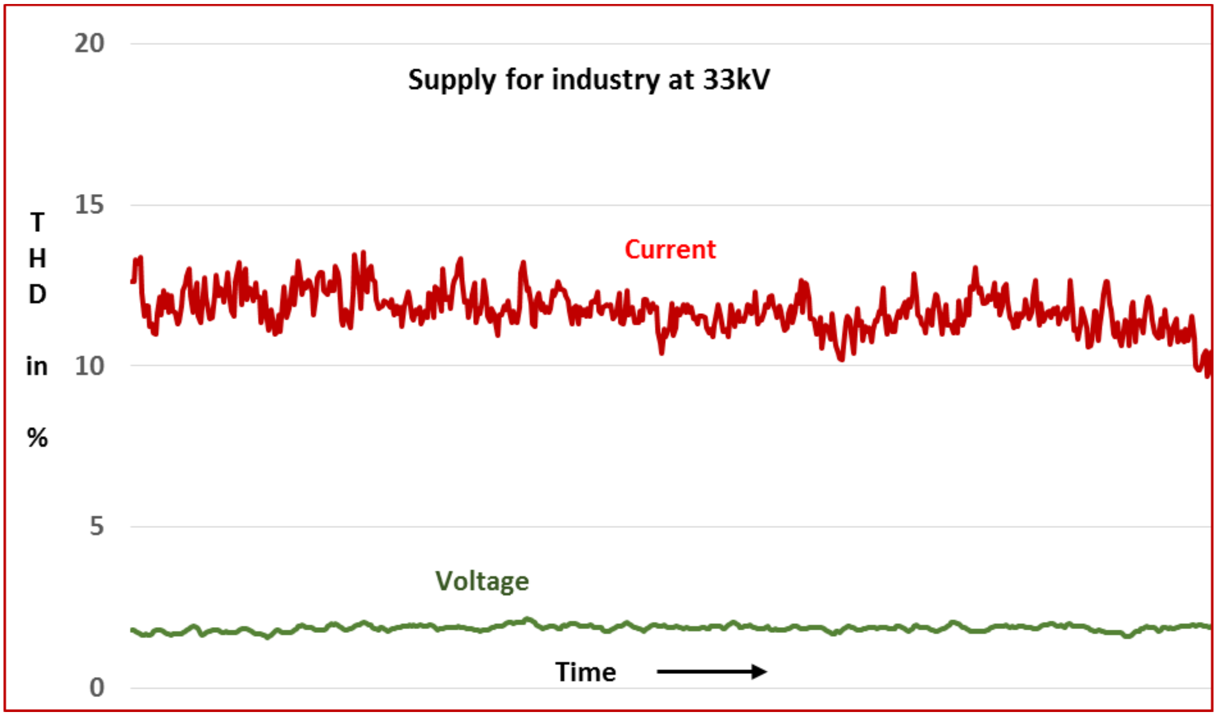
THD in current for traction load supply is about 25 ~ 30%. However, as it may be observed from the above graphs, voltage harmonic content is very less and of the order of 1 ~ 2%.

Measurement have also done for other categories of supply viz. big hotel, shopping mall, industries, large pumping stations and airport.





THD in current for hotel or shopping mall is about 15% and voltage harmonic content is very less and of the order of 1 ~ 2%.


Supply for industry at 33kV
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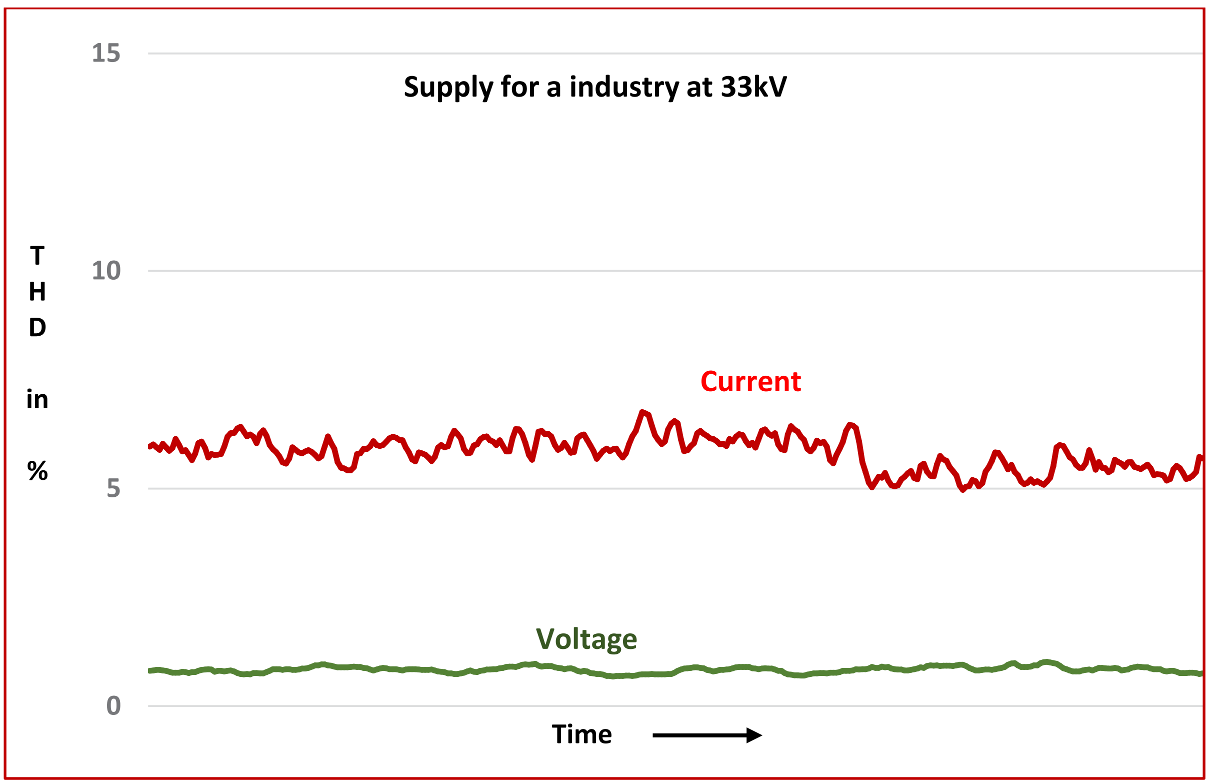
Supply for a industry at 33kV
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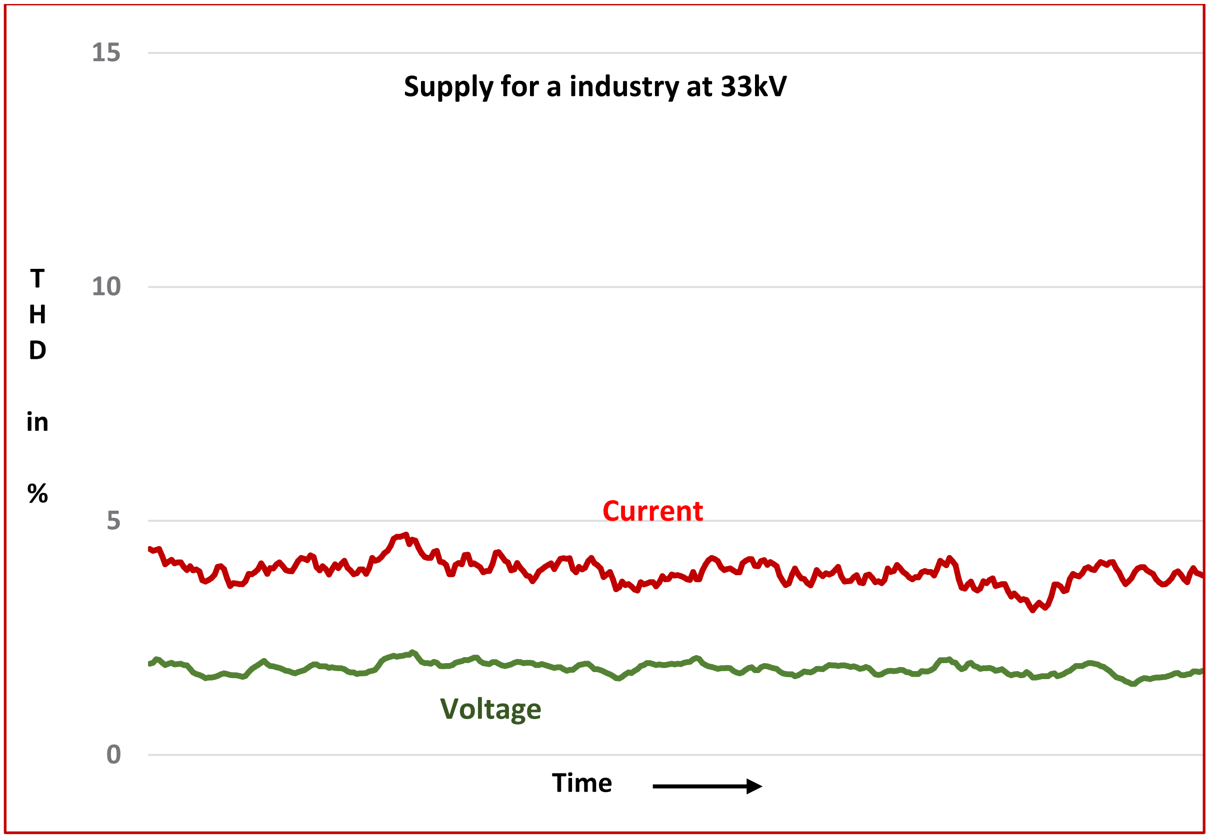
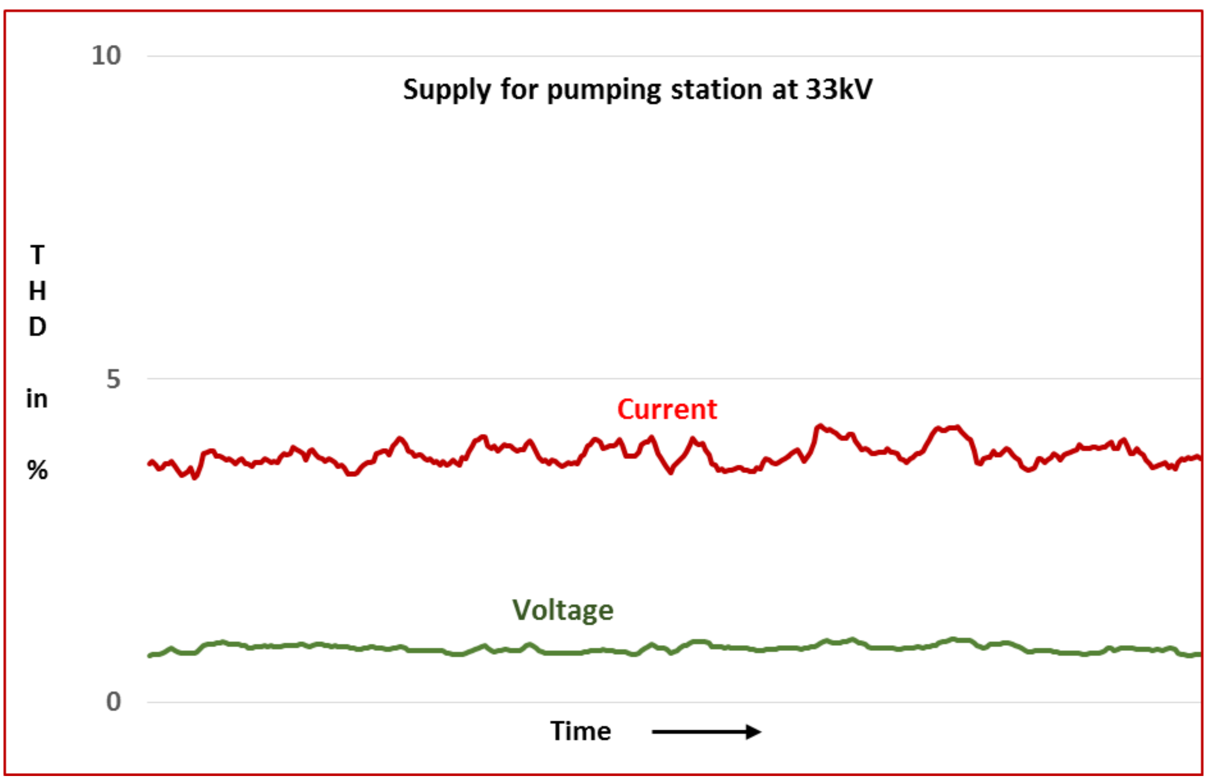
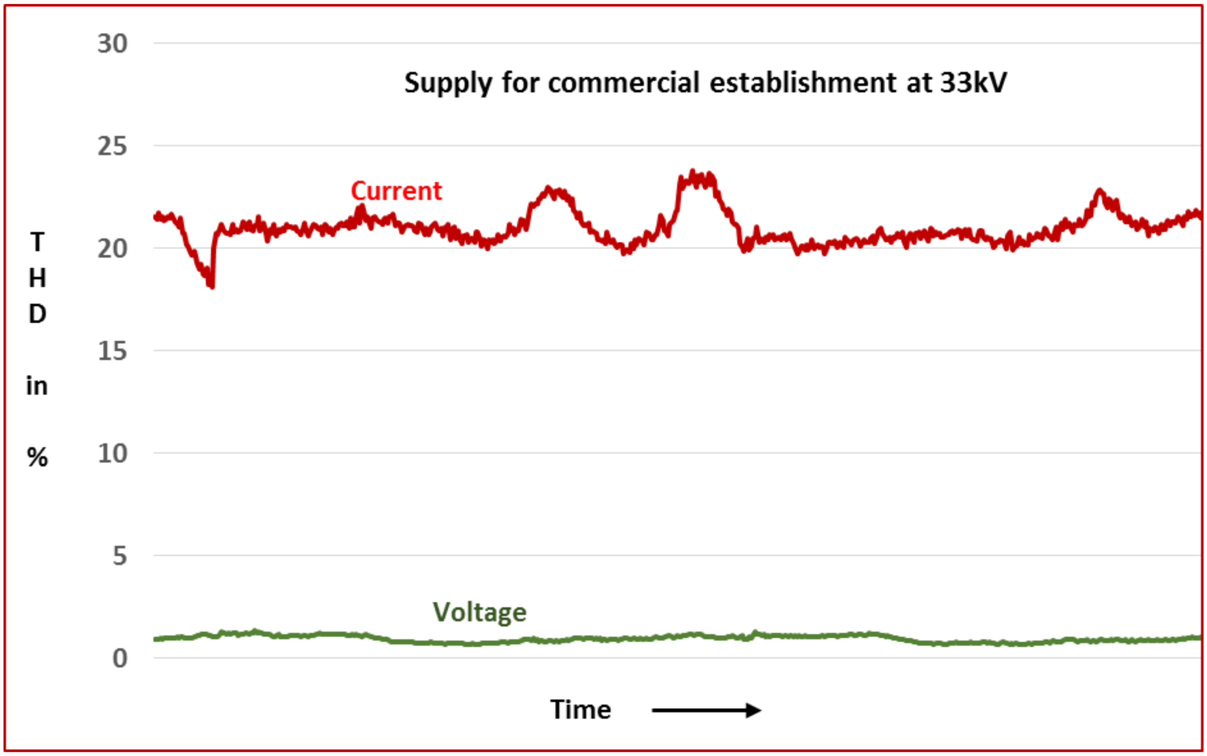


Harmonic contents vary widely for general industries depending upon equipment they use.

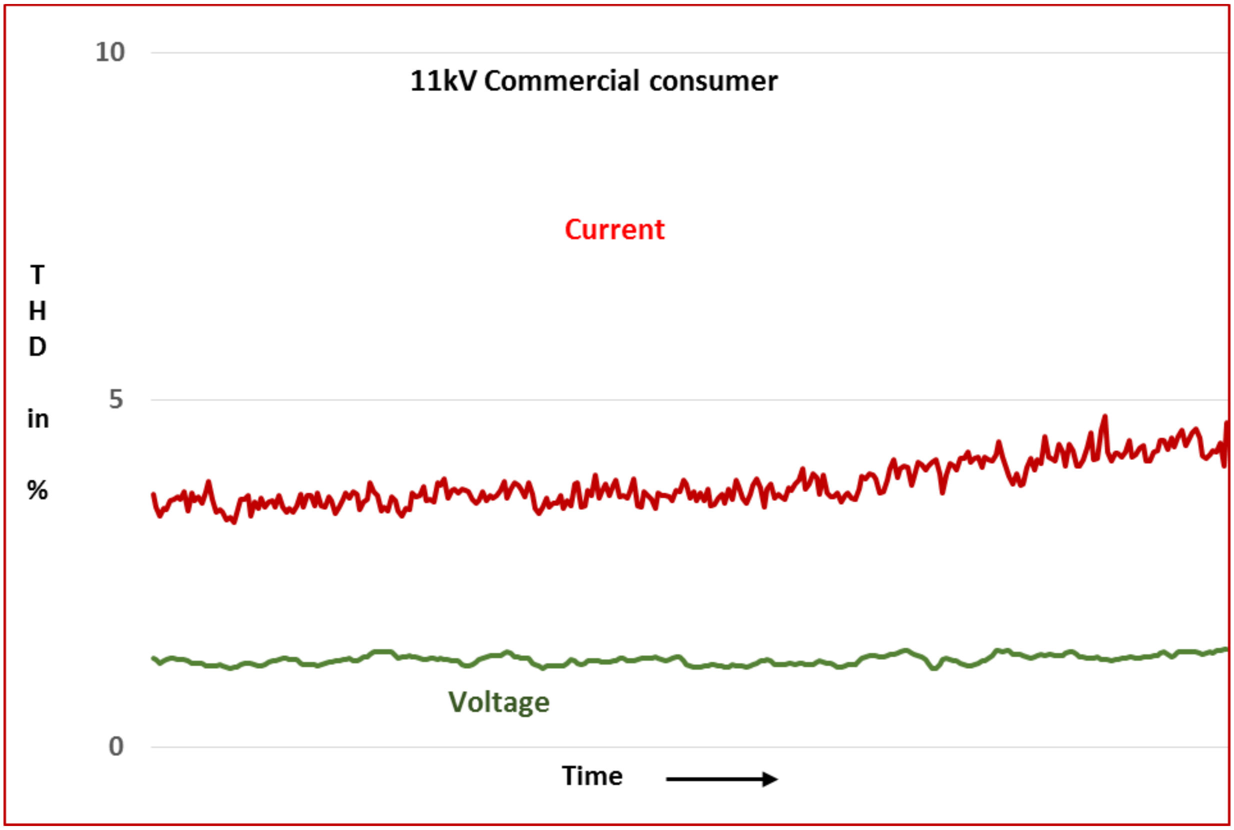
In three different industry supply, THD in current varies in the range of 4 ~ 12%. However, THD in voltage is about 1 ~ 2%.



For pumping station, THD in current is about 4% and voltage within 1%. Major loads are linear and not having many thyristor controlled drives.



Supply contain current harmonics of the order of 20%. However, supply voltage harmonics is about 1%. It is to be noted that this consumer (Airport) has very high capacity solar PV plant.



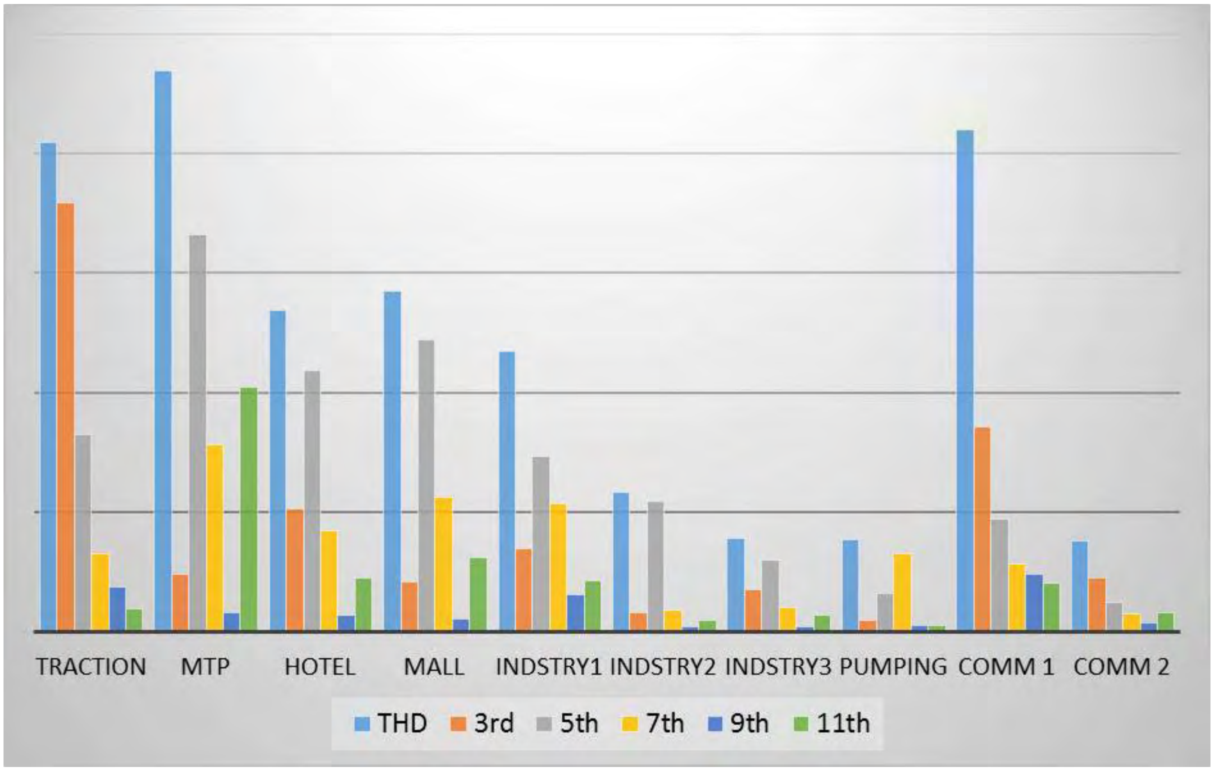
Measurement at a commercial establishment supply at 11kV with moderate rooftop Solar PV capacity show THD in current is less than 5%and supply voltage harmonics is about 1%.

The above graphs depict current harmonic content in the range of 4% to 25% whereas voltage harmonic content is very less and in the range of 1 to 2%. As we know, Voltage distortion depends on Short Circuit Ratio **(I_{SC} / I_L)** of the system. Short Circuit Ratio of CESC System is high due to higher capacity of transformers, underground and shorter cablesand parallel operation. SCR for 33kV supply points is in the range of 50 <100.

It is generally observed that the consumers using technologies such as VFD, UPS, LED lights are susceptible for higher harmonic generation. Most of the traction loads, generally consists of DC motors and hence prone to high harmonic generation.

Further, analysis have also been made for individual harmonics for the abovementioned categories of supply. In cases, 3rd harmonic is predominant, in majority cases, 5th harmonic is predominant. Presence of 9th order harmonic is not observed. However in one case 11th order harmonic is substantial. Since, even harmonic is more pronounced, we are not showing here odd harmonics.

The following diagram shows harmonics (THD, 3rd, 5th, 7th, 9thand 11th) in current:-



Measurements and observations on Harmonics for low tension consumers with Solar PV Plant:-

Harmonic distortion are also measured at consumers where Solar PV Plant is installed. With generation from Solar PV Plant, there is an increase in current harmonics. The following measurement was done for one HT industry which hadinstalled a 750kWp Solar PV Plant at itspremises.

	Solar Generation Off		**Solar Generation On**	
Phase	% THD Current	% THD Voltage	% THD Current	% THD Voltage
R	3.1	1.6	5.1	1.6
Y	2.8	1	4.7	1
B	2.9	1.4	4.8	1.3

Observations made in case of a LT consumer having Solar PV Plant of 35 kWp is given below:-

	Solar Generation Off		**Solar Generation On**	
Phase	% THD Current	% THD Voltage	% THD Current	% THD Voltage
R	6.1	1.6	17	1.8
Y	5.5	1.3	14.6	1.2
B	3.8	1.5	16.5	1.5

It is observed that harmonic currents are on higher side when solar generation is low and load in the premises is negligible.

Harmonics for LED lights:-

Another major concern for harmonic sources, is LED lights. There are LED lights in the market from various manufacturers. Harmonics was measured with LED lights from 3 different makes and the results are given below:-

RATED WATT	**5W**	**5W**	**8W**
VOLTAGE (%THD)	1.4	1.5	1.4
CURRENT (%THD)	17.3	13.3	14.8

Limits on Harmonics:-

As per the Central Electricity Authority (Technical Standards for Connectivity to the Grid Regulations):-

- THD for voltage at connection point shall not exceed 5% with no individual harmonic higher than 3%
- THD for current drawn at the connection point shall not exceed 8%

As per IEEE 519-2014, Voltage Harmonic Limits:-

Bus Voltage	Individual harmonics %	THD %
V ≤ 1.0kV	5	8
1kV < V ≤ 69 kV	3	5
69kV < V ≤ 161 kV	1.5	2.5
161kV < V	1	1.5

As per IEEE 519-2014, Current Harmonic Limits:-

For Voltages 120V to 69kV						
Isc/IL	3≤h<11	11≤h<17	17≤h<23	23≤h<35	35≤h<50	THD
<20	4	2	1.5	0.6	0.3	5
20 < 50	7	3.5	2.5	1	0.5	8
50 < 100	10	4.5	4	1.5	0.7	12
100 < 1000	12	5.5	5	2	1	15
> 1000	15	7	6	2.5	1.4	20
For Voltages 69kV to 161kV						
Isc/IL	3≤h<11	11≤h<17	17≤h<23	23≤h<35	35≤h<50	THD
<20	2	1	0.75	0.3	0.15	2.5
20 < 50	3.5	1.75	1.25	0.5	0.25	4
50 < 100	5	2.25	2	0.75	0.35	6
100 < 1000	6	2.75	2.5	1	0.5	7.5
> 1000	7.5	3.5	3	1.25	0.7	10

Status of regulatory measures in respect of harmonics:-

State	Harmonic Levy	Consumer category	Final view
HPERC Order Dt. 29.06.2005	Rs. 500 per kW	Large Industrial and Small&Medium Industrial Power	ATE view Dt 21.08.2006:- HPERC introduced suo moto. There is no guideline. CEA standards are still to come. There is no authority to levy harmonic injection penalty
MSEDCL petition	1% of energy bill for every rise in harmonic content above IEEE 519-1992	HT and LT industrial and commercial	MERC Order Dt 24.12.2012:- Introduction of penalty on harmonics is premature. Instead MSEDCL needs to analyse, create awareness
TNERC Order Dt. 30.03.2012	15% charge on respective tariff	HT & EHT consumers	Madras H.C.ERC Order Dt 05.06.2017:- 33kV or above consumers shall be covered for Harmonic Compensation No obligation for 22/11kV until CEA prescribes

General observation - Distribution licensees need to monitor harmonics at consumer metering point

Voltage Unbalance

Voltage unbalance is the measure of voltage differences between the phases of a three-phase system. Ratio of Maximum voltage deviation from the average phase voltage and average phase voltage is denoted as voltage unbalance. Voltage unbalance degrades the performance and shortens the life of three-phase motors.Unbalance current will flow in neutral conductors in three-phase wye systems and thereby increase in losses.

As per the Central Electricity Authority (Technical Standards for Connectivity to the Grid Regulations):-

- Voltage unbalance at 33kV and above shall not exceed 3%.

CESC network is small. So, impedance difference in phases may not have much effect. In CESC System, the loads at HT level are normally balanced. Unbalanced loads are observed at LT level. Often, network is reconfigured for load balancing. In CESC System, 100% DTRs are metered by Automated Meter Reading (AMR) system and readings are available online at remote. By studying DTR metered data, exercises are taken up for physical changes in network isolation, to make the network balanced.

Challenges:-

Major challenge towards addressing issues are:-

- Creating awareness amongst consumers about consequences of poor power quality and consumers about contribution towards power quality by the equipment / appliances being used by them.
- Measurement of power quality parameters – reactive power/power factor, harmonics
- Assessing impact of power quality on plant & equipment and/or appliances
- Assessment of losses in distribution network due to presence of harmonics
- Assessment of under / over registration of energy in standard energy meters
- Regulatory measures for mitigating power quality issues
- Recommendation of evaluation techniques (SAIFI, SAIDI, Harmonics)
- Cost benefit analysis in terms of pay-back period, Internal Rate of Return (IRR) towards investment for mitigating PQ issues - Applicable for Utilities as well as consumers

Way forward:-

Reactive power compensation is always desirable at load points. Thus, it is best suited when compensation is made by the consumers. As mentioned hereinabove, there is a strong commercial signal for HT consumers towards power factor improvement and consumers automatically choose for reactive compensation. Appropriate provision should be made for LT consumers as well. Utilities should also arrange for measurement. This will lead to win-win situation both for utilities and consumers.

Consumers should be made aware about the consequences of harmonics through various media. Utilities should provide suitable metering equipment for measuring harmonics. Thereafter, additional surchargesor rebate should be made for consumers dumping harmonics in the system. With appropriate commercial signals, consumers shall provide adequate harmonic suppression units to avoid dumping of harmonics into Licensee's distribution system.

Central Electricity Authority and appropriate Regulatory Commissions should take measures to include provisions relating to PQ issues including Harmonics in line with BIS, IEC or any other Standards of International repute (IEEE Standard) in Regulations (Standards of Performances of Licensees Relating to Consumer Services / Supply Code / Distribution Code etc.). Such provisions should be harmonious with applicable Regulations / Orders of the appropriate authority.

Conclusion:-

The availability of electric power with high quality is becoming crucial day by day. There would be huge losses due to PQ problems unless addressed properly. Duty of a distribution licensee is "*to develop and maintain an efficient, co-ordinated and economical distribution system in his area of supply*". CESC always endeavour its best to supply high-quality power to its consumers; there are concerns which would be improved by partnering consumers with appropriate regulatory guideline.

Implementation of Ancillary Services in Indian Power System - Benefits and Challenges

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Abstract: Central Electricity Regulatory Commission (CERC) introduced Ancillary Services Operations under the head Reserves Regulation Ancillary Services (RRAS) in Indian Power System. The paper discusses the introduction, implementation of Ancillary Services Operations in Indian Electricity Market. This paper also brings about the benefits harnessed from implementation in the form of frequency support, ramp and congestion management etc. The challenges and way forward in operation of Ancillary Services is also presented.

Keywords—Ancillary Services, RRAS, Indian Power System, Power Market.

I. INTRODUCTION

Ancillary Services is one of the four pillars required for mature and stable Power market [1] as shown in Fig 1. The definition of Ancillary Services pertinent to the Electricity Industry as given by Eric Hirst and Brendon Kirby [2] is quoted below:

“Ancillary services are those functions performed by the equipment and people that generate, control, transmit, and distribute electricity to support the basic services of generating capacity, energy supply, and power delivery.”

Ancillary Services are typically categorized into three types, namely, Frequency Support Ancillary Services (FSAS), Voltage or Reactive power support ancillary services (VCAS) and Black start support services (BSAS). FSAS are despatched to maintain grid frequency close to nominal frequency Viz 50Hz. VCAS are used to support voltage level at various nodes in the grid using reactors and capacitors. BSAS are used restore power system from blackouts.

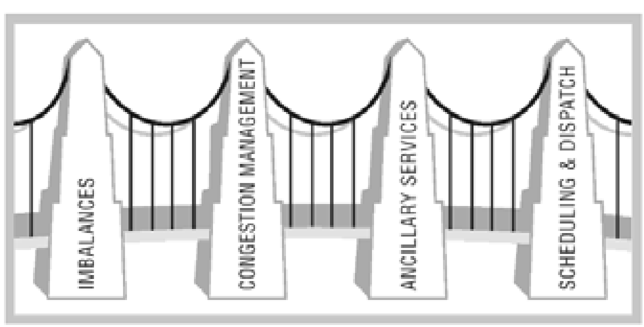


Fig 1: Ancillary as one of the 4 pillars of Market

II. EVOLUTION OF ANCILLARY SERVICES IN INDIA

CERC Indian Electricity Grid Code Regulations, 2010 (IEGC) define Ancillary Services as below:

"…*Regulation 2(1) (b)*

Ancillary Services" means in relation to power system (or grid) operation, the services necessary to support the power system (or grid) operation in maintaining power quality, reliability and security of the grid, eg. active power support for load following, reactive power support, black start etc.;…"

In March 2012, CERC Central Advisory Committee (CAC)[3] expressed the need for introduction of ancillary services in India for better security and reliability of grid operation. After due deliberation amongst the stakeholders CERC (Ancillary Services Operations) Regulations[4] were notified on 13th August, 2015 for providing FSAS under the head Reserves Regulation Ancillary Services (RRAS). CERC approved procedure for implementation of Ancillary Service Operations on 10th April, 2016 and the first RRAS were despatched on 12th April, 2016. There are 67 RRAS service providers aggregating to a total installed capacity of about 55 GW with a variable cost ranging from Rs. 1.05/kWh to Rs. 10.24/kWh[5].

III. MODUS OPERANDI

All the Generators, that are Regional Entities, and whose tariff for the full capacity is determined or adopted by the CERC have been mandated to provide Ancillary Services. NLDC, through RLDCs, has been designated as the Nodal Agency for Ancillary Services Operations. The Nodal Agency prepares the Merit Order Stack based on the variable cost of generation. A virtual regional entity called "Virtual Ancillary Entity (VAE)" has been created in the respective Regional Pool for scheduling and accounting. The quantum of RRAS instruction, by the Nodal Agency, is being directly incorporated in the schedule of RRAS providers.

During real time operations, the nodal agency kicks off Reserves Regulation Ancillary Services (RRAS) Up or Down from the RRAS providers on the following criteria [6].

(i) Extreme weather forecasts and/or special days such as festival / general holiday day etc.

(ii) Generating unit or transmission line outages.

(iii) Trend of load met.

(iv) Trends of frequency.

(v) Any abnormal event such as outage of hydro generating units due to silt, coal supply blockade etc.

(vi) Excessive loop flows leading to congestion.

(vii) Grid voltage in the important nodes downstream/upstream of the corridor is beyond the operating range.

(viii) Excess power flow in a corridor violating (n-1) criterion.

When additional generation is required to be added to the grid, the RRAS Up is triggered by dispatching the Un-requisitioned Surplus (URS) from the merit order stack (Lowest to highest) based on the variable cost to a Virtual Ancillary Entity (VAE). Similarly, when generation is required to be reduced in the Grid, the RRAS Down (highest to lowest variable charge) is triggered by reducing the Generation from the ISGS by notionally scheduling power from the Virtual Ancillary Entity (VAE) to the concerned ISGS, as shown in Fig 2.

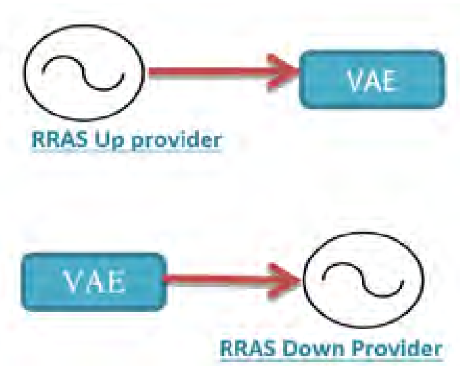


Fig 2: Modus operandi of RRAS to/from VAE

The services will start or stop with one time block notice effective from the earliest 15 minute time block. The original beneficiaries have the first right to recall the URS power during the period of RRAS Up service or surrender during the RRAS Down service. The Nodal Agency directs the respective RRAS Provider to withdraw RRAS when the circumstances leading to triggering of RRAS have been normalized.

IV. SETTLEMENT MECHANISM

The RRAS Energy Accounting is being done by the respective Regional Power Committee (RPC) on weekly basis along with DSM Account, based on interface meters data and schedule data provided by RLDCs. A separate RRAS statement is being issued by RPC along with Regional DSM Account as mandated in Ancillary Service Operation regulation as given below.

- In case of RRAS Up, fixed and variable charges are payable to the RRAS providers from the respective regional pool. Mark-up price of 50 paise/kWh as per present CERC order is also payable to the RRAS providers.
- In case of RRAS Down, 75 percent of the variable charges are payable by RRAS providers to the respective regional pool and fixed charges are reimbursed by RRAS providers to the original beneficiaries in proportion to the power surrendered.
- No commitment charges are payable to the RRAS providers. There are penalties for persistent failure to provide RRAS and violation of directions of Nodal Agency.
- Any post-facto revision in rates/charges by RRAS providers is not permitted.

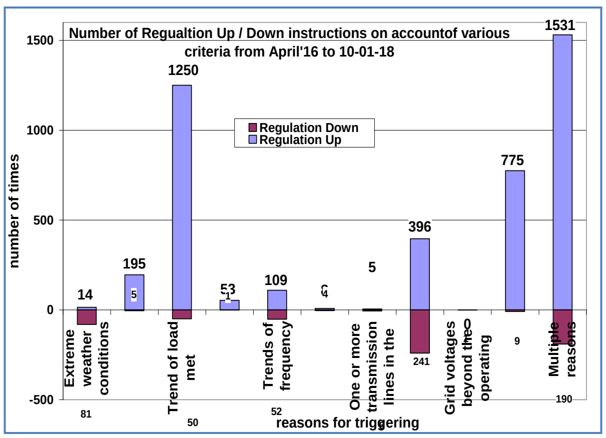
V. LEARNING EXPERIENCE

So far a maximum RRAS Up service of 3746MW and Down regulation of 1946MW was triggered. In terms energy, a maximum RRAS Up of 6Mu (0.2% of energy met) in a day and a Down regulation of 1Mu (0.03% of Energy met) in a day were triggered. From 12-04-16 to 10-

01-18, a total energy of 5347 Mu (~2% of total energy) costing Rs. 2473 Crores was dispatched under RRAS Up service. Similarly, 459Mu of energy at a cost of Rs. 98 crores was dispatched under RRAS Down service. A total no. of 4336 RRAS Up and 640 RRAS Down instructions were triggered on various criteria as shown Fig 3.

A. Improved Frequency Profile

After the implementation of RRAS, significant improvement in frequency profile and frequency is being maintained within the IEGC prescribed band (49.90-50.05 Hz) for about 80 % of the time. On 17 July, 2017, conditions of high demand in Northern region and low demand in Western region were prevailing implying a skewed scenario. Ancillary services were despatched to manage congestion and maintain flows on inter-regional corridors within the safe limits (Fig 4).



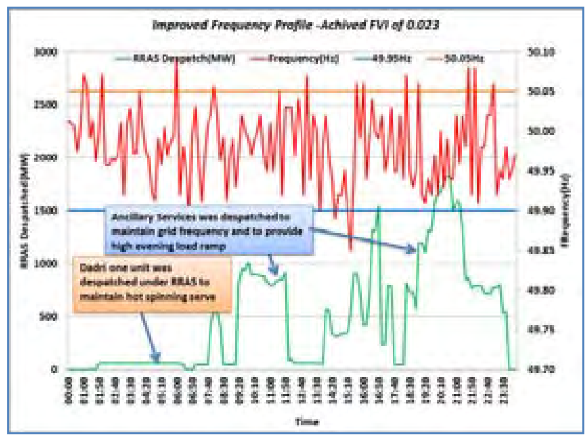


Fig 3: No of times RRAS was triggered

Fig 4: Case Study: Improved Frequency profile

Additional generation was also brought on bar in the Northern Region to manage congestion, maintain hot spinning reserve and facilitate ramping during the peak hours. Frequency remained 88.18 % of time within IEGC prescribed band on 17 July, 2017.

B. Ramp Management

Ancillary services have also helped in meeting the fast morning/evening load ramps, which can be up to 500-600 MW/min. On 07 June, 2017, RRAS Regulation Down of around 1000 MW was implemented due to low demand during early morning hours (Fig 5). Regulation Up of around 2300 MW was implemented during evening hours to meet the high peak ramp requirement.

C. Real Time Congestion Management

Ancillary services have helped in congestion management during outage of critical grid elements such as generating units, transmission lines etc. RRAS instructions are despatched by the system operators to control the loadings of critical inter-regional transmission corridors so as to minimize the impact of congestion on real time basis. On 01 May, 2017, HVDC Talcher –Kolar Pole-I tripped at 15:21 Hrs. Due to outage of this critical inter-regional HVDC transmission line, the net import Available Transmission Capacity (ATC) of Southern Region (SR) reduced from 7050 MW to 5050 MW (Fig 6). In order to manage the impact of congestion towards SR, all available Un-despatched surplus of SR RRAS providers was despatched through Ancillary Services till restoration of the HVDC transmission line. HVDC Talcher–Kolar Pole-I was restored at 13:17 hrs. on 02 May, 2017.

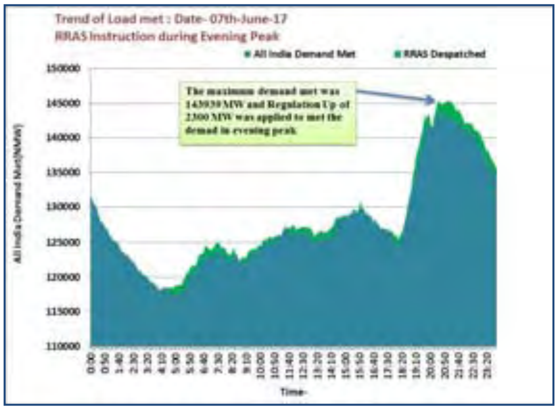


Fig 5: Case Study-Ramp Management

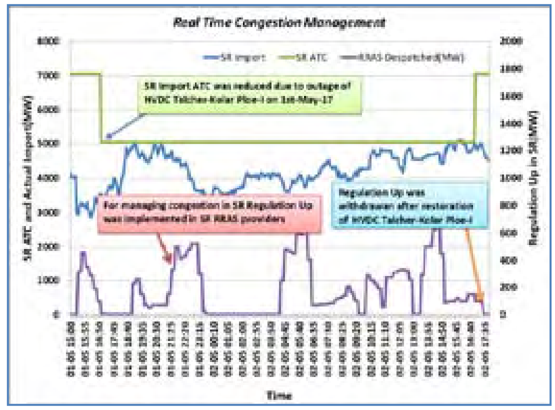


Fig 6: Case Study-Congestion Management

D. Extreme Weather Conditions

Ancillary services have helped the system operator in managing contingencies during low probability high impact events such as cyclones, earthquakes, storms, floods etc. On 07 June, 2017, there was load crash in Northern Region (NR) due to extreme weather conditions. RRAS Regulation Down was instructed to all RRAS providers in all the regions to maintain grid in a secure and reliable manner. The maximum RRAS Regulation Down instruction of 2200 MW was implemented during early morning hours (Fig 7).

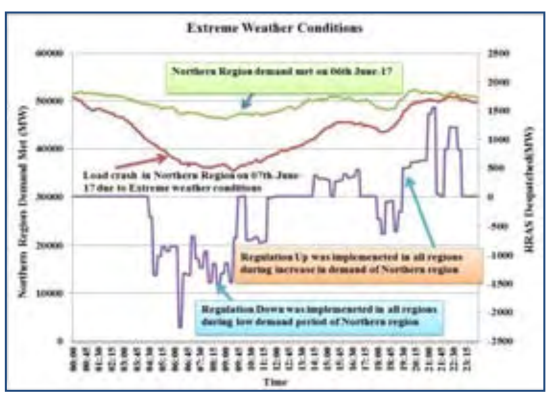


Fig 7: Case Study-Extreme Weather Conditions

The RRAS Regulation down instruction was withdrawn after normalization of Northern Region demand in the evening time and RRAS Regulation Up instruction was implemented to aid in the evening demand ramp. In the past too, when there was load crash in a particular region, the RRAS instructions in the other regions have rescued the affected region and helped it to maintain the vital grid parameters as close to normal as possible.

VI. IMPLEMENTATION DIFFICULTIES EXPERIENCED

a. Slow Ramp Down and Ramp Up rates of the Generating units:

As System Demand ramps sharply, it requires RRAS services at higher ramp rates, but the RRAS services have limited ramp rates due to inherent inertias in the Boiler, Turbine and Generator Sets. Thermal machines have inherently have slow Ramp Up compared to Hydel machines. While Ramp Up rates are relatively slower, the Ramp Down rates are higher in both categories. Typical ramp rates of various types of machines are shown in Fig 8.

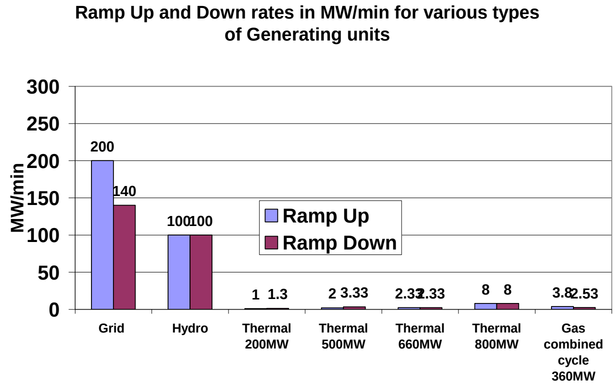


Fig 8: Typical ramp rates of machines vs Grid Requirement

b. Simultaneous schedules of RRAS and Recall / surrender by beneficiary :

Daily during load change over time, some of the beneficiary states shed chunk of loads leading to significant under-drawl and thereby rise in frequency. To address this problem states surrender their share from the Generating stations and simultaneously the Ancillary Down service also might be triggered suitably accommodating the station ramp rates. After the changeover is finished, loads rise steeply requiring restoration of the generation to the normal levels. While doing so, ramp up rates declared by the generator are to be honoured while increasing the requisition and reducing the RRAS Down service. Due to sharing of the ramp schedules among the Beneficiaries and RRAS, the duration is getting extended which is not the intended aim.

c. Short fall in funds for payment to RRAS service providers

Most of the times, energy scheduled in RRAS Up services would be more than that in Down service, due to which there would be a deficit. As per deviation regulations, drawee entities are charged at a higher penal rate for their over-drawls whereas the APM generating entities are compensated at lower rates. Including additional charges, there remains a surplus amount in the pool. Such surplus amount is utilized for settlement of the RRAS services. Sometimes, there are defaults in the payments of the deviation charges, due to which funds may not be available for paying the RRAS Up service providers. Sustainability based on DSM surplus on long run may be not be feasible solution

VII. FUTURE SCOPE:

In future, the IPPs and State Generators also can be brought under the ambit of RRAS mechanism. New ancillary products can be introduced for incentivising Hydro sources (for maximizing during the peak times) or Pumped storage plants (for energy arbitrage during lean and peak periods) or lift irrigation schemes for demand response. New services are on the anvil for ancillary services for Reactive support for voltage improvement and demonstrating preparedness for Black start capability for better disaster management. Some of the services may be made market based for better optimization.

VIII. CONCLUSION

Frequency Control RRAS service had proved quite a handy tool for the system operator for controlling various types of contingencies. New services for voltage improvement, peaking of Hydro, Pump Storage service, Black start etc. would further help to combat the emergencies in Grid operation.

References:

1) Making Competition Work in Electricity- Sally Hunt
2) Eric Hirst and Brendon Kirby– 'Electric Power Ancillary Services' – February 1996 http://web.ornl.gov/~webworks/cpr/rpt/84170.pdf
3) Central Advisory Committee (CAC) Minutes of Meeting http://cercind.gov.in/2012/Advisory_Committee/Minutes_ 14_03_2012.pdf
4) Central Electricity Regulatory Commission (Ancillary Services Operations) Regulations, 2015 http://cercind.gov.in/2015/regulation/Noti13.pdf
5) RRAS Providers Details published by NLDC https://posoco.in/reports/as3-details/
6) Detailed Procedure for Ancillary Service Operations approved by CERC.

Cyber Security Challenges to Smart Power Grid Infrastructures

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Synopsis

Indian Power System is presently having Power Generation of around 335 GW & the National Transmission Grid of EHVAC/UHVAC/HVDC is being managed by POSOCO through NLDC at National level & 5 Nos RLDCs at Regional levels to schedule & dispatch power efficiently to all states in a very transparent manner following all Regulatory guidelines/Grid Codes. Renewable Energy is now top priority of GoI as 100 GW of Grid connected Solar & 40 GW of Roof top Solar capacity is planned besides Wind generation plans & RE will contribute about 40% of total generation by 2030. RE integration into the Transmission & Distribution Grids will be a major challenge & will be met by deploying tools e.g. **Forecasting, Balancing mechanisms**, **Market Mechanisms**, Ancillary Services, **Flexible Transmission**, **Compliance to Standards & Grid Codes** , Fault Ride Through (FRT) and Low Voltage ride through capabilities. **Renewable Energy Management Centers (REMC)** are also being set up shortly. . At COP 21 in Paris, India made a commitment that 40% of electricity generation by 2030 will be from Renewables, which again translates into several hundred GWs of renewable energy capacity addition.

The traditional electricity networks designed for unidirectional flow of electricity, revenue and information will have a paradigm shift to bidirectional flow of these elements. Before the advent of Smart Grids, communication networks were used to monitor and control power flow using Supervisory Control and Data Acquisition (SCADA)/Energy Management Systems (EMS). Control & monitoring is now reaching upto the end consumer. Secure, reliable, scalable, interoperable and cost effective communication networks is required for Smart metering, SCADA, Substation and Distribution Automation, Wide Area Monitoring System (WAMS) etc. It is believed that the grid will soon emerge as a 'Grid of Things' just like the Internet has evolved as the 'Internet of Things'. Different applications in a Smart Grid would have different bandwidth, latency, reliability and scalability requirements. Nationwide Optical Fiber OPGW network on EHV Transmission lines is a unique communication backbone system to support all types of Smart Grid technologies with high speed & very low latency. Indian Power System has great potential for various automation technology trials in Smart Grid domain & Cyber Security has assumed high importance in view of the increasing threats to power Sector. Large RE capacity addition programs in years ahead will unfold interesting Power Sector scenario in India. As India is already an "Information Technology Leader", Smart Grid deployment in Power Sector has provided quantum jump to Information & Communication Technology (ICT) domain but Cyber Security vulnerabilities have posed bigger challange. This Paper discribes briefly the Cyber Threats, Vulnerability assessments, Solutions, need for Security Audits & following Cyber Security Standards.

1.0 Introduction

Indian Power Sector is expanding at very fast pace with large capacity additions in Generation, Transmission & Distribution in line with the GDP growth which is around 7.5 % in the current fiscal year. The installed Generation capacity is around 335 GW, largely Coal, Hydro, Gas with Renewable Energy component being around 17% only. Indian Power System has evolved gradually over last few decades but the real transformation started after the "Indian Electricity Act-2003"& this is clearly visible from the overall transformation in the Power Sector. After over a century of generating electricity centrally and building massive electric grids, the focus is now on de-centralised generation and Microgrids. This is causing the traditional boundaries between Generation, Transmission and Distribution to disappear. Consumers are becoming 'Prosumers' by generating electricity locally and having an option of feeding it back to the grid. The Government of India is keen to adopt Machine-to-Machine (M2M) communications and has recently released a M2M roadmap on May 12, 2015 to foster large scale deployment. India is a strong advocate of IPv6 and compliance to IPv6 is mandatory in today's scenario. In addition, the National Optical Fiber Network (NOFN) is envisaging to connect 250,000 gram panchayats (villages) on an Optical Fiber network for e-Governance, e-Learning, e-Health etc. Another innovative step by GoI decided to expand this effort to 600,000 villages under the "Digital India" program for providing universal broadband access to all. Electric Power Grid is a Critical infrastructure of the Nation which is man made miracle with large machines fulfilling diverse requirements of System Operation, Market Operation fulfilling Consumer needs.

2.0 Smart Grid in India;

Traditional electricity networks were designed for unidirectional flow of electricity, revenue and information. In a paradigm shift future networks enable bidirectional flow of these elements. Communication networks were used to monitor and control the power flow only up to the medium voltage and low voltage substations using Supervisory Control and Data Acquisition (SCADA)/Energy Management Systems (EMS). Smart grids will enable monitoring and controlling the power flow in the low voltage grid up to the end consumers using SCADA/Distribution Management Systems (DMS). Indian Smart Grids will have a holistic vision, quite different from SG Visions of many developed countries due to very specific requirements of Indian Power System.

Smart Grid is the most significant upgrade to Power Grid in the last 100 years which is flexible and transparent by the use of ICT. It has additonal new functionalities viz. Self-healing.Consumers motivation by Demand Response, accomodate all generation and storage options, enables Electricity Markets, Optimize asset allocation and operational efficiently. Smart Grid Projects in India are mainly targeting functionalities viz,Advanced Metering Infrastructure (AMI),Virtual Demand Response (DR),Street Light Automation, Outage Management System (OMS),Net-Metering by Renewable Integration, Power Quality Management, Smart Home, Micro Grid Controller & Electric Vehicle.

3.0 Need for Cyber Security:

Initially Power Systems organizations concentrated on Produce & Sell. Complexity in Operation led to the introduction of ICT (Information & Communication Technology) based Centralized Controls. With these systems, reliability and operational flexibility of Power Systems operation increased manifold. Efficiency and Monitoring ICT systems are slowly gaining ground in Utilities. Effective security measures are more important in a traditional SCADA system because of the added control capability and the importance of the SCADA function.

The SCADA/EMS systems were initially operated in closed group and isolated from corporate network and/or internet. In due course, Power Systems are adopting IT solutions to promote Corporate connectivity & remote access capabilities. Operational flexibility, Regulatory Directions and for commercial reasons, these systems are being connected with corporate network and/or internet. The Systems build on assumption of disconnect and obscurity are ill equipped from cyber security point of view e.g. virus, data theft, systems hijack, cyber attacks.

4.0: Consequences of Cyber Security failure:

It can cause Major/temporary loss of National property, Grid collapse causing all round economic loss, Disruption of essential services which may lead to loss of life and/or property. Important data can be stolen from the organization which could turn into major commercial losses & the credibility of product/company is affected.

5.0 Use of IT in Power Sector:

In **Generation** for DCS (Distributed Control Systems), PLC (Programmable Logic Controller), ABT (Availability Based Tariff) application. In **Transmission** for

SCADA/EMS ,SAS (Substation Automation System),WAMS (Wide Area Measurement System). In **Distribution** for SCADA/DMS, AMR/ AMI/ Billing and GIS, ABT (Availability Based Tariff) application. With automation in Power Sector ICT has entered all segments & Cyber threats vulnerability has increased many fold. Security incidents against SCADA worldwide are shown in **Figure-1**.

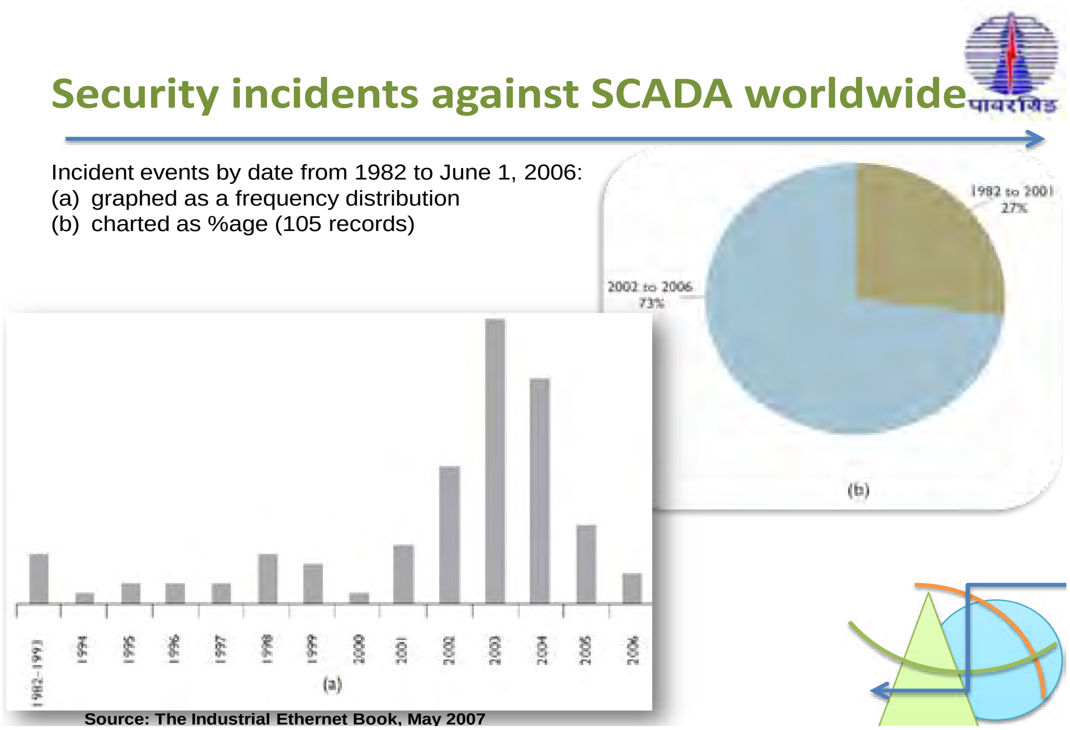

Figure-1

6.0 Cyber Security Challenges:

Increasingly integrated nature of Power System covering Generation, Transmission and Distribution makes them more vulnerable to large scale cyber attacks and hence damages. Renewable Energy and Distributed Generation integration into the Grid and control by Smart Grid Applications & moving to Open Standards such as Ethernet, TCP/IP, and Web Technologies are leading to improvements but increased vulnerabilities simultaneously.

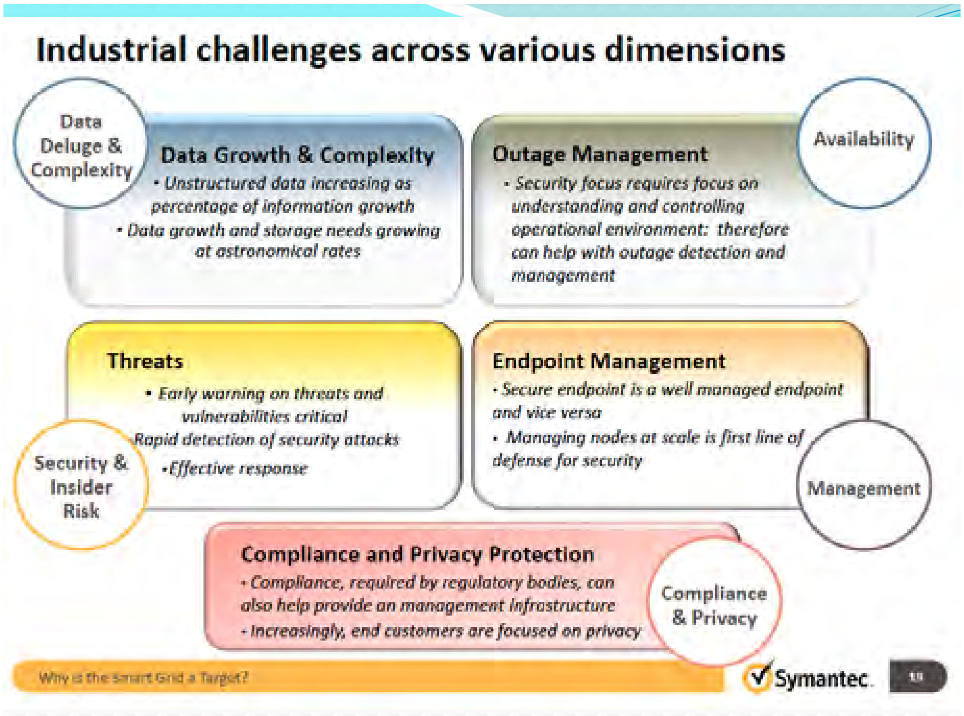

Figure-2

7.0 Objectives of Cyber Security:

Two main Objectives are 1) Securing the IT infrastructure for Secured Grid control leading to Reliable Power Infrastructure & 2) No single point of failure/attack should cause multiple/wider area power system getting compromised **(Figure-3)**

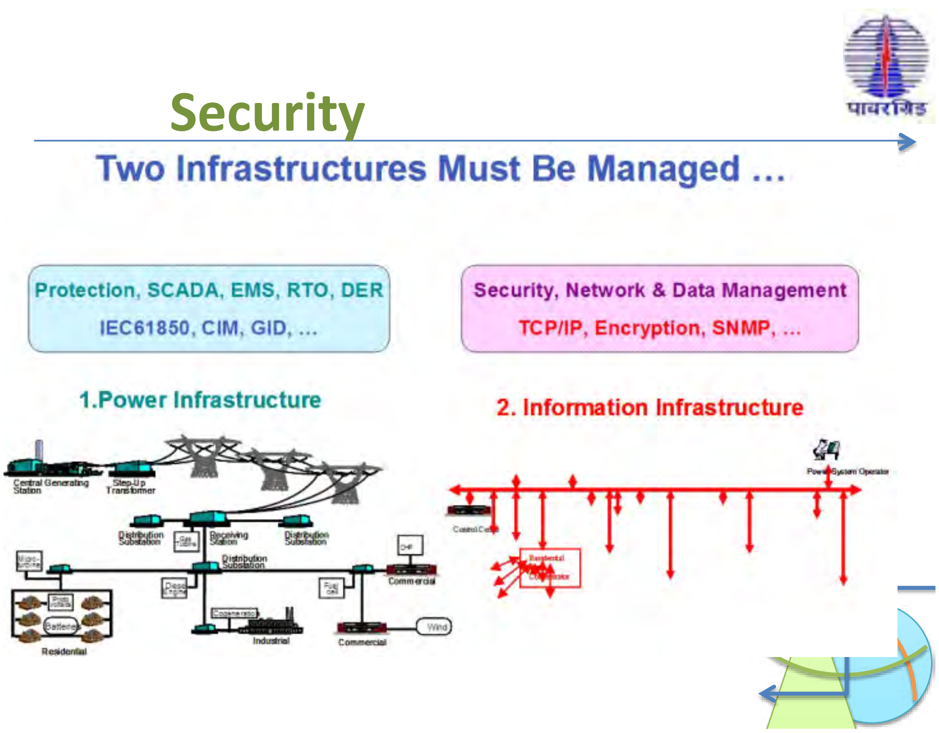

Figure-3

8.0 Cyber Security Tools & Methodology :

The Measures at Organization level are

1) Identifying the Critical Cyber Assets 2) Making vulnerability assessment in each area of operation 3) Creating a plan for implementation at the system level 4) Defining the user roles and access management authentication for each user 5) Creating awareness and training to all the personnel concerned with Cyber assets.6) Creating back up control and back data storage options.7) Creating incident response and disaster recovery plans in case of a cyber incident on SCADA networks.8) Cyber asset auditing on regular basis by reputed agencies and implementing the audit suggestions.Vendor development to comply with standards.

The Measures at the System level are:

1) Restricted Physical access to Utility Systems with continuous monitoring.
2) Implementing the Segmented Network architecture
3) Device configuration should be accurate, - Deny by default; White listing.
4) Hardware and OS hardening latest Standards.
5) Logging of all control command operations.
6) Restricted User access to servers and applications based on the functional responsibility.
7) Periodic Patch management and Passwords Change
8) Systems Personnel Training
9) Make people responsible for Cyber incidents.

9.0 Network Artitechture:

Network Architecture would have

1) Firewalls
2) Routers
3) Intrusion Detection Systems (IDS)
4) Intrusion Prevention Systems (IPS)
5) VPN / IPSec
6) DMZ

All the network architecture components have to be compliant with updated CERT-In Guidelines to enhance the Security Posture of the systems**. (Figure-4**)

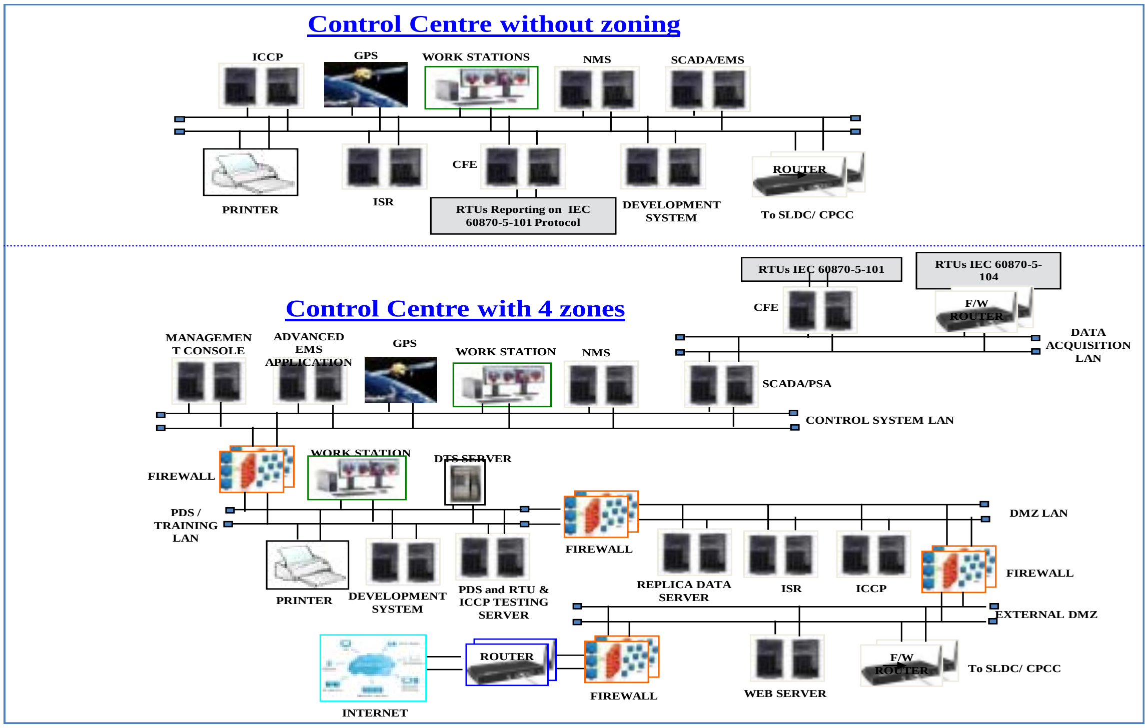

Figure-4

10.0. Sources of Cyber Security Threats : These can be Bot-network operators, Criminal Groups, Foreign intelligence services, Insiders, Phishers , Spammers, Spyware/malware authors, Terrorists, Industrial spies. **(Figure-5)**

11.0 What do Firewalls protect:

1) **Data**
   Proprietary corporate information
   Financial information
   Sensitive employee or customer data
2) **Resources**
   Computing resources

3) **Reputation**
   Loss of confidence in an organization
   Intruder uses an organization's network to attack other sites

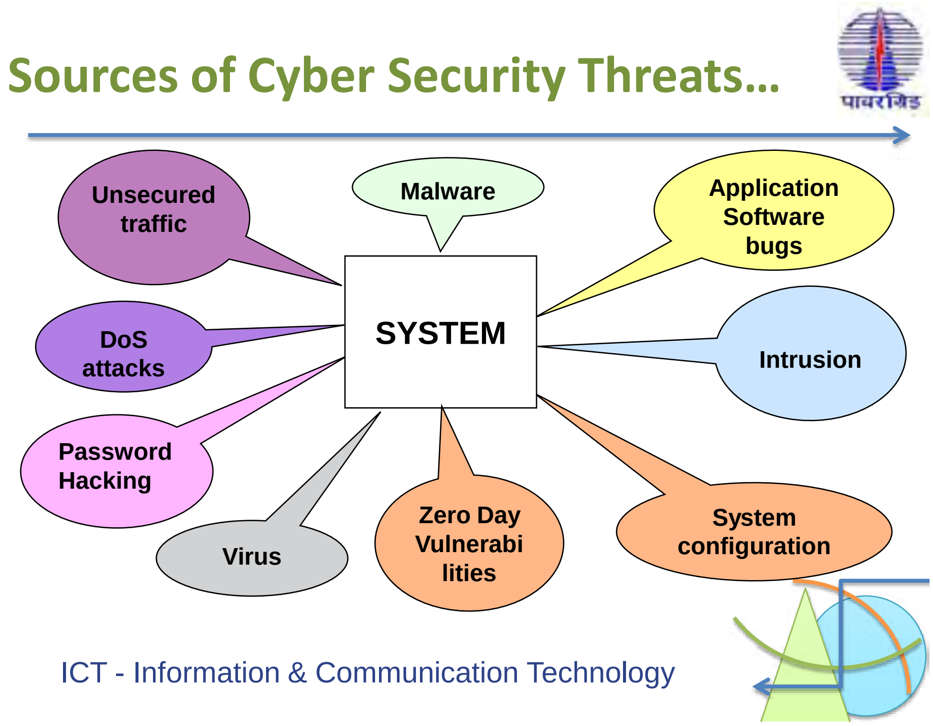

Figure-5

12.0 Network Management System:

- A network management system (NMS) is an application or set of applications that lets network administrators manage a network's independent components inside a bigger network management framework.
- NMS may be used to monitor both software and hardware components in a network. It usually records data from a network's remote points to carry out central reporting to a system administrator.
- The key benefit to NMS is that it permits users to monitor or manage their entire business operations using a central computer.

Network management system helps in:

- Network device monitoring - monitoring at the device level to determine the health of network components and the extent to which their performance matches capacity plans and intra-enterprise Service Level Agreements (SLAs).
- Network performance analysis - Tracking performance indicators such as bandwidth utilization, packet loss, latency, availability and uptime of routers, switches and other Simple Network Management Protocol (SNMP) -enabled devices.
- Intelligent notifications - configurable alerts that will respond to specific network scenarios by paging, emailing, calling or texting a network administrator.

13.0 Cyber Security Preparedness in Transmission Sector:

- All SCADA/EMS Systems have Identity management system
- Now a days all the SCADA/EMS systems implement Network Segmentation/DMZ.
- To check any vulnerability, practice of annual audit from CERT-In certified auditors introduced

14.0: Cyber Security:

The security level of a system indicates the severity of damage that might be done on penetration

- **What needs to be secured.**
  - IT and applications (SCADA Systems) controlling Power system.
  - Cyber connectivity of Operation Technology Solution
  - Communication Systems
- **How it can be secured**.
  - Firewalls, IPS, DMZ
  - Better monitoring and Deployment Practices
  - Continuous audit The attackers can be classified as:
  - Internal disgruntled employees-Can be handled by adopting Biometric access control, CCTV systems, Password authorizations etc.
  - Cyber-Hackers-They pose a more serious threat and can attack using the following mechanisms:
  - Targeted cyber attacks:
  - Sniffing packets at an ISP and manipulating the packets in network to achieve expected results
  - Flood based Cyber attacks:
  - Denial of Service (DOS) mechanisms and others that spread through viruses and worms- cause traffic avalanche in
  - short duration and hence bring down system
  - Communications hijacking (or man-in-the-middle):
  - False messages are sent to the operator, and could take
  - the form of a false negative or a false positive.

15.0 Cyber Security Vulnerabilities:

As per NIST guidelines, vulnerabilities can be classified as follows.

a) Policy & Procedural vulnerabilities
b) Platform Configuration vulnerabilities
c) Platform hardware vulnerabilities
d) Platform software vulnerabilities
e) Network configuration vulnerabilities
f) Network perimeter vulnerabilities
g) Communication vulnerabilities

16.0 Vulnerabilities specific to Transmissin: Involve 3 main components : Computers, Communication & Power System

Power Transmission System is Geographically spread across the country, any attack on the SCADA/EMS systems at the control centers can jeopardize the whole Grid.

A cyber Incidence at critical node substations can cause disruptions in the Integrated Operation of Grid.

17.0 Cyber Security Standards:

International standards on Cyber Security for Power Systems :

- Product and application level – IEC 62351- part 1 to 7
- Organization and Regulatory Level - NERC CIP-001 through 009 Requirements
- NIST Guide to Industrial Control Systems Security 800-82
- Guidelines from Center for Protection of National Infrastructure
- NIST Cyber security Framework

NIST GUIDE 800-82

This document provides guidance for securing industrial control systems, including SCADA systems and other systems performing control functions.

IEC STANDARDS

The scope of the IEC 62351 series is information security for power system control operations. The primary objective is to "Undertake the development of standards for security of the communication protocols defined by IEC TC 57, specifically the IEC 60870-5 series, the IEC 60870-6 series, the IEC 61850 series, the IEC 61970 series, and the IEC 61968 series. Undertake the development of standards and/or technical reports on end-to-end security issues.

18.0 Conclusion

Smart Grids have emerged as the necessary enabling infrastructure for several of GoI's new programs in the infrastructure sector such as: (i) 24x7 Power for All, (ii) 100 Smart Cities, (iii) 175 GW of renewable energy by 2022, (iv) National Mission on Electric Mobility with a target of 6-7 million electric vehicles; and (v) 35 million smart meters within the next 4 years. Under the initiative of 175 GW of Renewables, 100 GW is from solar and out of that 40 GW is expected to be from Rooftop PV systems spread over about 20 million roofs. 20 million buildings injecting electricity into the grid is going to make the grid drastically different and complex which will be a huge engineering challenge to manage. Similarly, millions of electric vehicles connected to the grid would require intelligent systems to manage the load on the grid as well as creating charging infrastructure will be a big challenge.The choice of operating frequency is vital for deciding the power consumption of the devices and range of the communications network. Having a long technology life-cycle, compliance to regulations and total cost of ownership are other key characteristics being considered by Power Utilities in India.

Power Grid Corporation of India have certainly made impressive progress towards Smart Grid implementation in EHV/UHV/HVDC Pan India Network by awarding world's largest WAMS Project using Synchrophasor Technology which is under execution now. POWERGRID is also supporting many Power Distribution Utilities across India in their Smart Grid Pilots.

Cyber Security is vital to all the Power Infrastructure from Generation to Consumer value chain as more IEDs are getting connected through various communication systems to automate the Smart Power Grid. We need to consider Cyber Security right from design stage & deliver totally Cyber secured network to the Indian Power Sector.

Bibliography

SG-Smart Grids, GoI-Government of India, MoP-Ministry of Power, EHVAC-Extra High Voltage Alternating Current, UHVAC-Ultra High Voltage Alternating Current, HVDC-High Voltage Direct Current, WAMS-Wide Area Monitoring/Management System, PMU-Phasor Measurement Unit, GW-Giga Watts, SCADA-Supervisory Control & Data Acquisition System, EMS-Energy Management System, DMS-Distribution Management System, AMI-Automated Metering System, DSM-Demand Side Management, PQ-Power Quality, CERC-Central Electricity Regulatory Commission, SERC-State Electricity Regulatory Commission, POWERGRID-Power Grid Corporation of India Limited, CTU- Central Transmission Utility

CIGRE- AORC Technical Meeting 2018 – International Conference on Global Energy Transition – Issues and Challenges, 24-25 May 2018, Gangtok, Sikkim, India

Benchmarking Reliability Indices in Power Distribuition

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The Tata Power Company Ltd

ABSTRACT

To achieve benchmarked reliability for any Distribution Network a systematic roadmap is required for adopting and implementing technological interventions for continuous learnings & improvements. Tata Power has always kept all the processes abreast of latest technological trends in the Power sector. Key aspects like Maintenance Practices, Automation, Network fault prevention using GIS/ GPS, Digitalization initiatives & Network Redundancy have been evolved in Tata Power over the period of time. This has helped Tata Power to achieve benchmark reliability indices as compared national & global Power Utilities.

INTRODUCTION

TATA Power, India's largest integrated power utility is in the business of Generation, Transmission and Distribution for the past 100 years. For more than a century, the Tata Power is serving to Mumbai city with stable, reliable and economical power, helping the city to achieve and retain its premium status as 'the commercial capital of India'. The challenging task of meeting the ever-growing power needs of Mumbai city has become possible because of efficient transmission and distribution of energy and continuous upgradation & adoption of technology by the organization.

Network spread of Tata Power Distribution across Mumbai license area is around 470 Sq Km with 920 number of Customer end Distribution Substation (CSS), 32 number of 33/11kV Grid Substations (DSS) and 4000 circuit Km of HT & LT network serving to 6.85 lakhs customers. Tata Power is serving esteemed consumers like, National Stock Exchange (NSE), Bhabha Atomic Research Centre (BARC), Mumbai International Airport Pvt. Ltd. (MIAL), Rashtriya Chemicals & Fertilizers (RCF), Hindustan Petroleum Corporation Limited (HPCL), Mahindra & Mahindra, Godrej Industries, Taj Hotel, SEEPZ etc. Mumbai metropolitan city has unique regulatory scenario where, three utilities (Tata Power, R-infra, BEST) operating in same license area with their own network & infrastructure. Spread of Tata Power Mumbai License area is depicted in map below (Fig-1)

RELIABLE POWER SUPPLY DISTRIBUTION

Geographical spread of Mumbai is longitudinal unlike other cities with highest customer density and vertical infrastructure growth due to acute space constraints.

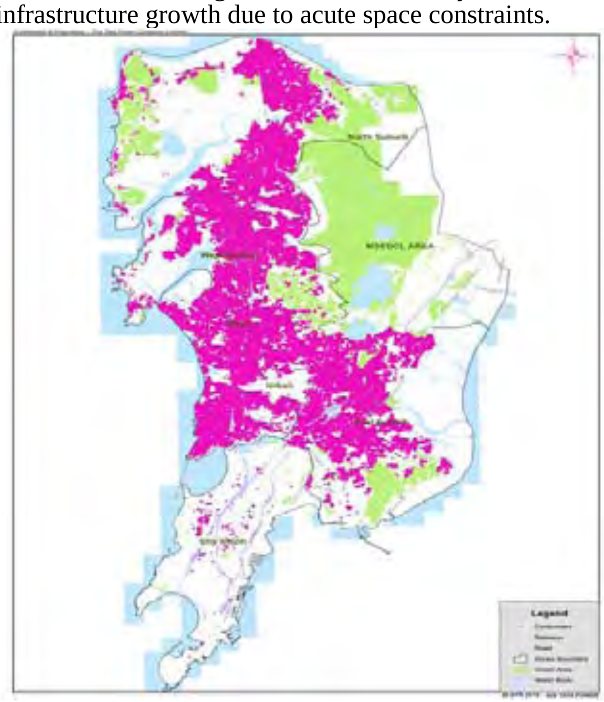


Fig -1: Tata Power - Mumbai Distribution License Area

It has resulted in narrow roads/ lanes having frequent traffic congestions in the area, restricting fast movement across the city. More than 28 utilities have also laid their infrastructure/ network alongside the narrow roads. Apart from these challenges number of new infrastructure developments are also happening across the city causing frequent damages to utility network. Being capital city of Maharashtra & commercial hub of India, it is live round the clock 24X7 and the expectation of consumers are very high for any service including uninterrupted power supply. Despite having above-mentioned challenges, Tata Power has achieved the benchmark reliability indices and highest System Availability in India. To achieve this benchmark reliability indices, number of continuous technological improvements and process improvements were meticulously followed by Tata Power, which are classified as below.

- Automation
- Maintenance Practices
- Network Fault Prevention using GIS/ GPS
- Digitalisation
- Network Redundancy

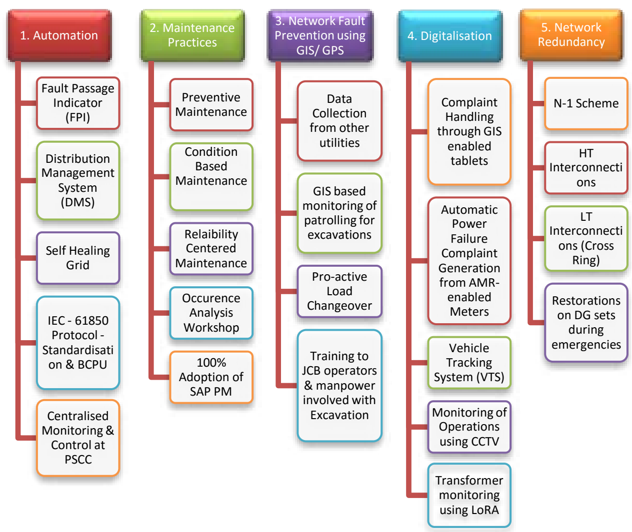


Fig-2: Technology & Process Impropvement Parameters

1. Automation

Quick restoration of power supply is one of the major expectation by customers and stakeholder where automation plays a key role in today's competitive world. This drives Tata Power to keep the system healthy and realiable with the help of automation. Tata Power has adopted different innovative technolgical advancements as explained below.

1.1. Fault Passage Indicators (FPIs)

FPIs are installed in all 920 Customer end Distribution Substations (CSS) in Mumbai Distribution area. They help in identifying the location of fault which inturn helps in quick isolation of fault and restoration of supply.

Verification & Checks of FPI Operations

Fault Passage Indicator (FPI) is a simple, but a very important component in quickly locating the faults in complicated distribution network. A correct operation of FPI is drastically reduce the fault restoration time and the physical efforts of Ppower System Controller and Fault Duty Engineers (Operations Engineers) to locate the faults. So this directly helps in increasing the reliability and maintaining the CAIDI.

Certain amount of expertise is required during commissioning of FPIs. A maloperation or a non-operation of FPI leads to wrong test charging, which in turn increases the stress on the electrical system, shutdown to more consumers and increases the CAIDI. Various wrong operations of FPIs in Tata Power were investigated and documented. Experiments were also carried out in HV Laboratory at Testing department for confirming the results. Based on these studies various recommendations, action points and guidelines were proposed for correction of existing FPI installations and commissioning of new FPIs. Various FPI features, inherent design errors, installation errors and their effects were studied thoroughly and corrections were made at site.

Fig -3 : FPI Checks

1.2. Distribuion Management System (DMS)

Tata Power is able to restore supply to its consumers (in the unlikely event of a power failure) in the shortest possible time. The system instantaneously determines fault location with a real-time geographical view and actual scenario of the affected area. This is a result of the various advanced functionalities of DMS like auto-fault identification, localisation, isolation and service restoration (FLISR), switch order management, feeder reconfiguration, state estimation and dynamic load flow, etc.

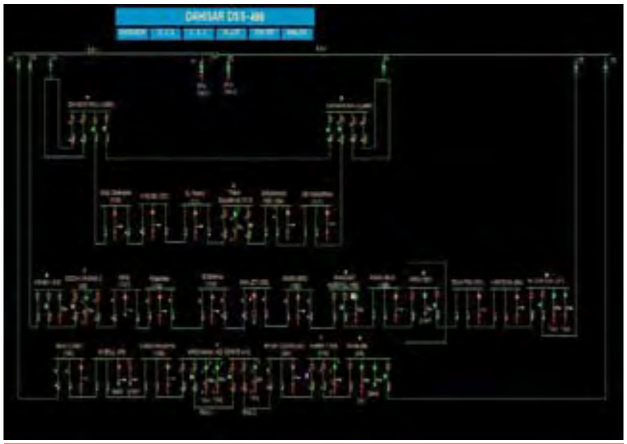


Fig-4 - Network on DMS

1.3. Self Healing Grid (SHG)

A Self Healing Grid is a grid where, in case of a fault, the faulty part of the grid will get automatically isolated and the healthy part stays energized or will be re-energized automatically. Customers will be affected for shortest duration which is in seconds.

The purpose of the Self-Healing Grid technology is to help & automate the process of restoration of power supply to keep interruptions (if any) to a bare minimum. Unlike the conventional centralised control approach, Self-Healing Grid (SHG) is a totally decentralised approach where, in case of any fault, every substation communicates with each other and executes the best possible sequence of operations for rapid fault isolation and restoration of supply in the network. In case of power interruption, the average restoration time with SHG is less than a minute, unlike the conventional restoration time which usually takes about 15 minutes. In addition, the Self-Healing Grid concept requires no manual intervention, thereby minimising all errors or delays in the restoration of supply to the consumers. SHG's less than a minute power restoration turnaround time is extremely useful in case of essential services like Hospitals, Banks, Shopping Malls, Data Centres and other emergency services.

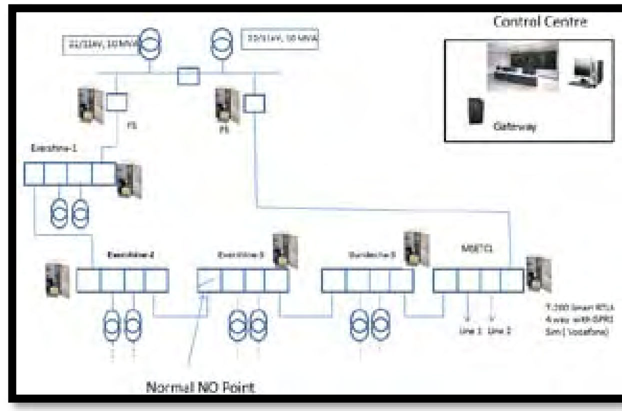


Fig-5 - Self Healing Grid

In case of Fault, SHG will isolate the faulty section and restore the supply. It will also update the new switch position in DMS.

1.4. IEC-61850 Protocol Standarsations & BCPU

Standarisation of IEC-61850 Protocol & BCPU was implemented to optimize the Services and O&M Cost by way of reduction in cables and hardware and also enabling fast peer to peer communication for interlocking applications in soft & faster restoration during faults. IEC-61850 Protocol is globally accepted standard protocol which helps in achieving standardization through systematic engineering using standard Logical Nodes/ Functions and improvement in inventory management. This also helped for reduction in OEM dependency due interoperability feature of IEC61850. Having BCPU implemented in the system, optimum space utilization was achieved due to elimination of hardwired panels.

1.5. Centralised Monitoring and Control

The entire distribution system is centrally monitored & controlled by Power System Control Centre located at Trombay. Real Time status of all Distribution Grid Sub-Stations (DSS) and automated Consumer Distribution Sub-Stations (CSS) is available for monitoring & performing operations. Tripping and Outages are centrally handled by the team at PSCC in coordination with the Operation Engineers suitable stationed at strategic locations (24x7) to ensure seamless operations across all zones.

Fig - 6: Centralized Operations at PSCC

Monitoring of abnormalities like tripping of feeders, alarms like low oil level, low SF_6 pressure, overload, etc are continously monitored by DMS system and alerted to the operators at PSCC who immediately coordinates with the zonal teams for quick action.

2. Maintenance Practices

Over a period of time and based on experience/ expertise, maintenance strategies changed from corrective maintenacne to preventive maintenance along with condition based maintenance. Considering maintenance cost optmization and predicting the failure of equipment, Tata Power is further being migrated to Relaibility Centered Maintenance where relaibility will be improved with minimum OPEX.

2.1 Preventive Maintenance

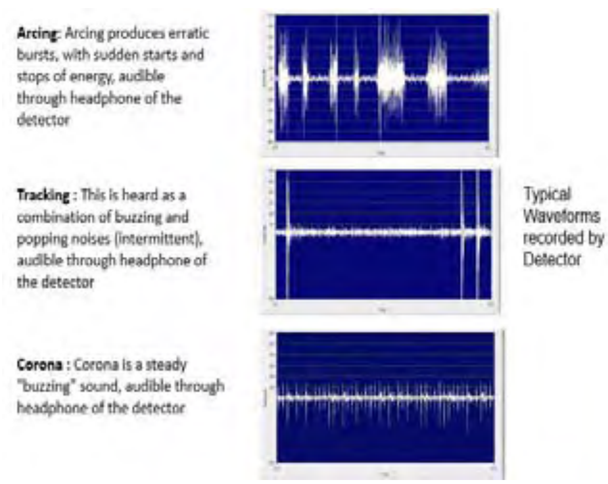
After commissioning of any substation, funcational locations and equipments are created in SAP PM and based on standard defined frequency for each equipment, maintenance plans and their measuring points are created. For the same maintenance plans, maintenance orders are genrated automatically in SAP every month. Once the preventive maintenance is carried out as per the plan, measuring points are uploaded from site itself using interface software i.e Liquid UI by using tab/ mobile. If any measuring points are exceeding its set limits,corrective maintenance notification is generated automatically and same is attended.

2.2 Condition Monitoring

2.2.1 Ultrasonic Detection of partial discharge

Ultrasonic Detectors are used to detect the chirping sound, hissing or humming sound inside equipment such as Transformer, RMU, cable compartment, breakers, etc. The Ultrasonic detection is carried out periodically for detecting the abnormality like moisture ingress, chirping sound caused by pit marks, ionization etc. & prevent the equipment from flashover.

- Used for following equipment:
  - a) HT /LT Switchgear & RMU
  - b) CT/PT Units
  - c) Transformers
- Ultrasonic detector used for detecting:
  - a) Arcing
  - b) Tracking
  - c) Corona



Problems identified and attended through ultrasonic detection				
Case Study	dB level	Waveform	Photograph	Remarks
22KV RMU Genext CSS no 2441	20db			**Problem:** Dark spot was observed where control cable was coming in close proximity of HT cable. **Action taken:** Control cable was re-routed

Fig - 7: Ultrasonic Detection

2.2.2 Thermovision Scanning:

It is used for detecting high temperature components of different equipments on monthly basis. Thermo vision scanning is carried out periodically for detecting hot spots at all substation equipments i.e. Cable terminations, LT panels, over head lines etc & necessary actions are taken where hot spots are detected.

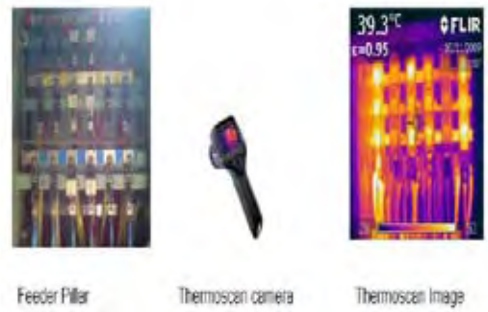


Fig - 8: Thermo-scanning

Purpose & objective of using thermo scanning

- Early detection of potential failures
- Visual identification of problems – Non Intrusive procedure
- Typical abnormalities that can be identified:
    - Loose connections
    - Overload
    - Load imbalance
    - Hotspots
- Applications:
    - Feeder Pillars, LT Panels
    - Cable Terminations
    - Overhead Lines
- Proactive measure – to identify, plan & repair faults instead of reacting to emergencies under pressure
- Reduction in force shutdown

2.2.3 Power Quality Monitoring

Power Quality Meters are installed at all 11 kV bus in Grid Substations to check the different parameters related quality of supply during normal and abnormal conditions. A power disturbance or event can involve voltage, current, or frequency.

- **Installations**
    - PQM meters are installed in DSS incomer bus
    - Portable PQM meters – installed on need basis at Customer Distribution Substation or near Consumers' meters
    - Online monitoring & retreival of PQM data from a centralized server
- **Voltage Fluctuations – Voltage Sags & Swells**
    - Voltage Fluctuations – Sags & Swells, voltage patterns are recorded in PQM Meters
    - Data is downloaded & Analysis is done – Events recorded in PQM are correlated with grid events
    - Response to consumers' complaints on voltage fluctuations
    - Guiding consumers for correcting settings in their equipments – to reduce sensitivity to voltage disturbances – to minimise downtime of their machines
    - Other Parameters – Power, Current, Harmonics, Power Factor
        - Analysis of Harmonics, Current, Power Consumption Pattern, Power Factor, etc

- Network Study & Augmentation to meet load demands

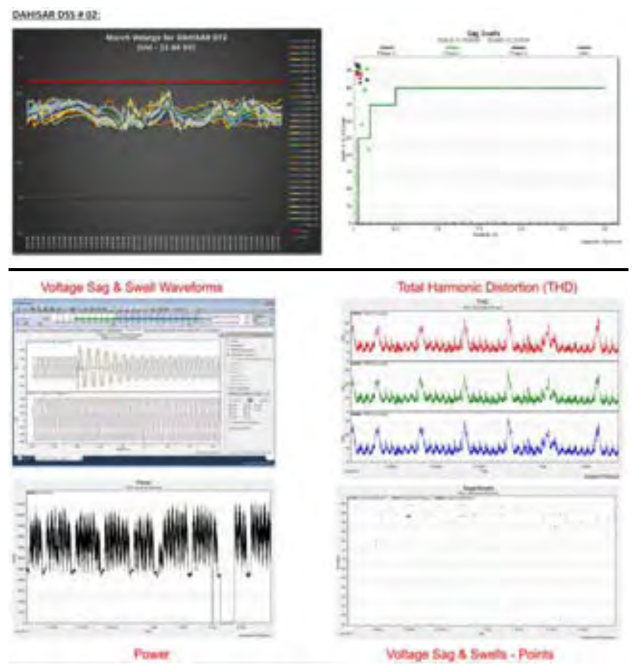
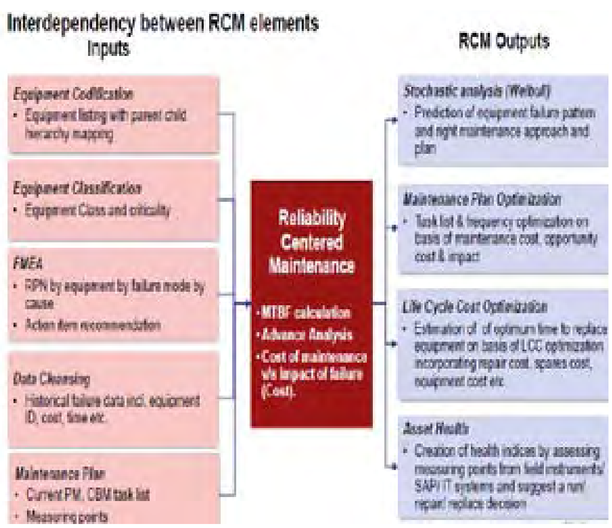


Fig - 9: Power Quality Monitoring

2.3 Reliability Centred Maintenance (RCM)

Reliability Centred Maintenance (RCM) at Tata Power has create an ingrained culture of O&M excellence through use of world-class practices. The program leads not only to tangible benefits in terms of enhanced operational and financial performance but would also instrumental in developing a forward looking & highly capable organization.

Fig - 10: Evolution in Maintenance Philosophy



2.4 Occurrence Analysis Workshops

Occurance analysis workshops are being organized on quarterly basis to share & brainstorm the different equipment related defects and their CAPA. Based on the findings, the maintenance task lists are reviewed and updated to avoid same type of failures. All zones along with support functions and top management executives are participating in the workshop to contribute their views and inputs. Such workshops foster knowledge sharing and analysis of issues from different angles leveraging the cross-functional expertise of the forum. The learnings of the workshop are implemented across other zones and functions.

2.5 100% Adoption of SAP PM

At Tata Power has adopted 100% SAP-PM module enabling a complete digital environment making data recording and retrieval very easy. The entire workflow of Preventive Maintenance is done in SAP -Annual Maintenance Schedule, Work Permits, Isolation List, Maintenance Checklists, Measuring Points of equipment like IR, PI values, OTI & WTI readings, notificattion closure, etc.This helps to analyze and track equipment healthiness index and complete history thus preventing future failures.

3. Network Fault Prevention using GIS & GPS

Tata Power firmly believe that the prevention is better than cure, and strictly strive towards patrolling of cables routes using Global Posisitioning System (GPS) superimpopsed in Network route map on GIS (Geographical Information System) to identify excavation sites near the netwrok so that external damages to network / cable faults are avoided and eventually providing the uninterrupted Power Supply to the city of Mumbai. Below are some key highlights of our cable patrolling activity.

3.1 Data Collection from other utilities & Proactive Load Changeover

Tata Power has deployed dedicated team for collecting excavation related data from other utilities so that preventive measures can be taken, like shifting or diverting the cable route & planning the actions to restore the power in case the cable is damaged.For critical cases we also divert the load toanother feeder even before the fault so that the shutdown can be avoided.

3.2 GIS based Patrolling

We have developed an Application for patrolling which is based on GIS & integrated with smart VTS .This inhouse developed system tracks the patrolling route & ensures 100% patrolling of cable routes. It also notifies the concerned team regarding unpatrolled routes for necessary actions. If any excavatio is observed by the patrolling team ,the data is enetred in the Application available in mobile devices, the data consists of excavation exact loaction, feeder section and other vital detail. Then the smart system notifies to the concerned team for necessary action such as load chageover, cable safeguarding, diversion etc.

3.3 Proactive Load Changeover

Based on dynamic condition of network due to faulty sections, load changeover is carried out considering current carrying capacity of cable sections. Normal Operating Points (NOP) are changed in system. Operating instructions are revised for emergecies scenarios.

3.4 Training to JCB operators & Field workers

While operating JCBs for excavation or in manual excavation the possibilty of damaging cables are very high due to lack of adequate knowledge and it is also a safety concern.This majour issue is minimized by providing essential trainings to the JCB operators and filed workers for taking preventive and cautious steps while excavating. By this we avoid the cable faults and breakdowns thus maintaining the expected high reliability index.

4. Digitalisation

Tata Power is in process of migration from Automated System to Digitalized System. Few key initiatives have been explained below.

4.1 Complaint Handling through GIS enabled tablets

To meet the need of quicker complaint handling Tata Power has developed a Mobile Application based on GIS named as maRC-mobile based system for Restoration and Care. This inhouse developed application is integared to VTS (Vehicle Tracking System), GIS, Consumer loaction, Substation location, HT and LT cable rotues, HT and LT equipments which not only enables a smoother way towards faster complaint handling but also with maximise the efficiency.

When a consumer logs a complaint via call centre, chatbot, SMS or social media the complaint along with consumer details consisting of customer location, network drawing and other vital details is highlighted on Field crew's tablet. This integarted system helps the team to navigate to the fault location on the possible fastest route, the interface also allows customer to provide the service feedback. This complaint data and service feedback is stored digitally and is analysed periodically for fine tuning.

Prior to implementation of this system, call centre used to manually call the field staff and pass the details of the complaint. Also the field technicians take time in searching the consumer's address to attend the complaint. They then close the complaint manually by filling up the feedback form and informing call centre. There has been a major transition from the conventional pen & paper method to a completely digital interface which has not only reduced use of paper but also reduced TAT (Turn Around Time) in resolution of complaints by avoiding phone call exchanges between call centre & field team for details, address, etc.

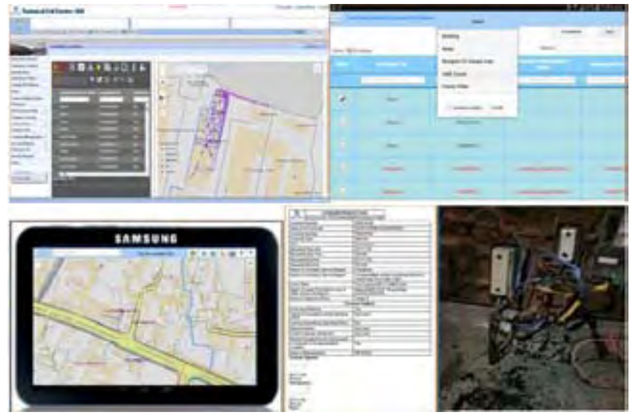


Fig - 12: Complaint handling using GIS on tablets

4.2 Automatic Power Failure Complaint Generation from AMR-enabled Meters

There is always a possibility of error and time delay where manual interventions are implemented. To overcome this and to serve the customers in better way Tata Power has implemented automatic complaint generation from AMR enabled meters. When power failure occurs the meter communicates with AMR server instantly for logging a power failure complaint even before consumer realising the power has gone. If there is a transformer tripping then also autogenerated complaint is raised and customer complaints can be linked with the trasnformer tripping. Thus we are able act much faster and with maximum efficiency.

4.3 Vehicle Tracking System (VTS)

Every vehicle assigned for complaint handling, attneding fault and patrolling are monitored with vehicle tracking system (VTS). This helps to direct the field crew to navigate the fault location much faster and in the same time it can be monitored the team's performance which eventually contributes to reliability indices and customer satisfaction.

Fig - 13: Vehicle Tracking System

4.4 Monitoring of Operations using CCTV

CCTV Cameras have been installed at strategic locations in operational of Distribution Grid Substations, which are unmanned. CCTV cameras installed in operational area are used by PSCC to check the operations and abnormal conditions during emergency events.

4.5 Transformer monitoring using LoRA

Distribution assets like Transformers, Breakers, RMUs, etc. are installed over a widely spread area and prone to malfunction/ premature failure, due to poor periodic monitoring. As on date, no cost effective solution exists that can report an oil leak from a Transformer, or temperature of a transformer rising beyond a safe operating point, on a real-time basis. One comes to know about such events only during the periodic maintenance visits. With the availability of the LoRA canopy across the city and long-life battery-operated Internet of Things (IoT) devices, real-time monitoring and exceptional reporting has become possible at an affordable cost. Battery-operated sensors (tags) that can measure temperature, oil levels are mounted in the Transformer oil pock e t and conservator tank respectively, to provide information on the oil temperature and level. The tags are pre-programmed to collect the temperature and oil level data and relay over the LoRA network, at a defined interval. The data sent over the air would be in an encrypted format and the application server at the service provider end would decrypt the same. The application server would port the data to the existing Distribution Management System (DMS). The DMS would display the values on the user interface and would also generate alarms and notify the O&M team in case of temperature/oil level crossing the threshold limit.

5. Network Redundancy

Distribution Systems in India typically have radial feeds - any fault in the a particular section affects the entire bunch of customers. Mumbai, being the financial capital enjoys ring -system where each Customer Distirbution Substation is fed from two sources. Tata Power has gone a step forward in ensuring that critical/long rings have more than two sources. Network schemes are regularly reviewed and if a ring has more than 7 Distribution Customer Sunstation, a third source is provided. Bigger rings may have 4 or more sources. Every Distribution Grid Substation has redundancy for transformers, bus sections and in case of an equipment failure, supply is restored within 5 minutes through automation system.

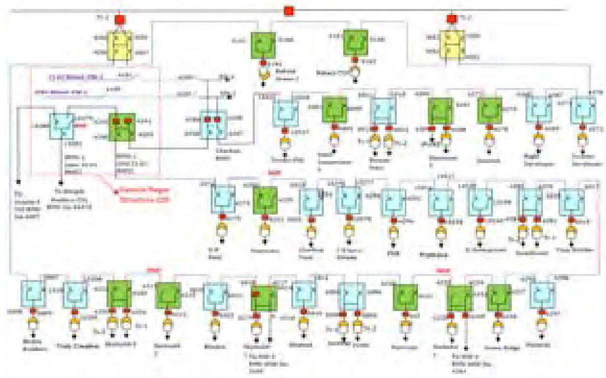


Fig - 14: HT Ring System

Furthermore, Tata Power also strive to ensure that every single transformer CSS are provided with an LT interconnection from another Distiribtuion Customer Substation. CSS with multiple transformers inherently have an LT interconnection between them. Wherever feasible, LT interconnections are provided between CSS of different rings to help in faster restoration during HT as well as LT faults.

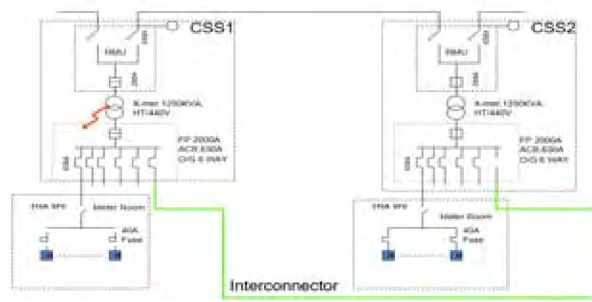


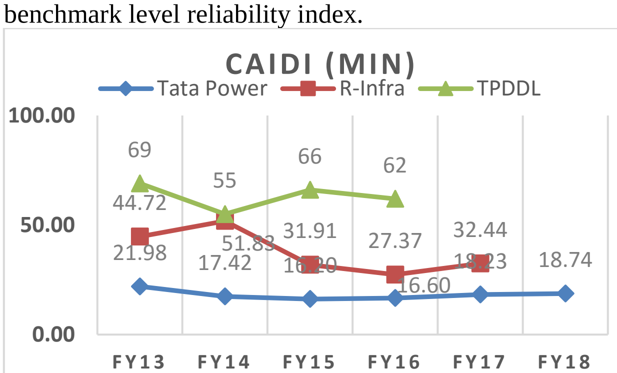
Fig - 15: LT Interconnection

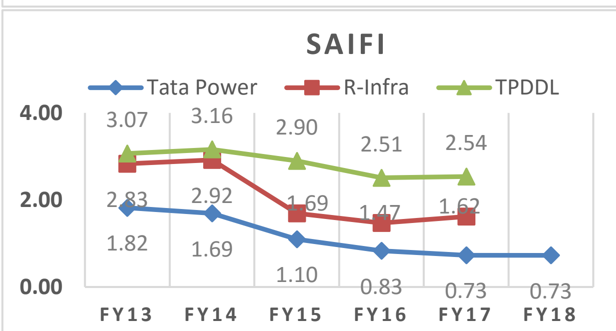
Tata Power has introduced 250 KVA x 4 Nos. mobile DG set vans to restore the power during emergencies i.e. multiple cable faults, flooding, equipment failure etc. This DG set vans are strategically located across Mumbai (i.e. Borivali, Andheri & Bandra) so that the same can reach to the destination within minimum possible time.

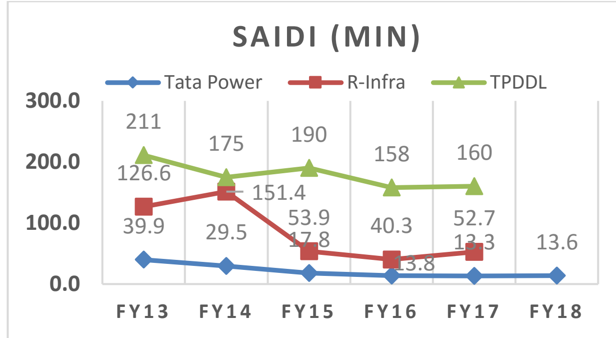
Fig -16 : Tata Power DG Sets for emergency supply

CONCLUSION

Tata Power has emphasized focus on adoption of new technologies and digitalization initiatives by optimizing the cost to achieve benchmark reliability indices. Instead of implementing 100% of Automation, strategic locations, like Interconnection points, first leg in ring, customers having critical equipment, etc., were selected for implementation of DMS to optimize the cost. This has Most of the digitalization initiatives are indigenous and developed with participation of field teams. This has fostered sense of ownership among the employees. Customers' feedback has played an important role in developing and improving the various processes like, complaint management, changes in network, implementation of Auto-changeover schemes, etc. This has been a journey of different challenges & moreover learnings for future. Tata Power has overcome every challenge and came out like a shining star in distribution reliability indices. Below is the trend of different reliability parameters which displays our harvest of adoption of new technology and practive measures for achieving benchmark level reliability index.







Parameters	CAIDI	SAIDI	SAIFI
Benchmark	12.6 St. Thomas Energy	13.2 St. Thomas Energy	0.44 St John Energy
Tata Power	18.74	13.6	0.73

Fig -17 : Reliability Indices Comparison

MISCELLANEOUS

Acknowledgments

This paper would not have been possible without the support & guidance of the Tata Power Team members who are working day in & day out on the field as well as back end.

REFERENCES

[1] CEA Benchmarking Data

[2] White paper on Distribution Network Planning for Urban Metros

[3] Decentralized control through Self-Healing Grids Paper

CIGRE- AORC Technical Meeting 2018 – International Conference on Global Energy Transition – Issues and Challenges, 24-25 May 2018, Gangtok, Sikkim, India

Ancillary Services for Bilateral Agreement of Cross Border Power Trade : Case Study in Thailand

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SUMMARY

Ancillary services are an important services which provides by the power generating sector to support transmission of the electricity from the generation to the customer. The term ancillary services is used to refer to a variety of operations beyond generation and transmission that are required to maintain grid stability and security.

Thailand has experience in cross border power trading for more than 20 years with Electricity Generating Authority of Thailand (EGAT), the state own enterprise of Thailand, responses for generation and transmission power in Thailand. In bilateral contract, EGAT as the single buyer responses for the management of the ancillary services.

The mechanism in the power purchase agreement between EGAT and neighboring countries for the ancillary services will be provided in this paper. The statistical data of operated project related to the number of failure according to each ancillary service and the discussion are provided herein as well.

The evaluation in this paper provides important information which benefits for any persons interested in the ancillary services in bilateral agreement and also investors who are interested in area of external power purchase for exporting to Thailand.

KEYWORDS

"Electricity Cross Border Trade", "Secure and Efficient of Energy", "Ancillary Service", "Power Purchase Agreement", "Foreign Independent Power Producer"

1. INTRODUCTION

Thailand has experience in cross border power trading for more than 20 years. Electricity Generating Authority of Thailand (EGAT), the state own enterprise of Thailand, responses for generation and transmission power in Thailand as the single buyer. The power trading between Thailand and neighboring countries both in the form of independent power producer and government-to-government are under the responsible of EGAT too. With total capacity of foreign independent power projects that is 3,878 MW and by being located in the center of ASEAN, Thailand becomes one of the most potential and experienced country in trading electricity with neighboring countries among ASEAN members.

Thailand started the cooperation to trade electricity with its neighboring country in 1997. Over two decades later, Thailand has 9 projects of independent power producer which trading in the form of the bilateral contract called power purchase agreement (PPA). Five projects are already in commercial operation period: Houy Ho, Nam Thuen 2, Thuen Hinboun ,Nam Ngum 2 and Hongsa. Four projects are under construction period: Xe-pian Xe-namnoy, Xayaburi , Nam Ngiep 1 and Nam Thuen 1. The locations and details of each project are shown in Figure 1.

Projects	Capacity (MW)	Operation Date
Project in Commercial Operation Period		
Houy Ho (Hydro)	126	1999
Nam thuen 2 (Hydro)	948	2010
Thuen Hinboun (Hydro)	440	2012
Nam Ngum 2 (Hydro)	596.6	2013
Hongsa (Thermal)	1473	2016
Project Under Construction Period		
Xe-Pian Xe-Namnoy (Hydro)	354	2019
Xayaburi (Hydro)	1220	2019
Nam Ngiep 1 (Hydro)	269	2019
Nam Thuen 1 (Hydro)	514.5	2022

Figure 1 : total contracted capacity from foreign independent power producer (FIPPs)

2. Ancillary Services for bilateral contract in cross border trading

Ancillary services are the special services or function which provides by the power generating sector to support transmission of the electricity from the generation to the customer. The term ancillary services is used to refer to a variety of operations beyond generation and transmission that are required to maintain grid stability and security.

Since EGAT is the single buyer, the form of trading are mostly in the bilateral form. The power trading along with the ancillary services are in the different form as in other countries trading in the platform of power market. In power market, the ancillary services are provided by biding system and performed by the independent system operator while in Thailand the ancillary services are trading in long term agreement and including in the electricity tariff. The ancillary services of Thailand are similar to pre-paid system. The details for the ancillary services in PPA are as follows:

2.1 Ancillary services stated in PPA

PPA states rights and obligations of EGAT and the generator as the buyer and the seller respectively. In satisfying its obligation to provide power and electrical energy to EGAT system, the generator shall make the declaration and availability and the ancillary services (called contracted operating characteristics : COCs) at contractual value or within the contractual range. EGAT has the rights to dispatch the facility for such contracted operating characteristics at any time.

The contracted operating characteristics stated in PPA which is the obligations of the generator to provide to EGAT are as follows :

- Reactive Power:

  The voltage stability is one of the major criteria for preserving system security. The reactive power is very essential for maintaining the voltage profile in transmission line. The voltage can be controlled by injecting or absorbing the reactive power to the system.

- Loading Rate/Deloading Rate:

  Since the demand in power in each period of time is varied sue to many factors such as temperature, timing and season etc., the power generated as the supply side has to adjust to match with such demand. The power plant should be able to increase or decrease load following the instruction of EGAT. Such incresing and decreasing of generating level is called loading rate and deloading rate respectively.

- Primary response :

  Primary response is the change of power output which the generator has to provide to EGAT system during the first 60 seconds of a frequency excursion. The governor droop of the generator shall be set between four percents to ten percents depend on EGAT system requirement.Generator has to start its primary response when frequency excursion is more than 0.05 Hertz from nominal frequency (50 Hertz).

- Automatic Generation Control Performance (AGC Performance)

  The generator has to operated complying to the command of automatic generation control (AGC) sent from national control center.

2.2 Type of Ancillary Services

Ancillary services are developed for maintaining the secure operation of power system. Ancillary services can be classified in six main categories following the Federal Energy Regulatory (FERC). While in PPA stated the ancillary services only in 3 categories with comparison details as provided in the following table.

The Ancillary Services Classification by FERC	**The Ancillary Services in PPA**
1. Reactive power and voltage control	Reactive Power
2. Loss compensation	-
3. Scheduling and dispatch	Active power
4. Load following	Primary response Loading rate Delaoding rate
5. System protection	-
6. Energy balance	-

Table 1 The ancillary services in PPA compares to the classification by FERC

PPA states the ancillary services to follow in 3 types: the reactive and power control, scheduling and dispatch and load following.

For the loss compensation, the concept of the virtual border for cross border trade is used. Both party has to set the border that will divided the responsibility of each party for loss occurred. So the loss compensation is already included in the generator’s obligation until the electricity reaches the delivery point to EGAT system.

For system protection defined as “operating reserves or other system protection facilities available in order to maintain the integrity of its transmission facilities [caused by] unscheduled [transmission or generation] outages.”. For the operating reserves, EGAT has the obligation to maintain the reserve of the country in the satisfaction level. For the system protection facility, the generator has obligations in PPA to install the protection facility following the standard of EGAT to protect the system when outage occurs.

For energy balance, normally the generator has to follow the instruction of EGAT. But if energy imbalance occurred more than the allowance, the generator has to pay for the fine as stated in the PPA.

2.3 Principle of the ancillary services in PPA

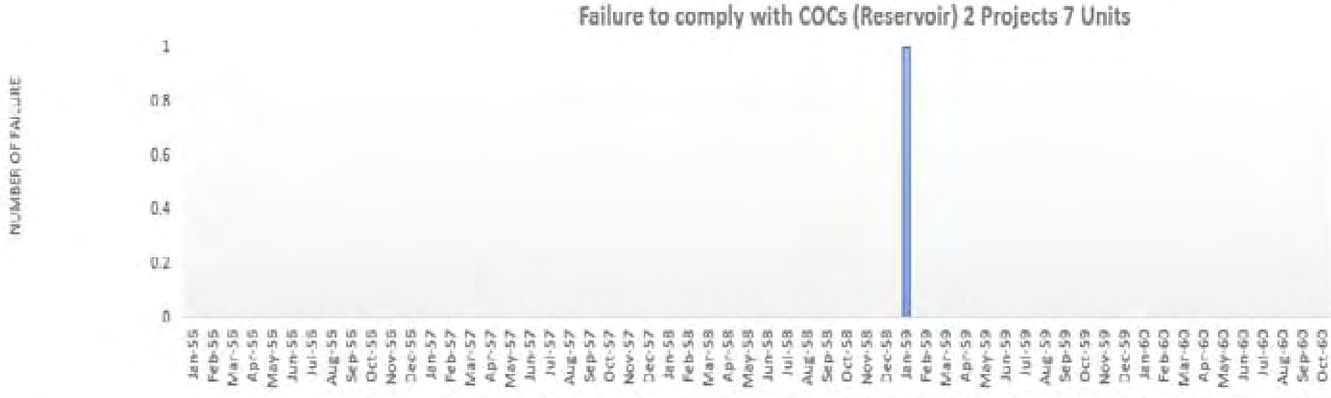
The power plant generates power to the system of Thailand producing by the independence power producers can be classified into 2 categories: domestic independence power project and foreign independence power project. Both are in the form of bilateral contract between the generator and EGAT. The easiest way to procure the ancillary service is to include the ancillary services together with the power generated. The principle for both type of power plant is that the overall power plant should transmitted both electrical and ancillary services to the system in the electricity tariff as agreed prior in the contract. The generator has the obligation to provide the electricity and the ancillary services according to the capability of the power plant. Generator has to provide as follows:

1. ability to provide service
2. readiness to provide service when necessary and
3. actual provision of the service when needed

EGAT has rights to ask for the electricity and ancillary services any time the system needed but not more than capability of the power plant. In the case that generator cannot provide electricity or ancillary service as stated, the generator has to pay for liquidated damages for such portion.

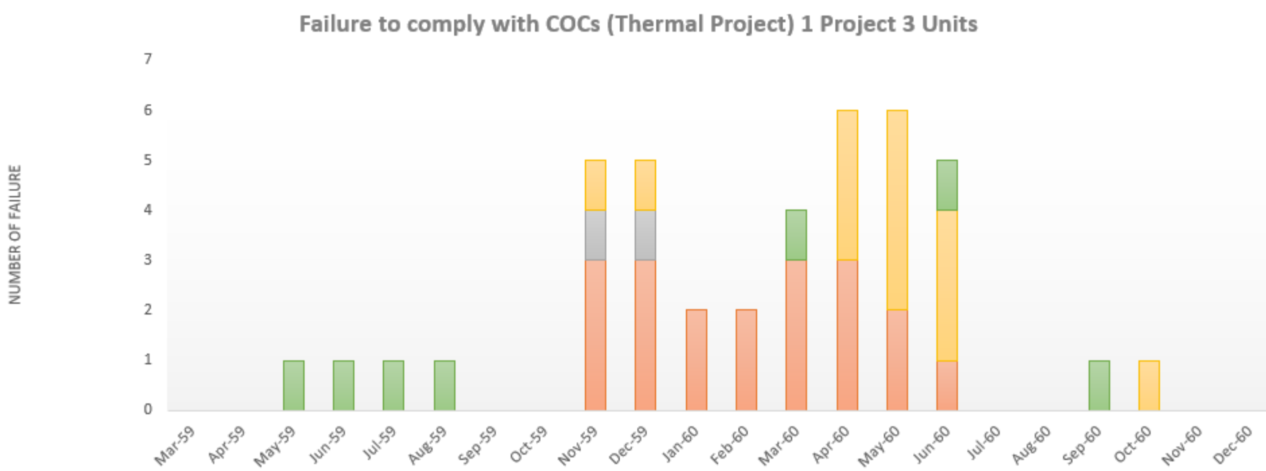
3. Evaluation of Ancillary Services Provided During 5 Years

We collect the statistical data from the commercial operation projects for the period of 5 years which has the ancillary services provided to EGAT systems according to the PPA. The graph of number of failure per month are as shown in figure 2 and 3.



	Jan-56	Apr-56	Jul-56	Oct-56	Jan-57	Apr-57	Jul-57	Oct-57	Jan-58	Apr-58	Jul-58	Oct-58	Jan-59	Apr-59	Jul-59	Oct-59	Jan-60	Apr-60	Jul-60	Oct-60
AGC Performance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Primary response	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Deloading rate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Loading Rate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Reactive power	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Minimum Generation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 2 Graph Shown Number of Failure for each COC in Reservoir Project



	Mar-59	Apr-59	May-59	Jun-59	Jul-59	Aug-59	Sep-59	Oct-59	Nov-59	Dec-59	Jan-60	Feb-60	Mar-60	Apr-60	May-60	Jun-60	Jul-60	Aug-60	Sep-60	Oct-60	Nov-60	Dec-60
AGC Performance	0	0	1	1	1	1	0	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0
Primary response	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Deloading rate	0	0	0	0	0	0	0	0	1	1	0	0	0	3	4	3	0	0	0	1	0	0
Loading Rate	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Reactive power	0	0	0	0	0	0	0	0	3	3	2	2	3	3	2	1	0	0	0	0	0	0
Minimum Generation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3 Graph Shown Number of Failure for each COC in Thermal Project

As shown in the figure 2 and 3, the PPA stated the COCs to be followed for reactive power, loading rate, deloading rate, primary response and AGC performance. The data of number of failure of each COC for each month is stated. The project tends to have no failure in performance to provide the ancillary services to EGAT system.

For Hongsa project which is operated in March 2016, the failure rate is rather high comparing with the other reservoir projects which operates long before. One of the main problem is that when the project started the operation at first, there may be something for the generating units that have to adjust. The other point may come from the quality of the generating unit itself.

5. Discussion

The ancillary services are important to support transmission power from the generator to customers while maintaining the reliable operation in control area. Failure to maintain a balance will cause a frequency deviation. Electrical failure or quality drop will occur creating damages to system and equipment along with customer satisfaction.

EGAT as a single buyer manage the ancillary services through PPA between EGAT and the generator. The concept of pre-paid for the ancillary service and deduct when the generator cannot provide such services seems to be a simple but efficiency. Since the trading of the ancillary services is in long term agreement with the cost included in the electricity tariff and from the failure statistical data as shown above. But in the country trading in the power market, the ancillary must be provided in the different form and controlled by the independent system operator. Moreover, the integration of intermittent generation and the development of smart grid technologies have prompted a shift in the equipment that can be used to provide ancillary services in the future too.

BIBLIOGRAPHY

[1] Ancillary Service in Indian Power System, Indu Maheshwari

[2] PDP 2015, http://www.eppo.go.th

[3] LECTRIC-POWER ANCILLARY SERVICES, ERIC HIRST and BRENDAN KIRBY, February 1996

CIGRE- AORC Technical Meeting 2018 – International Conference on Global Energy Transition – Issues and Challenges, 24-25 May 2018, Gangtok, Sikkim, India

Deployment of Various Smart Grid Technologies at Tata Power Mumbai Distribution

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Tata Power Company Ltd.

ABSTRACT

Smart grid is an emerging concept which works as an enabling engine for our economy, our environment and our future. Power Distribution Utilities play a pivotal role in developing the electrical network of a city and development of the smart grid. This paper elaborates on the Technological Interventions done by Tata Power to promote the concept of smart networks.

INTRODUCTION

According to United Nations India is all set to become the world's most populous country by 2022, overtaking China. With increasing urbanization, urban areas are expected to house 40% of India's population by 2030. In order to accommodate this massive urbanization India needs to find smarter and more efficient ways to manage its resources. Electricity being one of the most important and essential commodity, handling it smartly becomes even more necessary.

Tata Power Company is India`s largest Integrated Power Utility which has been working towards development of smart networks through various initiatives in the Indian metro cities of Delhi and Mumbai.

Incorporation of the smart grid technology in the smart cities project will offer a unique opportunity to jump into an improved electricity environment and provide reliable 24*7 electricity to consumers. Through smart grids it will be possible to integrate the coal and crude oil generated electricity with the solar and wind. This will reduce fossil fuel use and encourage price drops in renewable technology. Further, current smart grids are also building the technology to integrate consumer owned energy systems which will benefit customer further- they will not have to pay for the electricity generated by themselves. Smart grids can also monitor loading thus avoiding load shedding and blackouts.

Implementation of smart grid has many advantages like combating space constraints, load management, etc. Smart Infrastructure is another important aspect of the Smart cities project. Intelligent power networks with the implementation of specialized IT solutions are going to be essential. Tata Power not only contributes to the infrastructural advancement but also innovates new technology so as to enrich customer contentment and manage assets effectively.

SMART GRID TECHNOLOGIES AT TATA POWER MUMBAI DISTRIBUTION

Tata Power Distribution has introduced/developed various innovative technologies and engineered solutions for Safe, Compact and eco-friendly Installations in Mumbai. Each of these are explained to bring forth the same and it can be replicated by utilities for improving the distribution infrastructure which would enable better management.

1) Use of RF ID for Enhanced Safety and Effective Underground Asset Management:

It has been a practice to place concrete markers in the ground immediately above the underground cables for cautioning the existence of HV cable below. These concrete markers are quite heavy, require periodical maintenance with respect to painting as well as removal of grass and soil erosion is also to be taken care of. They can easily be dislodged by earthmoving equipment, which can erase any trace of the existence of the underground cable in the vicinity. These markers used to provide a means for guiding the maintenance crew to the location of the cable below the ground.

Mapping of the Underground assets has become a challenge given the fact that the fast changing topography on account of developmental activities is going to render the existing references obsolete .Though these assets are mapped in the Geographical Information System (GIS) database the accuracy of the same takes a beating. It was imperative that a better methodology be developed for marking and locating underground cable routes.
Buried electronic markers (RF IDs) were found to be a viable option as they are safe from being dislodged, require no maintenance and can give very accurate location. The electronic markers contain a passive antenna that reflects the probing signal back to the locator above the ground surface and effecting the location of the buried marker to be pinpointed accurately. These markers are very sturdy and require no external power source, have almost indefinite life unless disturbed and give an accurate

location. The markers are pre-programmed with unique identity, Tata Power details and are installed adjacent to specific locations or along the length of the cable by using nylon ties and passing them through the grooves provided on body of the marker and the cable there by fastening the marker to the underground cable.

RF ID Marker installed adjacent to a splice

RF ID Marker being located on road widening Project

Fig 1- Use of RFID

The next logical extension to the underground markers was the incorporation of GPS coordinates for the marker locations. A mobile mapper interface to the marker locator can precisely map the coordinates of the marker locations. The integrated system is depicted below:

Fig 2- Integrated System of RFID

Benefits of using RF ID markers:

1) Accurate location of underground cable routes immune to the changes of the geographical land base.

2) Accurate location of underground cable splices immune to the changes of the geographical land base. The information with respect to the make of splice, date of installation, depth of the splice with a unique identification is also be available with the location.

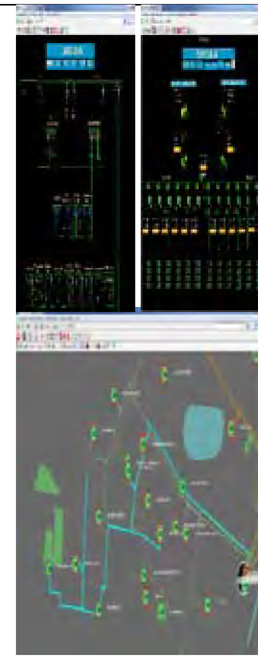
3) Synergies with the already mapped underground assets on the Geographical Information System (GIS).

4) Offline location of the underground facilities accurately with the stored in information.

2) Geographical Information System

All the network assets both Overhead and Underground are mapped in the Geographical Information System right up to the consumer on the backdrop of land base

Network Assets Mapped in GIS



Electrical and Geographical view of the network in DMS

Fig 3 -GIS and DMS View

Business Process Re-engineering with Mobile GIS App

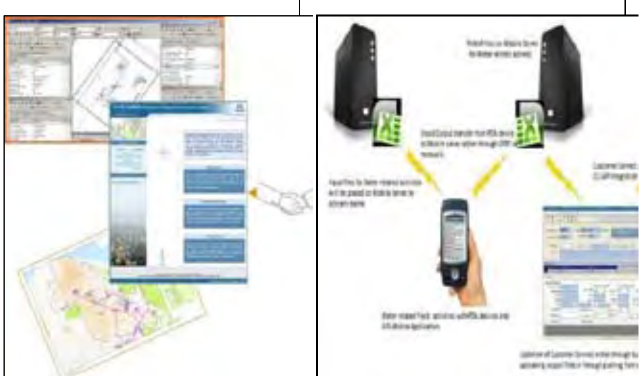
TATA Power Mumbai has developed a comprehensive Mobile GIS system for work force optimization and automation of important distribution processes so as to quickly serve new and existing consumers and manage network assets. Mobile GIS has empowered field people with up to date network maps in their mobiles to view, analyze and collect data in e-forms from field thus eliminating back office data entry. It has significantly reduced cycle time of commercial and operational processes with speedy decision making. It's one of the initiatives of TATA Power's Digitalization drive.

Issues addressed with this Innovation:

1. Reduction in time of scheduling emergency work orders of meter services

2. Challenges of marketing team to convince potential

consumers (builder) with some presentable information about network in vicinity.
3.Difficulty to do site technical feasibility for new consumer while in the field as exact location of assets was not known, high dependency on locals, O&M people and back office GIS support.
4. Discrete systems used by different departments to capture consumer location, creating communication gap w.r.t. consumer location for operational activity.
5. Duplicate data entry (on paper and in other Enterprise systems) decreasing productivity, increasing human errors and cost. Tata Power has hundreds of field engineers from departments like Marketing, Connection Management, Meter Services, Bill distribution, Projects and O&M serving consumers on the field. These teams spend a lot of time in searching for consumers, location of underground network asset and fill hard copies of site activities which is then manually entered in SAP system. Tata Power has developed Mobile GIS system which has been built with the approach of 'User first'. Focus was to build simple product with excellent user experience. Mobile GIS has addressed the challenges faced by field teams and has empowered them to find assets, do analysis and take better decision while on the field. Cost of deployment is low and it has helped for mass deployment of the solution.



Integration of GIS with other Enterprise Systems | Mobile GIS

Fig 4 -GIS integration and Mobile GIS

3) Distribution outage information system through display in customer portal

On Tata Power customer portal, a map view of monthly substation wise planned outage information is maintained under Scheduled Power Outage section. A system has been developed that provides functionality of searching planned outage information on Customer Portal using their consumer number.
This is a unique web based application that has been developed on GIS platform which provides functionality of searching planned outage information on Customer Portal for Tata Power Direct consumers. A complete new backbone mechanism of outage data management system was made. This new application provides consumer specific planned power outage information to consumers.

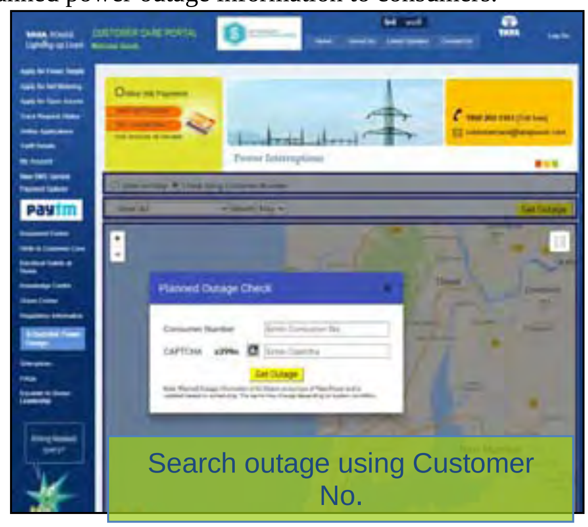


Fig 5 -Map view of power interruption data in customer portal

4)Distribution Management System

The Distribution operations at Tata Power are automated upto 40 % of its network through deployment of Distribution Automation at its 33 /11 kV Distribution Substations and 11 /0.4 kV Consumer substations with the use of Remote Terminal Units and Feeders Remote Terminal Units with the medium of communication being Fiber and GPRS. The success rate of automated operations is maintained in excess of 95 % at all times. This has ensured the best in class reliability indices to the consumers of Tata Power who enjoy near 24 x 7 uninterrupted power supply. The next level of Distribution Automation System was the deployment of Distribution Management System (DMS). DMS has the following benefits: Centralized Monitoring and Control of Network at Power System Control Centre (PSCC), Real time monitoring and control of the Distribution Network, Minimal interruption and faster restoration to consumers. Integration of GIS and DMS allows geographical and electrical visibility with the network loading on a single platform resulting in faster decisions and ensuring lesser interruption time to consumers. Dynamic Network colouring gives an effective visualization of live and dead sections of the network.
Advanced features of DMS such Switch Order Management , Fault Location Isolation Supply Restoration

are also being deployed for enhanced monitoring and control of the network.

5) Automatic Transfer of source using Distribution Automation Systems

Distribution Automation System is a system which enables the monitoring and control of complete Electrical Distribution network remotely. The availability of the automated distribution network helps to ensure the reliable and efficient operation of entire distribution network.

In present scenario, whenever any tripping takes place on a feeder, the operator has to take the decision about the fault identification, isolation and supply restoration. Thus, without intervention of operator supply restoration to the customer is not possible.

Tata Power has tested a new concept on a pilot basis of Automatic Transfer of Source which will ensure the restoration of power supply to the consumer within approximately 1 minute. This wholly autonomous system will isolate the system from no voltage presence source and restore the supply to the consumer from voltage presence source on its own without operator's intervention.

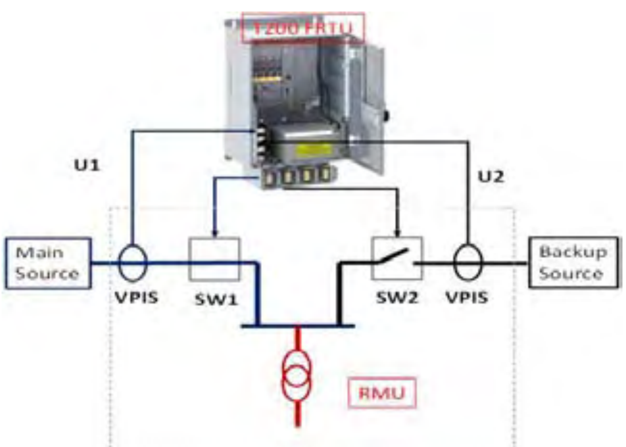


Fig 6: ATS arrangement.

Automatic Transfer of Source (ATS) is a smart application which has intellectual and self-conclusion logic. In order to ensure maximum availability of power and minimum downtime to customer, if one of the MV network fails then automatic switching of two different voltage sources works. ATS model facilitates any Power utility to minimize down time to end consumers and no revenue loss due to energy.

The following improvements are expected: 1) Improvement in Power Supply restoration time. 2) Elimination of mal-operations due to human errors. 3) Safety of field engineers as well as electrical equipment's. 4) Customer satisfaction.

6) Decentralized Control thorugh Self-Healing Grids

Self-Healing Grid (SHG) is a smart application which has intellectual and self-conclusion logic. In case of fault, the system executes the best possible instruction for rapid fault isolation and restoration of supply in network. This Model eliminates manual intervention and minimizes the down time by 95% as compared to conventional restoration philosophy/methodology. SHG model facilitates Power utility to minimize down time to end consumers and no revenue loss due to un-served energy.

In SHG, Field Remote Terminal Units communicating with SCADA system are made to communicate with each other. The real-time information about condition of the network is available with all FRTUs. When there is fault in the network then all FRTUs can self-understand the faulty section and isolate the faulty section by their own and restore the power supply without any manual intervention. SHG will restore the power within 2 to 3 minutes. This is a totally de-centralized and fully automated approach towards the restoration of the power supply. As SHG is de-centralized and automated system, multiple faults can be handled without much time delay and manual interventions.

Advantages of SHG

1. The fault clearance is typically less than a minute while communicating via CDMA on installed RMUs. It is very useful for critical consumers like Hospitals, banks, datacenters and VIP customers etc. where the security and supply continuity is a concern. Also, major improvement in the reliability indices
2. No operator intervention.
3. Easy migration path from Switch solution to self-healing solution
4. The SHG scheme en-compasses 100% automation without any manual intervention
5. Life of the transformers and associated cables will increase due to full proof fault isolation process
6. FPIs (Fault Passage Indicator) are inbuilt in FRTU so separate FPI's are not required.
7. Pre-fabricated Cables are well structured and part of SHG and separate cables are not required between the Ring Main Unit and SHG system.
8. Existing SCADA system can be used to monitor the system.
9. SHG is easy for implementation due to plug and play structure.

10 Reduced use of transport vehicles for performing manual operations at remote substations facilitating reduction in carbon footprint

Fig 7- Digging activity detected in real time is available on computers at remote location

7) Power Line Intrusion Detection Systems

Presently, Power Distribution Sector is facing serious challenges from infrastructural development activities (such as digging, excavation, trenching, etc) in the city resulting in underground cable faults as many of the HV and EHV cables are laid below the ground. The transmission sector is also facing major challenges to curb asset thefts and pin point actual line fault location.

To address these issues, Tata Power has adopted a new technology as a pilot project i.e. Power Line Intrusion Detection System (PLIDS). The system works on principle of Distributed acoustic sensing, where in acoustic signals generated by intrusion activities are picked up by optical signals. In overhead system OPGW cable can be used as a sensor to sense this signal & for underground cables FOP laid along with the power cables will serve the purpose. Each type of Intrusion has distinct acoustic signature by which it can be uniquely identified.

Intrusion sensing system is able to detect, accurately locate & even identify Intrusion type along the entire monitored length in real time on a map and notify the owners by means of e-mails, SMS, alarms, etc.

PLIDS has been installed for testing purposes in Dharavi-BKC feeder. The same will be installed in various other feeders in the future.

Major advantages of PLIDS are reduction of cable faults thus reducing repair costs, easily identify and pin point transmission line faults, avoid theft of assets and continuous monitoring of network.

8) Remote Intelligence Electronic Device Management System

Remote management of Intelligent Electronic Devices (IEDs) such as Bay Control Protection Unit (BCPU), Gateways, Remote terminal units (RTU) etc has been a challenge. To address this issue Tata Power has installed Remote IED management system (RIMS) which is a server connected in the secured Automation Network. All IED's are communicating to the RIMS through secured automation WAN with proper firewall and security. All tools/configuration software required for configuration of the IED is installed in the RIMS. Respective user can log to the system with proper authentication from their official PC/Laptop by using remote desktop connection. The user is able to access the required application tool for configuration of IED's.

Major benefits of RIMS are as follows-

a) Quick analysis of the Disturbance/Occurrence will help in maintaining the reliability Indices within limits and quick restoration of power supply to consumer

b) Configuration of IED is person/PC/Laptop independent.

c) Troubleshooting of communication issues is faster.

d) Time and Cost saving due to reduction in frequent site visits.

e) RIMS is commissioned without incurring any additional cost

f) As IED's are managed by centralized system, malfunctioning of the IED's due to wrong backup installation is eliminated.

g) As secured path is available for accessing the IED's, virus attack and intrusion of malwares is eliminated

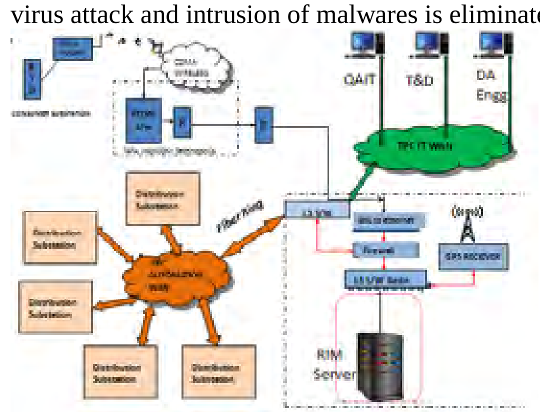


Fig 8- Architecture of RIMS installed at Tata Power Server Room at Trombay

9) Remote Factory Acceptance Test

It is imperative for quality control of electrical equipment by witnessing acceptance tests/routine test on equipment at OEM/Vendor factory for acceptance as per specifications.
TPC-D has engaged in regular inspection of all electrical equipment at various OEM locations within India & abroad. As a cost effective measures for reduction in travel cost & productive time of engaged employees, Remote Factory Acceptance Test has been adopted.
The system works on real time video & audio data transfer on high speed fibre network across two locations. This enables virtual meeting & collaboration on documents for observations during the conference.

ADVANTAGES:

a) Reduction in travel time as well as overall cost
b) Easy Communication
c) Improvement in team engagement
d) Contribution to reduction in GHG emission by

Fig 9- Remote Factory Acceptance Test

10)Automatic Meter Reading and Infrastructure

Tata Power has deployed Automatic Meter Reading (AMR) System and has covered varied segment of consumers viz. Commercial and Industrial, high value residential, slum dwellers and frequent payment defaulting consumers, under AMR. Meters on Distribution Transformers, and Boundary meters have also been covered under the AMR system. The prime objective of AMR system deployment are as follows:

• To automate the process of meter reading and billing without any human intervention.
• Faster detection of metering abnormalities, theft and network faults.
• Facilitate accurate Load forecasting.
• Facilitate Demand Response Initiatives.
• Achieve one milestone towards Smart Metering which is one of the drivers for Smart Grid.

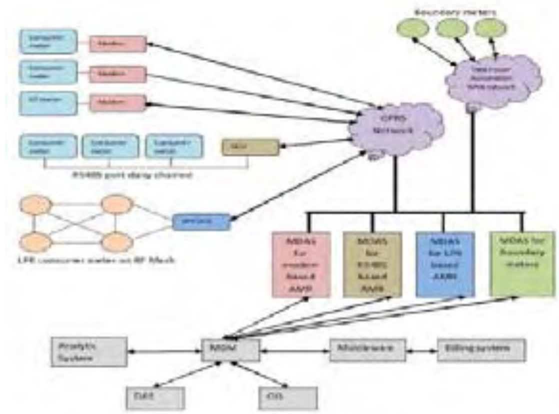


Fig 10- AMR system architecture

AMR/ Smart meter Implementations

1. GPRS modem based AMR – For Industrial and Commercial consumers and meters on Distribution Transformer.
It was decided to not replace the existing Electronic energy meters for the purpose of AMR. To cover these meters under AMR, GPRS modems are installed at each individual metering installation. These meters are read through optical port / RS232 port using API provided by meter manufactures as per MIOS standards. Legacy meters on Distribution Transformer were replaced with meters that can communicate using DLMS/COSEM protocol. The modem is preprogramed to acquire the meter data viz. billing, load profile, tamper and events at 30 minutes interval and push the same to MDAS through public cellular GPRS network.

2. MODBUS protocol based AMR – For high value residential consumers in clusters.
High value residential consumers and those in clusters have been covered under AMR through this technology. The RS485 communication port of 3 phase energy meters are daisy chained using shielded pilot cable and connected to a Data Concentrator Unit (DCU).

3. Low Power Radio Frequency based AMR – Low cost AMR for mass residential consumers
Mass residential consumers in housing societies and in slums have been covered under AMR through this technology. The meters are fitted with low power radio (LPR) communication modules that transmit data over radio wirelessly. The frequency of transmission is in the range of 856 – 867 MHz with a power output of less than 1 W.

4. AMR for boundary meter

ABT meters are installed at all the G <> T and T <> D interface points of Tata Power. The boundary meter data is used for calculation of distribution loss, AT&C loss, receiving station energy balance and feeder wise energy audit.

11) Meter Data Management System

Meter Data Management System (MDMS) is tightly integrated with MDAS deployed for different technology. The ability of MDMS to store and manage meter data and its seamless integration with other operational systems like Analytics, GIS, DAS etc. offers many benefits to the utility.

a. Billing

Meter register data is validated with the load survey data and is sent to billing system only if it passes validation. This ensures the correctness and authenticity of billing data and helps improve consumer satisfaction.

b. Asset management

The load survey data of Feeder and DT meters captured in MDMS provides trend of load pattern of Distribution Transformers and Feeders. This helps utility to transfer loads from over loaded to less loaded Transformers and Feeders. Alternately, DTs can be swapped as per their capacity to areas where they can be loaded optimally to reduce losses.

c. Meter event analysis

The MDMS captures events recorded in the meter and generates report that provides list of all the meters that have recorded a particular event (Event wise meter list). It also provides all the events registered by a particular meter (Meter wise event list). Such analysis helps in early detection of meter abnormalities and to identify tamper and theft.

d. Energy audit

MDMS provides consumption variation report for all consumer meters and Feeder / DT meters. Sudden change in consumption pattern of consumers in relation to the consumption pattern of concerned DT / Feeder helps utility to detect meter discrepancy / energy theft

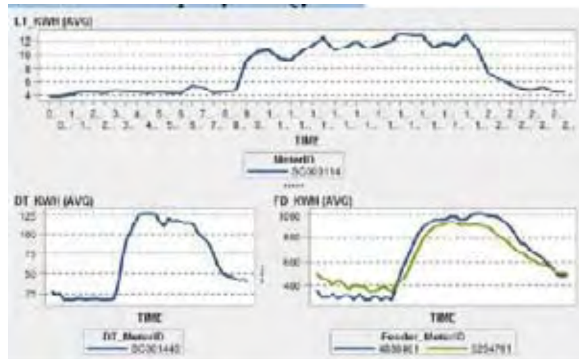


Fig 11- Consumption pattern of consumer meter as compared to DT/Feeder

e. Customer profiling

MDM system helps utility to group consumers as per category like industrial, commercial, residential etc and compare their load profiles for any period.

f. Baseline consumption for DR

MDMS has been configured to include multiple algorithms as defined by the regulatory body to calculate baseline consumption for individual consumers participating in a DR event. This helps utility to determine the incentive to be offered to a consumer for curtailment in load during a DR event.

g. Benchmarking and Customer Benefit

The MDMS enables utility to define a consumption benchmark for different category of consumers and compare consumption of individual consumers with the benchmark. This feature identifies the best and worst performing consumers vis-a-vis benchmark. This data can be shared with concerned consumers to improve their behaviour.

MDMS enables utility to provide detailed usage information to consumers through web page. This helps consumers to understand their consumption and relate it to energy costs. Thus consumer can take energy efficiency measures to manage their energy efficiently and reduce cost of energy.

Conclusion:

The metropolitan city of Mumbai is water locked from three sides and there is very less scope of horizontal development. In line with the vertical development of major cities in India, it has become necessary to innovate and put forth space saving solutions to the end consumer with regard to power supply and at the same time ensure uninterrupted and reliable power supply.

Tata Power has introduced various Smart Technologies in its Power Distribution Network to enable faster restoration of power supply, automation of operational processes, effective data analysis and space & cost optimization.

Other utilities may opt the best design solutions depending on their requirement.

MISCELLANEOUS

Acknowledgments

This paper would not have been possible without the guidance of the Tata Power Team who work every day to innovate new solutions and give the best to the end consumer.

REFERENCES

[1] Technologies adopted for successful deployment of AMR at Tata Power presented at SWITCH 2016

[2] Decentralized control through Self-Healing Grids Paper presented at CIRED 2017

[3] Engineering of Compact, Safe and Eco-friendly Electrical Installations for Mumbai City presented at Engineering Smart Cities 2015

[4] Indian Power Sector and the Smart Cities Project- Article by Ashok Sethi- COO & ED Tata Power

Innovative Technological Interventions for Distribution System Infrastructure

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ABSTRACT

Power Distribution Utilities play a pivotal role in developing the electrical network of a city and achieving the last mile connectivity to supply power to the end consumer. This paper elaborates on the Technological Interventions for addressing the challenges of reaching the last mile in an Urban Metropolitan landscape.

INTRODUCTION

Tata Power Company is India`s largest Integrated Power Utility with presence across the value chain from Fuel, Fuel Logistics, Generation, Transmission, Distribution and Power Trading. The Power Distribution arm has its presence in the Metropolitan cities of Mumbai, Delhi and Ajmer. Tata Power Distribution plays a pivotal role in developing the electrical network of a city and laying the last mile connectivity to supply power to the end consumer The main considerations that drive power distribution utilities in urban cities like Mumbai are Safety, Space, Reliability and quality of supply, Environment and Equipment/Asset Life. The main enablers to address the above factors are Technology (both IT and OT) and Innovation.

Safety: Electrical Installations are required to be located in the midst of localities which makes the duty of ensuring safety in and around the installations all the more challenging. Introduction of latest technologies to ensure safety of the equipment, workforce and the society is of prime importance.

Space: Availability of clear space in metropolitan cities like Mumbai is getting difficult as well as prohibitively expensive. Also with the increasing trend of vertical high rises, Innovative Solutions for Compact Electrical Installations with enhanced capacity are clearly the differentiators for the utility.

Reliability -Being a metropolitan city would mean that the city is the financial, commercial or the IT capital of the country which necessitates continuity of quality power supply as a perquisite for the power distribution utility to exist and further in the event of an interruption, ensure minimum restoration time through minimal or no manual intervention.

Environmental Concerns: Introducing eco-friendly electrical installations with no harm to the ecosystem is an equally important requirement of an urban power distribution utility.

Equipment Life Expectancy: Ageing assets of any electrical utility are a reality, the challenge is not in replacing these assets by incurring huge capital expenditure but in enhancing the life of existing assets. This involves Re-Engineering of existing installations by developing retrofit solutions so as to accommodate the reengineered solutions in the existing space. Also the new network elements added into the system by way of capacity enhancement or new demand should have a larger life expectancy than the conventional network elements in the system.

TECHNOLOGICAL INTERVENTIONS AND INNOVATIONS IN POWER DISTRIBUTION INFRASTRUCTURE

Tata Power Distribution has introduced/developed various innovative technologies and engineered solutions for Safe, Compact and Eco-friendly Installations in Mumbai. Each of these are explained to bring forth the same and it can be replicated by utilities for improving the distribution infrastructure's last mile connectivity which would enable better asset management.

1) Ensuring Safe, Compact and Environmental friendly installations with the Use of Natural Esters as Alternative Insulating Fluids:

a) Green Field areas: Mineral Oil has been traditionally used as an Insulating and Cooling medium for Transformers. Mineral Oil used in Transformers has limitations in terms of low fire, flash point and limited biodegradability, its toxic effects in case of a spillage.
As an alternate to mineral oil, esters are used as dielectrics and coolants. Esters have very high fire point that makes them safer with the added benefit of being readily biodegradable and thus more environment friendly. They have good tolerance to moisture and can increase lifetime of the asset along with allowing compact designs. Natural esters, with these benefits, form a suitable choice to be used in transformers. Comparative properties of both these insulating fluids are summarized below:

	Mineral Oil	Natural Esters
Fire Point	170-180 0C	>350 0C
Flash Point	160-170 0C	>250 0C
Biodegradability	Slow to biodegrade	Readily biodegradable
Breakdown Voltage	70kV	>75kV
Water saturation at ambient (ppm)	55	2600
Cellulose ageing transformer life	Poor	Slower ageing-more transformer life
Compact Transformer Design	No	Yes

Table 1 =Properties of Mineral Oil Vs Natural Esters

Tata Power has designed and developed transformers collaboratively with Original Equipment Manufacturers (OEMs) with Natural Esters as Insulating and Cooling medium. The various benefits that have been accrued with the use of Natural Esters in Distribution Transformers has been summarized below:

Parameter	Before	Results envisaged	Impact
Potential Safety Hazards due to Fire resulting from a Fault in the equipment	Very High	Nil	Safety
Fire Point (Deg. C)	150	300	Safety
Climate Change : Annual Reduction in Co2 emissions by sequestering carbon from air.	5.7 MT/MT of Mineral Oil produced	~0.5 MT/MT of Natural Ester produced	Environment
Biodegradability (Days)	900	30	Environment
Toxicity	High (Mineral Oil)	Non Toxic	Environment
Continuous Loading of Transformer (%)	100	120	Economic & Customer
Reduction in Footprint of the Transformer	100	80	Economic

Table 2- Benefits of Natural Esters

Thermal Imaging of the developed transformer has proven that the Transformer can be continuously loaded to ~120 %.

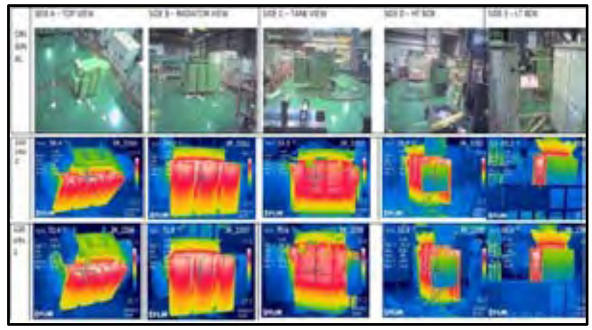


Fig 1 -Thermal Pattern of Ester Filled Transformers

The use of Natural Esters has also been extended to Power Transformers .Tata Power is the first utility in India to have introduced Natural Ester filled Power and Distribution Transformers.

b)Brown Field Areas : Natural Esters have an inherent property of absorption of moisture from the paper insulation that is impregnated with, further the temperature rise offered by Natural Esters are higher than that with Mineral Oil .These properties lead to the possibility of higher loading and prevent further degradation of the paper insulation of the transformer .This is in effect means that existing transformers old and optimally loaded transformers can be retro filled with Natural Esters to reap the benefits of enhanced loading and life. Tata Power has identified Distribution Transformers that are loaded beyond 70 % and aged more than 15 years for retro- filling with Natural Esters and has already retro filled a couple of Distribution Transformers with satisfactory results.

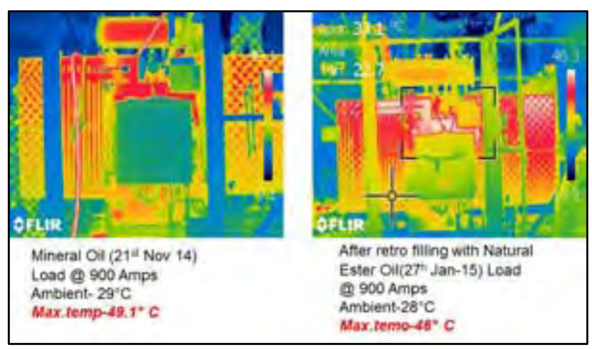


Fig 2-Thermal Pattern of Retro filled Ester transformers

Seen above is the improved thermal pattern after retro filling of transformers with Natural Esters.

2) Ensuring Safety, Space saving and improving the aesthetics of city by introduction of Underground Feeder Pillars in the Distribution System:

Feeder Pillars are the integral part of a LT Distribution system of a utility. Conventionally these are placed above the ground along the footpaths or along the center line of the roads.

Fig 3-Conventional above the ground LT Feeder Pillars

These are normally made of metal, prone to rusting and cause obstruction to the general public and traffic. The doors of Feeder Pillars are often stolen resulting into public Safety Hazards. Also these are vulnerable locations for Pilferage of electricity.
Tata Power has introduced a Smart solution in association with Raychem to these conventional Feeder Pillars in the form of an underground Feeder Pillar as depicted below

Fig 4 -Underground LT Feeder Pillar

3) Introduction of E Houses to replace conventional 33/11 kV Substations: [3]

A conventional 33/11 kV Distribution Substation (DSS) requires a space of about 1000 Sq.Mtr. which houses Outdoor Power Transformers and Switchgear in a building. The gestation time of such a substation is about 6 months with major time and money being spent on the construction of civil structure/buildings. Availability of space and its cost are a major bottleneck in construction of these substations. Pre-fabricated substation E-House (Electric House) which is compact in design and ready to install at site is an innovative solution to overcome all the above challenges.
Tata Power has designed and developed two such site specific solution in Mumbai.

Fig 5-Conventional DSS Vs E House DSS

Benefits from E-House are:
-Reduced Footprint- footprint is 30% lesser than a conventional Substation.
-Cost reduction by about 20% as compared to conventional Substation
-Civil construction reduced by 82% as compared to a conventional Substation
-Gestation period of establishing the substation would reduce by two months which is vital from power supply point of view.

Fig-6-E house in its final stages of implementation at a Tata Power Substation

4) Introduction of Pad Mount Substation:

A unique solution to address the challenge of Space and Fire Hazard is the Pad Mount substation .Conventionally any Consumer substation has a Ring Main Unit, Transformer, LT Switchgear and Distribution panel. These are discrete units requiring clearances to be maintained for each of the equipment. These substations typically require an area in the range of 8 x 5 Sq. Mtr or 40 Sq. Mtr.; availability of this kind of space is also a challenge .In order to overcome this challenge an integrated unit with incoming isolating switches, transformer and LT Switchgear called the Pad Mount Substation can be deployed. In addition to being compact it also uses Esters as the Liquid Insulating medium thereby making it a Fire Safe Installation. The area required by this substation is about 15 Sq. Mtr which is almost three times lesser than conventional substation.

Fig 7-Conventional Vs Pad Mount Substation

5) Internal Arc Flash Detection System

Traditional time-grading or blocking based protection coordination principle may not provide fast enough protection of substation faults. Further, high-impedance type earth-faults may cause prolonged operation times of earth-fault relays leading to the significant release of arcing energy. These facts pose a considerable risk to operation personnel and economical assets.
Thus Tata Power has made an effort to use Internal Arc Flash Detection systems which has the following advantages-

a) Personnel safety
Fast and reliable arc protection systems improve safety and may save human lives in case of an arc fault arising in switchgear during work or near the installation

b) Reduced loss of production
The faster the operating time of an arc protection system, the lesser the damage caused by the arc fault, reducing the possible outage of the power supply.

c) Prolonged switchgear cycle
A modern arc protection system increases the life expectancy of switchgear installations, investment decisions in new switchgear installation can then be postponed.

d) Reduced insurance costs
The faster and better the protection system, the more generous the insurance terms and lower the cost should be.

e) Low investment costs and fast installation
A comprehensive arc protection is characterized by low investment, fast installation and commissioning time. One successful operation of the arc protection system provides immediate return on investment.

6) Refurbishment and Utilization of Civic Amenities for Substation

Mumbai is a unique model of operation with multi licensees operating in a defined area which leads to space constraints. The space required for substation is allotted by the consumer. Since land in Mumbai comes with a high premium, there is a resistance for allotment of land. Need of the hour was to brainstorm the solution for space constraints. After much efforts were put in, it was deduced that the space on the upper floor of civic amenities ((like urinals, etc) can be utilized for substation space and supplying power to the low end consumers. Discussions were carried out with civic authorities to understand the functioning & structural design of the toilet blocks. The first substation on the public civic amenities was made functional, enabling Tata Power to serve people at large in the vicinity of the civic amenities.

Fig 8- MCA substation. Top Image- Before, Below Image- After construction of substation

7) Trafo-connector

Transformer is a vital component of a distribution system. It has to deliver Reliable Power in a safe & efficient manner. However, 8% of the transformers installed

Fig 9: LT Cable connections using Trafo-connecctor

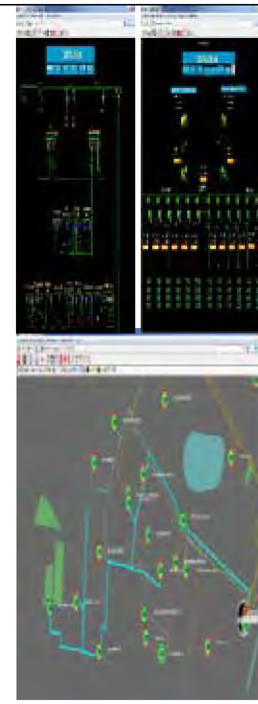
World-wide fail on account of improper connector systems. A conventional connector system used for LV cable connection, deploys crimping and tightening of the bolts. Over a period of time, it leads to a loose electrical contacts which causes sparks and hot spots. The contact resistance is high which adds to the losses of ailing utilities. The weight of the connector causes mechanical strains on the bushing of the transformer, leading to oil leakages. Trafo connector is engineered to keep the contact resistance low for the lifetime of the transformer. It's lighter & pretty simple to install as it uses the modern shear bolt technology, hence avoiding the skill & tool dependent crimping methodology. It significantly increases the reliability of the transformer.

8) Geographical Information System

All the network assets both Overhead and Underground are mapped in the Geographical Information System right up to the consumer on the backdrop of land base.

Multiple Business processing is enabled from site helping cycle time reduction, faster response and single point data entry. Integrated features of application for multiple queries, redlining, application processing has made this system as one click solution for many business activities of distribution to be done from field

Network Assets Mapped in GIS



Electrical and Geographical view of the network in DMS

Fig 10 -GIS and DMS View

9) Distribution Management System

The next level of Distribution Automation System is the deployment of Distribution Management System (DMS). DMS has the following benefits: Centralized Monitoring and Control of Network at Power System Control Centre (PSCC), Real time monitoring and control of the Distribution Network, Minimal interruption and faster restoration to consumers. Integration of GIS and DMS allows geographical and electrical visibility with the network loading on a single platform resulting in faster decisions and ensuring lesser interruption time to consumers. Dynamic Network colouring gives an effective visualization of live and dead sections of the network.

10)Automatic Meter Reading and Infrastructure

Advanced metering infrastructure (AMI) is defined as the communications hardware and software, and associated system and data management software that creates a network between smart meters and utility billing systems. Through smart metering and AMI, it is possible to fully automate the process of meter reading and billing. The meter data can be shared with consumer which will facilitate consumer engagement/satisfaction level. Going forward, pre-paid functionality and remote connection/disconnection can also be deployed using smart metering and AMI solution without any need to install a special prepaid meter. Various technologies like GPRS and RF technologies can be deployed for AMR.

Conclusion

Tata Power is working on several fronts simultaneously to ensure technical upgrade of the existing distribution network to ensure safety of consumers, overcoming space constraints and provide reliable power supply at all times. The initiatives described in the paper is proof of continued efforts put in by Tata Power towards enhancing and improving the power distribution infrastructure for the benefit of the end consumer.

MISCELLANEOUS

Acknowledgments

This paper would not have been possible without the guidance of the Tata Power Team who work every day to innovate new solutions and give the best to the end consumer.

REFERENCES

[1] Engineering of Compact, Safe and Eco-friendly Electrical Installations for Mumbai City presented at Engineering Smart Cities 2015

[2] White paper on Distribution Network Planning for Urban Metros

[3] E-House- Solutions with pre-fabricated and compact HV/LV substations presented at Conference on Advances and Innovation in Substation- CIGRE 2015

Measurement, Monitoring and Reporting of Power Quality at Tata Power Mumbai Distribution

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ABSTRACT

As consumers become more sensitive to Power Quality concerns with the rise in use of sensitive electronic, precision equipment's, it is imperative for a responsible utility to ensure not only reliable but also Quality Power supply to its consumers.

It is now an established practise and focus area of all progressive utilities to provide reliable power supply, monitor and report on the basis of reliability indices and also as standards of performance defined in terms of SAIDI, SAIFI and CAIDI by the respective regulatory commissions. Power Quality does find a mention however norms for measurement, monitoring and reporting are not followed uniformly and hence the need to device a methodology for the same. Also, as a result of better understanding of the Power Quality Concerns it becomes easier for working on solutions for mitigating the same both on the Supply side and the load side collaboratively with end consumers.

To address these requirements, Tata Power started monitoring the trends of different attributes and arrive at selective action plans to improve on the quality of power. One such case study is also presented in the paper starting from measurement, monitoring, data analysis, action plans and mitigation of power quality issue.

As mentioned earlier, in the absence of any uniform methodology, Tata Power has also developed its own Power quality scoring criterion of individual power quality attributes.

This paper highlights the approach adopted by Tata Power to measure, monitor, analyse, report and action plans to improve the power quality to Key HT Consumers.

1. INTRODUCTION TO POWER QUALITY MONITORING AT TATA POWER

Today's Consumer demands are ever growing in terms of quality of the product they purchase, and this is true with Power too. They expect the perceived value of the product being purchased. Reliable and Quality Power supply is an essential need in today`s world . Also, future regulations calling for the oligopoly market in Power distribution business, Consumer will have the option of choosing supplier based on utility's tariff, reliability indices, power quality indices etc. Thus, it becomes important for utilities to start monitoring the power quality parameters.

2. TRIGGER FOR POWER QUALITY MONITORING AT TATA POWER

There has been an increasing trend of Power quality complaints from most of the HT consumers getting fed from Tata Power on either 22kV or 11kV. The manifestation of power quality concerns into complaints relate mostly to Voltage variations and Voltage Dips experienced by the consumer.

Some of the consumers using highly sensitive equipment started complaining on failure of Luminaries, stoppage of lifts, Server room electronic card failures, UPS failures, Compressor failures etc. At this point it is not clear whether the problem is resultant from the upstream or downstream area. This has triggered the necessity to monitor the Quality of Power being supplied to its key consumers.

Key Consumer Management group at Tata Power being a single point of contact for all High Revenue

Base consumers as a process aggregates all the technical concerns inclusive of the Power quality concerns and correlated them with power quality attributes being measured.

All the Power quality parameters are measured, recorded, analysed for different geographies in power distribution in terms of Zones. These are brought on a common platform on providing weightages to each of the attributes and calculating monthly PQ Index for each of the 6 operating Zones of Tata Power Mumbai distribution. This serves as a Score card of each of the Zones and a ready repository of PQ issues in the particular month for corrective and preventive action as possible

3. MEASUREMENT OF POWER QUALITY AT TATA POWER: Tata Power is distributing to Mumbai consumers for over a century now and is structured in to 6 zones for decentralized operations. At present, Tata Power has 17 Receiving stations (220-110 / 33-22kV) and 32 Distribution stations (33-22/11kV) spread across Mumbai license area of 485 Sq.kms.

Power Quality Meters (PQM) are installed on 22kV and 11 kV bus sections of substations spread across Mumbai License area as depicted in the SLD below :.

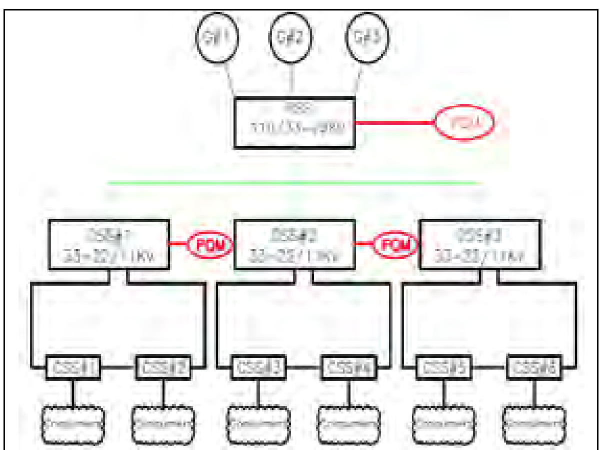

Figure 01: SLD arrangement of PQMs at Tata Power RSS / DSS

Tata Power has mapped all its Distribution Assets on its Geographical Information System (GIS) as also its consumers. A pictorial view of the Spread of Power quality monitoring through PQ meters and the consumers covered under them is depicted in Figure 02.

These meters can be accessed remotely to cull out the Power quality attributes data and report. HT Feeders emanating from RSS & DSS at 22kV & 11kV voltage level are spread across Mumbai license area.

- Blue Polygon indicate Tata Power's 110/33kV Receiving stations (RSS) Pink Circle around these RSS indicate the PQM availability and the geographic spread which the PQM can measure and report the data.
- Pink Squares indicate Tata Power's 33/11kV Distribution substations (DSS).
- Cyan Circle around these DSS indicate the PQM availability and the geographic spread which the PQM can measure and report the data.

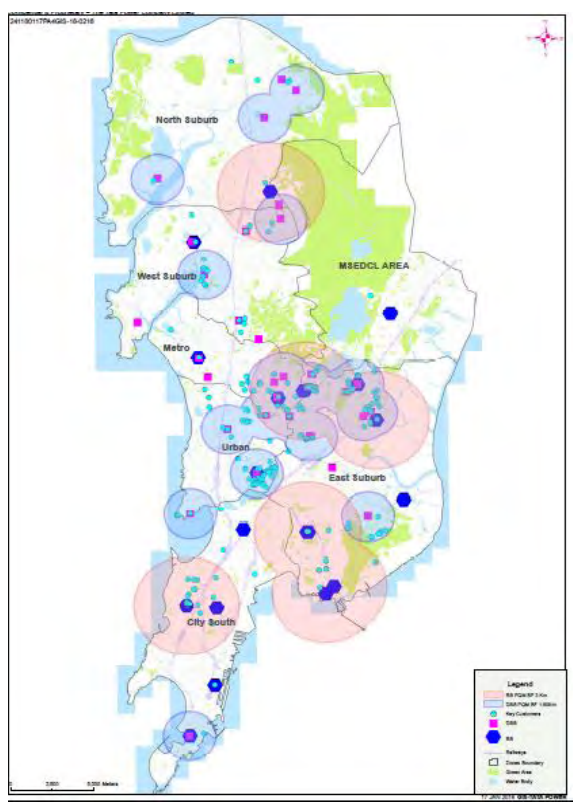

Figure-2: Geographic map of Mumbai with PQM spread

High Revenue Base Key consumers: Key High revenue base consumers mostly on HT supply from Tata Power are mapped to individual RSS & DSS from which they are being supplied.

Cyan coloured dots in figure 2 indicate these Tata Power consumers spread across Mumbai.

PQM monitoring availability vis-à-vis Key consumers as well as complaining consumers on Power Quality is depicted below. This gives action plans on strategic locations of PQM and corrective actions to mitigate the effects.

COMPLAINTS VS COVERAGE MATRIX			TOTAL
PQ Monitoring available	124	65	189
PQ Monitoring not available	53	**40**	93
	Non-complaining HRB consumers	Complaining HRB consumers	282

- 67% of total HRB consumers are covered through PQMs
- 62% of complaining HRB consumers are covered through PQMs.

Table-1: Complaints vs Coverage matrix

4. PQ DATA COLLECTION: Power quality data is being collected at a central server and is accessible remotely as shown in the schematic arrangement in Figure 02. However, there are integration issues being faced in extracting data remotely from PQMs of different OEMs. This is because no uniform software can be used for different make of PQMs and make specific software is required for remote extraction as indicated in the figure 02. This hurdle can be overcome if PQMs are compatible with Power quality data interchange format (PQDIF).

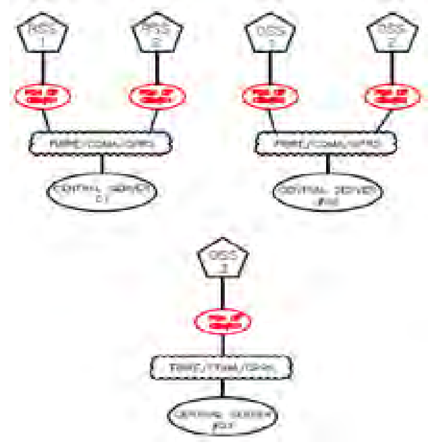

Figure 02: Schematic arrangement of remote data extraction from PQMs.

5. PQ DATA ANALYSIS: Key attributes indicating the healthiness of Power quality and Tata Power monitoring & analysis of these attributes is as below:

5A1) Voltage Variations: Power is supposed to be delivered by deemed distribution licensees to consumers at Steady State permissible voltage limits defined in Indian Electricity rules1956 - Chapter I sub clause (av) as below:

Voltage Level	Voltage Range	Permissible variation
Low Voltage (LV)	< 250 V	+/- 6%
Medium Voltage (MV)	250 V < V < 650 V	+/- 6%
High Voltage (HV)	650V < V < 33000	+ 6%, -9%
Extra High Voltage (EHV)	> 33000	+ 10%, -12.5%

Table-2: Voltage Level defined under IE Rules

5A2) Monitoring at Tata Power: PQMs measure the 10 / 15 min interval of bus voltages and is flexible to extract this data over a pre-defined interval. At Tata Power, monthly voltage data is being extracted and profile is populated along with permissible limits mentioned in table 01 to understand the voltage profile of a particular RSS / DSS as shown in figure 03.

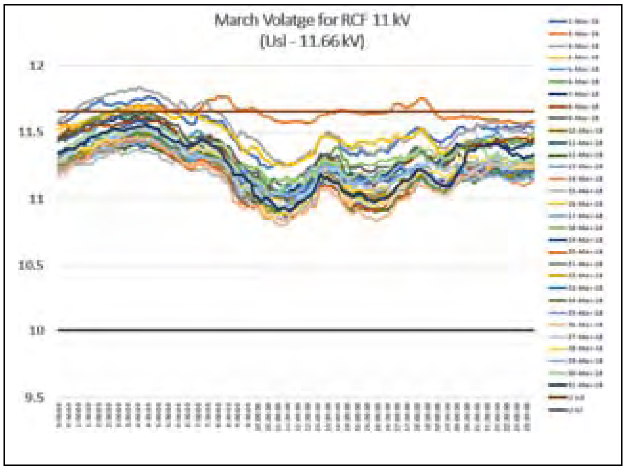

Figure 03: 24 Hr voltage profile of 11kV Bus for a month.

5B1) Voltage Swell & Sag (dip):

Voltage Swell: are almost always caused by an abrupt reduction in load on a circuit with a poor or damaged voltage regulator, although they can also be caused by a damaged or loose neutral connection.

Voltage Sag: is a brief reduction in voltage typically lasting from a cycle to a second or so or tens of milliseconds to hundreds of milliseconds. These are caused by abrupt increases in loads such as short circuits or faults, motor starting, or electric heaters turning on, or they are caused by abrupt increases in source impedances typically caused by a loose connection. Some electronic equipment lacks sufficient internal energy storage and, therefore, cannot ride through sags in the supply voltage. Equipment may be able to ride through very brief, deep sags, or it may be able to ride through longer but shallower sags.

The semiconductor industry developed a specification (SEMI F47) for tools used in the semiconductor industry in an effort to achieve better ride through of equipment for commonly occurring voltage dips and therefore improving the overall process performance.

5B2) Monitoring at Tata Power: Power quality Reports from all PQMs installed are extracted. Report shall comprise of a Sag/Swell Graph.

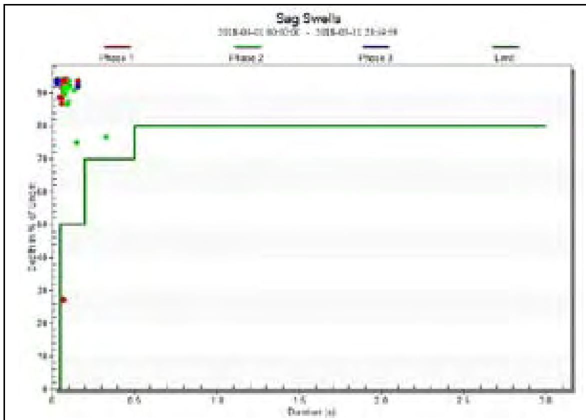

Figure-4: Sag & Swell report

This graph represents the Sag instances within & outside the permissible limits of Depth vs Duration table 02 shown below. Any dots above the green line indicates Sag instances within permissible limits means consumer equipment must have the tolerance to withstand Sags within thus depth and duration. Dots below the green line indicate instances outside tolerance limits for which utility is responsible to control such instances. Also, these instances may affect the consumer equipment such as lifts, compressors, tripping of industry machinery etc.

Depth (d) / Duration (t)	10ms < t < 50ms	50ms < t < 200ms	200ms < t < 500ms	500ms < t < 3s
80%<=d<90%	1	5	0	0
70%<=d<80%	0	1	1	0
50%<=d<70%	0	0	0	0
10%<=d<50%	0	1	0	0
0%<=d<10%	0	0	0	0

Table-3: Depth & Duration table for Sags

Data is also available on the day, time and exact depth and duration of every Sag/ swell incident recorded for a month. This helps in correlating this information with the trippings for that month, study the tripping trend of that RSS/DSS and arrive at corrective actions.

5C1) Total Harmonic Distortion: Harmonics are multiple frequency waveforms disturbing the shape of fundamental frequency wave as shown in Figure:2. Harmonics are caused by non-linear loads, that is loads that draw a non- sinusoidal current from a sinusoidal voltage source. Some examples of harmonic producing loads are electric arc furnaces, static VAR compensators, inverters, DC converters, switch-mode power supplies, and AC or DC motor drives.

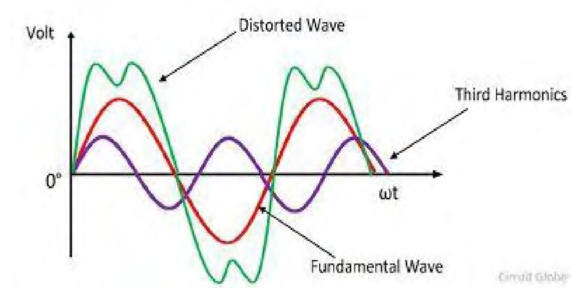

Figure-5: Distorted waveform due to harmonics

Total Harmonic Distortion (THD) is used to estimate the degree to which a system is nonlinear. THD is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency.

5C2) Monitoring at Tata Power: For a system to be defined as harmonics free, THD of the supply voltage shall be less than or equal to 8 %. Sample of such THD report for individual phases is as shown in Table 03 below.

Phase	Time within limit	Max Value	Min Value	95% Value	Result
THDF U1	100%	1.66%	0.59%	1.48%	Passed
THDF U2	100%	1.66%	0.59%	1.45%	Passed
THDF U3	100%	1.7%	0.68%	1.51%	Passed

Table-4: THD analysis of supply voltage with Norm; Max8%, during 100 % of time

As the max value of THD in all 3 phases in less than 8 %, this particular substation has passed THD test which means that the power being delivered to consumers from this substation is with THD within limits.

5D1) Flicker: Power-line flicker is a visible change in brightness of a lamp due to rapid fluctuations in the voltage of the power supply. The voltage drop is generated over the source impedance of the grid by the changing load current of an equipment or facility. These fluctuations in time generate flicker. Flicker may be produced, for example, if a steel mill uses large electric motors or arc furnaces on a distribution network, or frequent starting of an elevator motor in an office building, or if a rural residence has a large water pump starting regularly on a long feeder system.

5D2) Monitoring at Tata Power:

PQ meters generate a report on Flicker which is divided in to Pst and Plt as explained below.

Short term Flicker Perceptibility (Pst) is calculated according to a statistical process over a standardized 10-minute observation interval. PST measured over 10 minutes shall not exceed 1.

Phase	Time within limit	Max Value	Min Value	95% Value	Result
PST1	99.57%	2.78	0.02	0.31	Failed
PST2	99.62%	4.27	0	0.21	Failed
PST3	99.51%	9.05	0.04	0.29	Failed

Table 05: Short term flicker effect. Norm: Max: 1, during 100 % of time.

As the max value of Pst in all 3 phases in greater than 1, this particular substation has failed Pst Flicker test which means that the power being delivered to consumers from this substation has short term flicker.

Long term Flicker Perceptibility (Plt) is calculated as the cubic mean of several Pst values over a standardized two-hour period. PLT caused by voltage fluctuation should be < = 0.8

Phase	Time within limit	Max Value	Min Value	95% Value	Result
PLT1	98.66%	1.58	0.05	0.48	Failed
PLT2	98.12%	1.86	0.02	0.37	Failed
PLT3	97.58%	3.95	0.08	0.4	Failed

Table 06: Long term flicker effect, Norm: Max: 0.8, during 100 % of time.

As the max value of PLT in all 3 phases in greater than 0.8, this particular substation has failed PLT flicker test which means that the power being delivered to consumers from this substation has long term flicker.

Flicker is generated by load changes. Only the amplitude of the load change is relevant, not the absolute value. A reduction in flicker can be attained through making less frequent load changes, or smaller load changes. If the load is changed gradually (for example, by the help of power electronics) instead of step fashion, this also makes flicker less perceptible.

5E1) Power Frequency: is the nominal frequency of the oscillations of alternating current (AC) in an electric power grid transmitted from a power station to the end-user. In large parts of the world this is 50 Hz, although in the Americas and parts of Asia it is typically 60 Hz. exact frequency of the grid varies around the nominal frequency, reducing when the grid is heavily loaded, and speeding up when lightly loaded. However, most utilities will adjust the frequency of the grid over the course of the day to ensure a constant number of cycles occur.

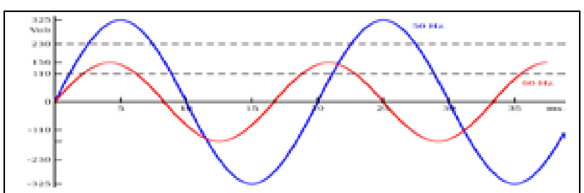

Figure-6: Sinusoidal waveform Frequency

5E2) Monitoring at Tata Power:

PQ Meters monitor the Power frequency over a predefined interval and generate report on minimum and maximum value over a selected period of time.

The compatibility level for short duration frequency is +/- 1 Hz of the nominal frequency. Sample report for one of the Tata Power substations is as below.

Phase	Time within limit	Max Value	Min Value	95% Value	Result
Favg Max	100%	50.24Hz	49.67Hz	50.04Hz	Passed

Table 07: Frequency Variation table

The frequency is well within the limits and the test is passed.

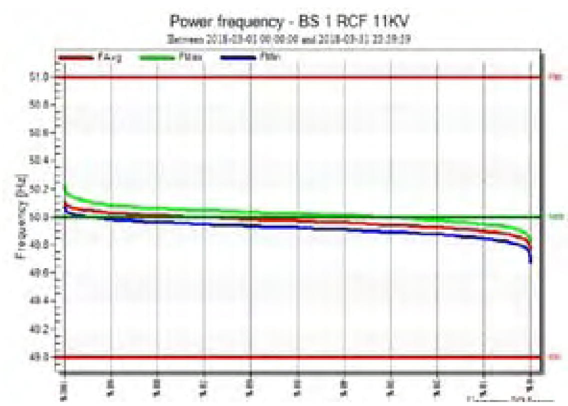

Figure-7: Power Frequency variation graph

6. NEED FOR POWER QUALITY INDEX:

Having data on all key attributes, it is possible to score the Power quality of each RSS/DSS/Zone. Need is felt to arrive at quantitative figures to rank on the zonal Power quality performance mapped to Key consumers getting affected.

This monthly scoring arrives at readily available action items on a particular attribute affecting the score. It also helps in detailed root cause analysis and corrective / preventive actions either by a utility or consumer or by a joint effort ultimately resulting in delivery of a quality power to end consumers.

Hence, it is proposed to have DSS / /RSS / Zone specific Power Quality Index scoring every month at Tata Power.

7. ASSUMPTIONS ON POWER QUALITY INDEX Data

7. ASSUMPTIONS ON POWER QUALITY INDEX Data availability with different RSS / DSS and analysis part of it is explained in earlier sections. This section deals with the assumptions made at Tata Power to arrive at RSS wise, DSS wise and Zone wise Power Quality Index of Key attributes.

As there are no standards available as of now for Power Quality scoring, Tata Power has developed an internal scoring criterion for key Power attributes explained in "Introduction" Section and listed below:

i) Voltage Variations

ii) Voltage Sag / Swell

iii) Total Harmonic Distortion

iv) Flicker and

v) Power Frequency

Remote / Local accessibility of data is possible from the Power Quality Monitors installed at various RSS / DSS. With data analysis, Power quality attributes are scored as mentioned below:

Power Quality Scoring Criteria:

Voltage Sag/ Swell scoring criteria: No. of Sag/Swell instances within limits are not considered. But no. of instances outside permissible limit are given score based on % share of these instances over total sags /swells for a particular month.

Voltage variations scoring criteria: Voltage variations being the major pain point of key HT consumers which is also under utility scope to control, this Power quality attribute is given the major weightage of 50 %. Voltage variations score is further divided in to % Magnitude of violations and % instances of violations as explained in below tables 3, 3A, 3B.

Table 01: Weightage Criteria

Sr.No.	PQ Attribute	Weightage	Individual Score	PQ Score
1	Power Quality Healthiness (% Sags outside Limits)	30%	As achieved in Table 02	30% * Score achieved in Table 02
2	% No. of days - Voltage within Permissible Limits	50%	As achieved in Table 03	50% * Score achieved in Table 03
3	THD (Pass / Fail)	20%	As achieved in Table 04	20% * Score achieved in Table 04
4	Power Frequency within Limits (Y/N)	0%	As achieved in Table 05	Not Applicable
5	Flicker (Pass / Fail)	0%	As achieved in Table 06	Not Applicable
6	Power Quality Score for the month	100%		Sum of Sr. Nos 01, 02 & 03

Table 02: Scoring Criteria for Sag / Swell

Sr.No.	Description	% Sag outside limits	Score
1	% Sags Outside permissible limits	0 - 10%	100%
2		11 - 25%	80%
3		26 - 50%	60%
4		51 - 75%	40%
5		75 - 90%	20%
6		90 - 100%	0%

Table 03A: Scoring Criteria for % instances violations

Sr.No.	Description	Average % Instances violation for the month	Score
1	Average % Instances violation for the month	1 to 5 %	100%
2		5 - 15 %	75%
3		16 - 25 %	50%
4		26 to 50 %	25%
5		> 50%	0%

Table 03B: Scoring Criteria for % Magnitude violations			
Sr.No.	Description	% Magnitude outside limits	Score
1	% Magnitude Outside permissible limits	1 to 5	90%
2		6 to 10	75%
3		11 to 20	50%
4		21 to 25	25%
5		> 25	0%

Both Magnitude and no. of instances exceeding the permissible limits are given equal weightage to arrive at Voltage violation score.

Table 03: Scoring Criteria for % Voltage violations			
Sr.No.	Description	% Values arrived from Table 3A, 3B	Weightage
1	% instances violations		50%
2	% Magnitude violations		50%
	TOTAL		100%

THD Scoring Criteria:

Table 04: Scoring Criteria for THD			
Sr.No.	Description	Pass/Fail	Score
1	THD Pass or Fails for a month as per PQM report	Pass	100%
2		Fail	0%

Power Frequency scoring criteria: As frequency is considered to be the hygiene factor of Power supply, no weightage is given to this attribute.

Table 05: Scoring Criteria for Power Frequency			
Sr.No.	Description	Pass/Fail	Score
1	Frequency Pass or Fails for a month as per PQM report	Pass	NA
2		Fail	NA

Flicker scoring criteria:

As Flicker are related to voltage variations and Sag/Swell instances, no separate weightage is given to this attribute.

Table 06: Scoring Criteria for Flicker			
Sr.No.	Description	Pass/Fail	Score
1	Flicker test Pass or Fails for a month as per PQM report	Pass	NA
2		Fail	NA

8. INTEGRATION WITH GIS:

Based on the assumptions defined in section 6, individual RSS / DSS wise Power Quality Indices are calculated for every month. Thus, overall Zonal Power Quality Index is arrived and depicted in Geographic Information System (GIS) of Mumbai for every month as shown in figure 08.

Complete Distribution infrastructure of Tata Power is mapped in Geographic Information System (GIS). To provide graphical representation of Power quality based on the scores achieved for a particular month, separate layer is created in GIS which takes scores as the inputs and outputs the visual representation of Power quality over entire Mumbai License area bifurcated in to 6 zones as depicted in Figure 8.

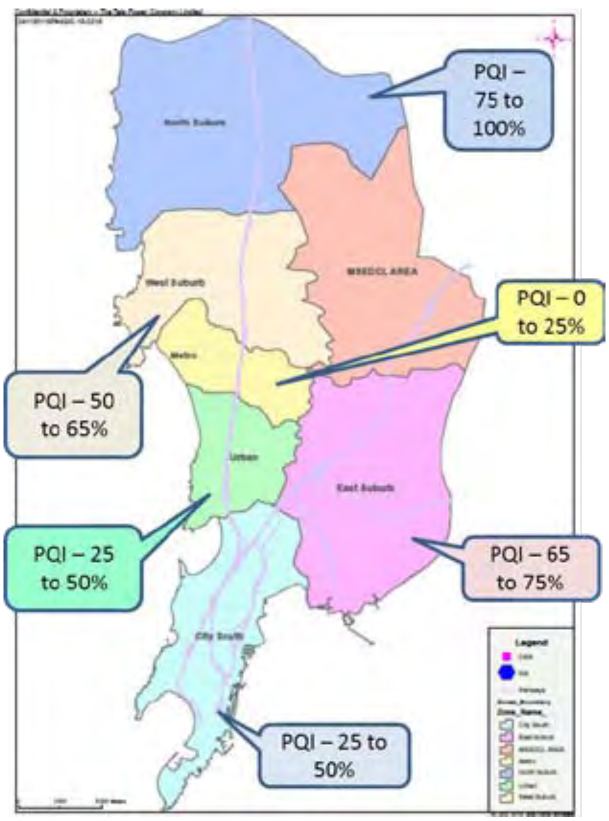

Figure-8: Visual representation of Power Quality over LA.

9. CASE STUDY:

Typical Hospitality Consumer of Tata Power getting supply on 22kV is considered in this paper for case study. This consumer is at a very close proximity to the source RSS of Tata Power.

This consumer was repeatedly complaining on the problem of voltage exceeding permissible limits thereby causing auto changeover of supply from utility to DG to protect sensitive equipment for high voltage. Key consumer is also complaining on consistent high voltage during late night and early hours due to which there is failure in luminaries, stoppage of lifts, failure of cards in server room etc.

Analysis of Power quality attributes:

To identify the problem, it is needed to monitor the power quality of source substation. For this purpose, PQM is installed at both 22kV bus sections of Tata Power RSS. Actual monitoring and measurement of Power quality attributes is given in detail based on assumptions mentioned in section 6.

a) Voltage Sag/ Swell:

Out of total 22 instances, 5 (23%) are outside permissible limits.

Depth (d) / Duration (t)	10ms < t < 50ms	50ms < t < 200ms	200ms < t < 500ms	500ms < t < 3s
80%<=d<90%	1	7	1	1
70%<=d<80%	2	2	0	0
50%<=d<70%	0	3	0	0
10%<=d<50%	0	2	0	0
0%<=d<10%	0	0	0	3

Table 06: Sag report of DSS

Inference: *Total sags observed are 22 nos. out of which 5 instances are outside tolerable limits. These 5 instances are correlated with Utility level and grid level trippings / disturbances occurred during the period to understand the responsibility and possible reasons for Sag/Swell. Corrective actions can be designed not to repeat issues pertaining to utility.*

PQ SCORE: Basis table 2 of "ASSUMPTIONS ON POWER QUALITY SCORING", score awarded to Voltage Sag / Swell is 80 %.

b) Voltage Variations:

15 min recorded voltage Data from Power quality monitor is extracted and graph plotted with time of day against Voltage magnitude for all days of a month.

Data model arrives at

a) no. of instances, voltage violated permissible limits and

b) % Magnitude of voltage violated permissible limits.

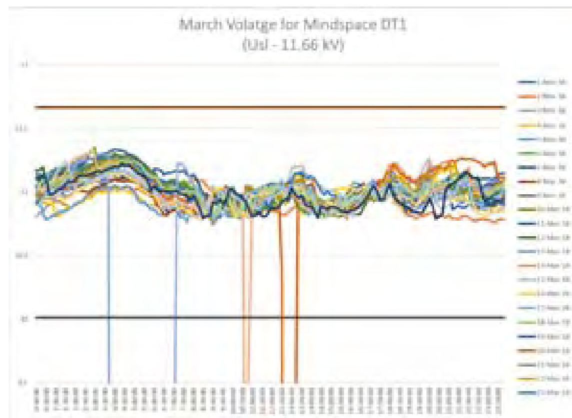

Figure-6: 24 Hr Voltage Profile plotted for all days of a month

Inference: *In this case, as the supply voltage was well within lower and upper permissible limits, it is ensured that tap settings on utility side of Power transformers are at best possible positions over 24 hr period.*

PQ SCORE: For this particular RSS, there are no violations for the month as depicted in figure:6. Thus the voltage score is 100 % for the month.

c) THD: Based on the report, Power quality has failed the THD test

Phase	Time within limit	Max Value	Min Value	95% Value	Result
THDF U1	99.15%	150%	1.07%	1.92%	Failed
THDF U2	99.53%	150%	1.05%	2.06%	Failed
THDF U3	99.53%	150%	1.11%	2.03%	Failed

Table 08: THD report of RSS

Inference: *This indicates there are harmonics in the system. Reason for harmonics injection may be due to either Utility or the consumer. This need to be further drilled down by analysing the equipment of both Utility and Consumer to identify the harmonics source and take necessary action by the responsible authority*.

PQ SCORE: THD score for the month is 100 %.

d) Overall Scoring Criteria:

*With individual power quality attributes scores availed from a) to c) of case study, Power Quality Index for this particular RSS for the month is calculated as (50% * Voltage variation score) + (30% * Voltage Sag/Swell score) + (20 % * THD score) which comes to be **74%** which means there is a scope of improvement by the joint effort of consumer and Utility to improve on power quality of this particular RSS/DSS.*

BENEFITS

Power Quality Monitoring and Indexing can be beneficial to Power utilities for following reasons:

- Identical to the regular health check-up, Power quality monitoring benefits in identifying recurring issues affecting the quality of supply
- Minute details in to THD and IHD help in identifying consumers polluting the source supply and take corrective actions
- Voltage Profiles pattern give picture of the time of the day where there is either over or under voltage thus giving guidelines to set tap positions of respective Off-Load tap changers.
- Mapping of Sag / Swell instances recorded in the report with grid disturbances can isolate utility specific reasons for Sag/Swell occurrence. This can help utility in planning corrective / preventive measures to arrest such incidents.
- Power Quality scoring can help to gauge the performance of individual zones and bring that competitive spirit to push the scores to 100 %.
- Ultimate benefit goes to the consumer in getting Reliable and Quality Power supply thereby extending the life of their sensitive equipment too.
- Recorded Grid level disturbances can be taken up with STU to arrest them.

CONCLUSION

- In metropolitan cities, reliability has become hygiene factor. To meet increasing consumer's requirements / expectations, we need to benchmark on Power quality too. Thus, it is need of the hour for regular monitoring of power quality and arrive at corrective actions to arrest the reasons effecting power quality attributes.
- However, as of now there are no standards to refer for scoring of a utility based on its performance on different Power quality attributes. Also, Power Quality meters available in the market are manufacturer specific in the sense, original equipment manufacturer's software is required to access the PQ data from remote end, data analysis and reporting on Power Quality.
- There are no interoperability standards available to have a common platform irrespective of original equipment manufacturer for data collection, analysis and standard reporting.
- Remote collection of data is another challenge which needs either Fibre / CDMA / GPRS connectivity whose reliability may be a question for accessing data and for auto alerts in case of discrepancy.
- With the availability of Power quality attributes data, it is possible to highlight both utility level and also at Grid level to come up with optimistic solutions to ensure power quality.

  In the coming times, , PQ monitoring & measurement shall be an important measure for benchmarking power distribution utilities

REFERENCES

[1] Semistandard F47.

[2] J.F.G.Cobben, Jasper F.L. van Casteren 2006, "Classification methodologies for Power Quality" "Electrical Power Quality and Utilisation, MagazineVol II, No.01 2006.

[3] https://en.wikipedia.org/wiki/

Renewable Energy

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Adaptive Control Strategies and Communications for Utility Integration of Photovoltaic Solar Sites

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Abstract—**The integration of photovoltaic (PV) solar sites and other distributed energy resources (DERs) into utility control systems is an increasingly important topic as the penetration levels of these resources continue to increase. The evolving regulatory and operational landscape between DER operators and regional utilities is creating opportunities for DERs to be used in grid support activities. The inherently fast-acting characteristics of inverters make them especially suited for short-duration sourcing and sinking of reactive power. This paper discusses how to address the communications integration and activation of adaptive control strategies for these DER sites. An integrated control solution needs to address methods of collecting wide-area power system state information in such a way that the feedback is available for potential control strategies. Network topology, communications protocols, time coherence, and data update rates are considered. Additionally, PV sites can operate in a number of different control modes based on grid conditions and available solar radiation. These modes can include power factor matching, power factor correction, voltage support, and net metering, among others. This paper presents an overview of the control and monitoring infrastructure necessary to support emerging PV control methodologies.**

I. Introduction

The adoption of distributed energy resources (DERs) into the electric power distribution system has increased rapidly over the past decade. This trend has accelerated greatly in the past few years, with photovoltaic (PV) power production playing an increasingly important role. The growth in DERs is expected to continue into the future, largely driven by renewable energy portfolio standards (RPSs) and concern over the adverse environmental impacts of hydrocarbon-based energy production. Utilities, especially those in states with aggressive RPS targets, need to adapt to a changing paradigm in which distribution grids are intelligent and multidirectional and contain intermittent generation.

The increased DER deployment into the distribution grid, designed for radial power flow, presents certain technical challenges for maintaining power system stability. Present regulations governing DER integration into electric power systems do not allow these resources to participate in power system support activities. In fact, DERs are mandated to disconnect from the grid during periods of instability, which in some circumstances actually exacerbates the instability. Various industry and regulatory groups have identified this as an area for improvement. The IEEE has established a working group to amend the IEEE 1547 Standard for Interconnecting Distributed Resources With Electric Power Systems to reflect an industry-wide desire for these resources to behave similar to conventional generation. California has the most aggressive RPS that targets 33 percent renewable energy resources by 2020 with a goal of 12 GW of localized electricity generation. California has also recognized the importance of revising the DER technical requirements in California Public Utilities Commission (CPUC) Rule 21 to accommodate the expected rise in DER adoption into the distribution grid [1]. The purpose for revising both IEEE 1547 and CPUC Rule 21 is to allow DERs greater flexibility in grid support activities, which will enhance the reliability of the power system.

In addition to changes in operating practices, grid operators, over time, need to modify the existing infrastructure to transition from a passive distribution model in which energy is pushed from a central location to an active model where generation is located throughout the power distribution network. Such a system requires many intelligent nodes with the dual capabilities of operating autonomously and dynamically modifying operating parameters in response to utility control signals. Power conversion devices are the base components in building this architecture. As an important first step, inverter manufacturers need to design and incorporate state-of-the-art technologies that enable these devices to provide voltage and frequency regulation at the point of common coupling (PCC).

Another important consideration is the communications network that acts as the link between the intelligent nodes located throughout the distribution system. Without adequate communications, it is impractical for automation systems to ascertain the correct system state and react appropriately to changing system dynamics. An interface capable of concentrating communications from power conversion devices and integrating with utility supervisory control and data acquisition (SCADA) systems decreases network bandwidth requirements and mitigates integration issues between different technologies. These interface devices should also be capable of processing automation logic and coordinating the sending of control signals to localized device arrays or devices located across a wide geographic area. Depending on the distribution architecture, there will likely be other components necessary to implement a reliable and dependable power delivery system.

The protection paradigms governing modern distribution systems are also affected by increased DER penetration. While this is an important topic and deserves consideration, it is outside the scope of this paper. This paper describes in detail the component characteristics deemed essential to enable DERs to actively participate in grid support activities and to respond to control signals sent from a utility control center. Control functions deemed essential for grid support are outlined along with discussion of their implementation in power inverter technologies. Methodologies for establishing an effective communications network capable of transmitting data securely and reliably with minimum latency are discussed. Consideration is also given to the data models needed to ensure data coherency between the utility and the DER. Finally, this paper provides an overview of the integration characteristics necessary in a DER control network.

II. Inverter Control Functions

Inverters, as power electronics-based devices, have the capability to rapidly change the characteristics of their output waveforms to respond to grid transient events such as voltage and frequency sags and swells. The inverter itself can control real and reactive power (up to its nameplate kVA rating) in subcycle time frames in an attempt to counteract the grid transients as well as at a longer time scale (continually) to assist in the steady-state operation of the bulk distribution and transmission grid infrastructures. The three primary categories of inverter response are as follows:

- Static or steady-state operation.
- Dynamic operation.
- Trip envelopes and ride-through capabilities.

While these control actions are feasible with modern technology, grid and DER site operators need to remain cognizant of the regulatory environment governing the activation of these control strategies. The following discussion summarizes the most commonly employed inverter control functions.

A. Static or Steady-State Operation

The following functions belong to a class of inverter operating modes identified as static or steady state. These functions respond to an operating set point for an internal inverter parameter, such as output watts or power factor. The unit does not automatically change the operating state based on external measurements in these modes.

1) Fixed Power Factor

To achieve interconnection requirements where system voltage is a concern due to the variability of real power output from the inverter, operators use nonunity power factor operation (either sourcing or sinking VARs). Typical power factor ranges are 0.8 leading to 0.8 lagging; inverters accept this range as a direct set point.

2) Fixed VAR Output

This function provides a means for the inverter to source or sink a specified amount of reactive power, regardless of the real power operating point or power factor. As an example, local transformer and motor VARs can be offset by the inverter. In some cases, this action alleviates demand charges resulting from poor power factor at a PCC or load center.

3) Curtailment (Fixed Real Power Set Point)

In curtailment mode, inverters produce a fixed amount of real output power that is below the nameplate capacity. For no-backfeed interconnection agreements between a utility and DER operator, designers commonly activate this mode to ensure the main breaker stays connected, even under a loss-of-load event, by reducing the real output power delivery of the inverters.

4) Ramp Rate

The physical characteristics of power electronics-based devices allow rapid changes to the output waveform, which can cause harmonic injection and transient behavior at the PCC. The ramp rate setting allows the user to program a rate of change of real power from one set point to the next in an attempt to smooth out deviations in output current.

B. Dynamic Autonomous Functions

Unlike static operations, dynamic functions employ externally measured feedback to maintain an operating parameter within the power system. Either the inverter or master controller (for a fleet of inverters) calculates the error between measured values and set points to control the inverter outputs. The controller collects measurements either locally or remotely.

1) Volt/VAR

In volt/VAR mode, the inverter modifies the reactive power output (VAR) as a function of the measured system voltage. The intent of this mode is that the inverter operates as a local voltage regulator. If the measured system voltage dips below the operating thresholds, the inverter supplies VARs to boost the voltage. Similarly, if system voltage rises, the inverter sinks VARs to reduce the system voltage to within the operating threshold. Inherent to this mode is the capability to either prioritize VAR output or watt output to meet the needs of all the stakeholders. Different hysteresis bands and slopes for the volt/VAR function allow for a more flexible solution to meet local interconnection requirements.

Fig. 1 provides an example of this type of operating curve.

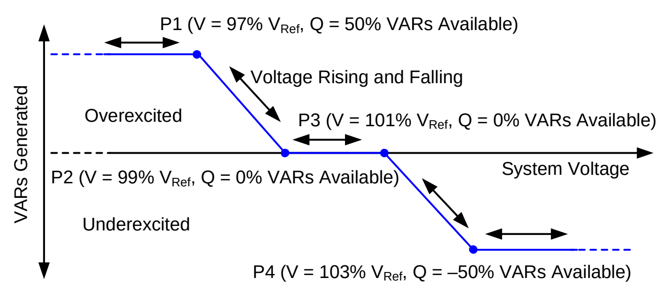

Fig. 1. Example settings of volt/VAR mode using available VARs.

2) Watt-Frequency

Similar to the volt/VAR function, the inverter can modify its real power output in response to measured frequency events and perform droop control to assist the bulk power system in regulating system frequency. This function can be either an open or closed loop and benefits from a programmable droop characteristic that provides flexibility in meeting interconnection requirements.

3) Dynamic Reactive Current

In addition to volt/VAR, the dynamic reactive current function operates on the measured voltage rate of change rather than the actual quantity. This control action helps to stabilize rapidly increasing or decreasing system voltages.

C. Trip Envelopes and Ride-Through Capabilities

Present regulations require inverters to rapidly disconnect from the power system during system events. The disconnection time period is based on the voltage per-unit deviation. The existing IEEE 1547 low- and high-voltage ride-through limits along with the new proposed limits are illustrated in Fig. 2. The black voltage-time curve represents the existing IEEE 1547 limits. The green and red curves are the limits proposed in IEEE 1547a. The green curve represents the must-stay-connected range, while the red represents the must-disconnect limits.

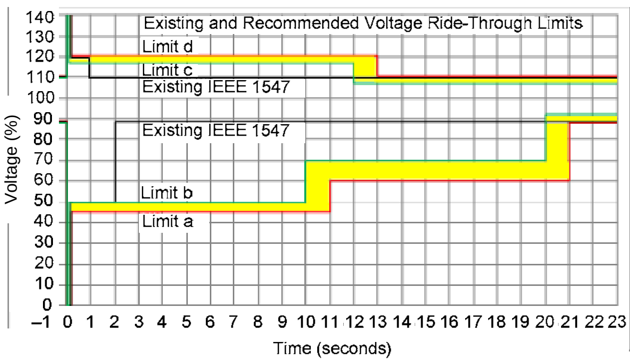

Fig. 2. Existing and proposed voltage ride-through limits.

Similar to the new proposed voltage ride-through limits, the limits proposed by IEEE 1547a for frequency ride through provide greater flexibility in inverter operating conditions. This is becoming increasingly important in low-inertia distribution systems (especially those created by islanded systems) because the frequency tends to drift over a wider range with respect to load. Fig. 3 shows the default frequency-time curve along with underfrequency (UF) and overfrequency (OF) primary and secondary limits, which can be activated by the master controller in coordination with the power system operator.

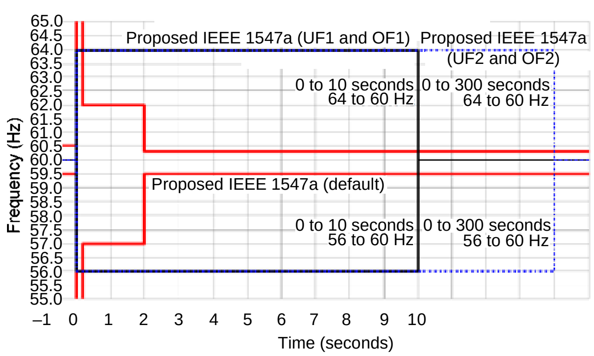

Fig. 3. Proposed frequency parameters in IEEE 1547a.

The changes proposed in CPUC Rule 21 and IEEE 1547a stipulate a large role for DER generation to assist in grid support during events. Industry groups, along with regulatory authorities, are working to harmonize the proposed operating standard to limit the adverse effects of DER installations during power system events. The ability for DER operators to configure trip envelopes allows for a wider variance in inverter operating bounds while preserving the need to coordinate with local system protection.

III. Communication

Under normal operating conditions, advanced functionality in inverters enables these devices to operate autonomously in regulating voltage, frequency, and power factor at the PCC. However, under certain grid conditions, the potential exists for autonomous inverter action to exasperate grid instability [2]. Using communications-assisted control actions to modify operating parameters and send permissive and blocking signals from SCADA gives operators and asset owners the flexibility to respond to changing conditions.

In the existing regulations and current effort to revise the regulations governing DER interconnection, CPUC and IEEE have recognized that communications capability in DERs is an essential functionality [1] [3]. Two key considerations, interoperability and extensibility, should govern the design for the interface between the DER local-area network (LAN) and the wide-area network (WAN) that is responsible for transmitting information to utility SCADA systems and other stakeholder energy management systems (EMSs).

Interoperability is the ability of one or more devices to exchange information without special effort. This is achieved when system designers and integrators use standard data objects, protocols, and methods for transmitting data. Extensibility refers to the ability of a system to accommodate future technological advancements. This is an important characteristic because the capability of devices in the network continues to evolve at a rapid pace and is usually upgradable via software patches. Equipment owners need to incorporate both of these considerations early in the project decision-making process, reducing the likelihood of expensive system upgrades or redesigns in the future.

DER installations are located based on available resources, proximity to existing utility infrastructure, and local financial incentives, among many other factors. When considering future installations, time should be spent evaluating the existing physical constraints—such as the distance to the nearest substation, the legacy communications infrastructure, and the project budget constraints—in order to help select the best communications method for the DER installation. In this context, the chosen method must also fulfill the performance criteria for the given application.

A. Performance Metrics

This subsection describes the performance metrics that should be considered when specifying the communications technology used at the DER site. Note that each performance criterion discussed is not mutually exclusive and each interacts with one another. The asset owners and the interconnected utility must determine the appropriate balance.

1) Throughput

Throughput is the amount of information that is successfully transmitted through a network, usually expressed in bits per second (bps). This parameter contains protocol overhead and message retransmissions due to errors encountered in the network. A more useful performance metric is goodput, which is the amount of useful data or application-level data that reaches the destination application. Carefully consider which communications protocols exhibit the lowest overhead, especially when network throughput is limited, in order to maximize network goodput.

2) Latency

Latency represents the time that elapses between when a message is generated until it is processed in the destination device. The network throughput, message size, and processing required in intervening equipment contribute to message latency. Communicating only the information necessary for the application and reducing the number of intervening nodes reduce message latency.

3) Reliability

Reliability as defined in IEEE 1547.3 includes "reliability, availability, and maintainability of the communication system" [4]. The parameter accounts for software and hardware malfunctions, downtime due to maintenance, and network reconfiguration times. Reliability represents the likelihood of a sent message reaching its intended destination within permitted time constraints.

4) Security

Security describes the ability of a network to protect against unauthorized intrusions. Intrusions manifest as attempts to collect application and user data and/or attempts to disrupt normal communications and system operation. Physical security is achieved by limiting access to physical communications infrastructure such as multiplexers and switches. Cybersecurity is generally a more complex topic that requires careful choices in technologies employed throughout the communications network. Examples of cybersecurity technologies are encryption algorithms, firewalls, password management, and antivirus. There are several protocols that operate at different layers within the Open Systems Interconnection (OSI) communications model that provide mechanisms for securing data transmission. Internet Protocol Security (IPsec), Transport Layer Security (TLS), and Secure Shell (SSH) are examples of popular security protocols for Ethernet networks.

B. Network Technologies

There are many network technologies used in modern communications networks. This subsection is a brief discussion of the technologies that utilities and DER owners are likely to use in WANs and LANs. Understanding the existing technologies deployed in communications networks provides insight into how performance metrics affect DER applications.

1) Wide-Area Networks

a) Synchronous Networks

Time-division multiplexing (TDM) is a long-established method for WAN communication. TDM technology provides the deterministic and high-availability performance required for mission-critical information transfer. Synchronous optical networks (SONETs) and synchronous digital hierarchy (SDH) are examples of modern TDM standards widely used on dedicated fiber-optic networks. These technologies provide a point-to-point communications link that provisions dedicated bandwidth for each application. There are existing technologies that promise 5-millisecond network failover times if the network is configured in a ring topology, as shown in Fig. 4. This provides a redundant path and significantly increases communications reliability.

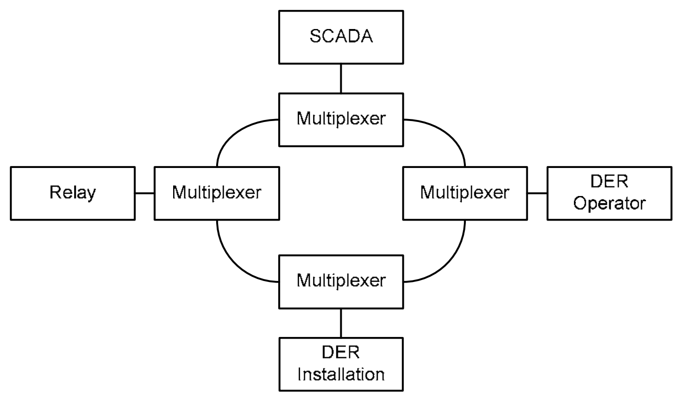

Fig. 4. A SONET ring architecture with multiple access points.

b) Asynchronous Networks

Asynchronous communication in modern WANs is dominated by a group of communications technologies generally referred to as Ethernet. These technologies are widely used in private and proprietary networks and have gained increased acceptance in the electric power industry. Developments in information technology (IT) and the deployment of these technologies into Internet infrastructure have put downward pressure on equipment and installation costs, which has contributed significantly to the rising popularity of Ethernet across a wide spectrum of industries. Many utilities lease communications resources from local service providers that employ Ethernet technologies.

In Ethernet networks, LAN and WAN infrastructure devices (such as managed switches) route data packets through a wide variety of network topologies, depicted commonly as clouds (see Fig. 5). By design, the path a message takes to a destination can be varied and is not known by the end user. Packet rerouting and network reconfiguration are commonplace, and as such, the communication is not deterministic. This makes it difficult for designers to estimate latency and reliability metrics, especially when the network is not owned by the utility. There are several technologies that seek to address the nondeterministic nature of Ethernet, and careful examination of these technologies is required when applications require fast and reliable information exchange.

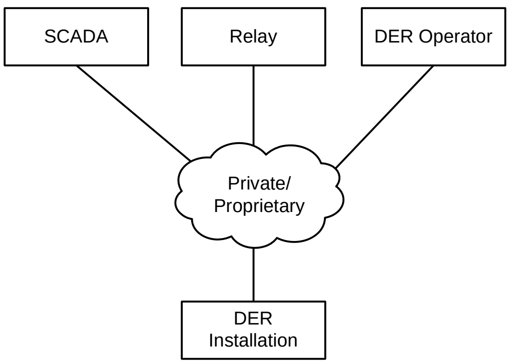

Fig. 5. An Ethernet architecture.

2) Local-Area Network

The LAN that links the intelligent electronic devices (IEDs) throughout a DER installation is an asynchronous network that incorporates either serial (EIA-232, EIA-485, EIA-422) or Ethernet communication, or a combination of both. The installation of Ethernet communication in power system architectures has accelerated in the last couple of years. This is driven by reduced cabling requirements, the perceived plug-and-play nature of the technology, and adoption of the IEC 61850 communications standard. Ethernet networks are usually characterized by routable protocols, high bandwidth, and interfaces capable of supporting multiple protocol sessions simultaneously. Additional infrastructure (i.e., switches and routers) supports the interconnection of devices within the communications topology. In many cases, Ethernet network designs require segmentation of traffic from devices into virtual LANs (VLANs) to reduce the processing burden at the network interface controller and improve reliability. Although Ethernet has been the main topic for discussion recently, serial communication still provides many benefits, such as point-to-point topologies, accessibility to serial protocols, and proven troubleshooting methodologies.

3) LAN-to-WAN Interface

As mentioned previously, the link connecting LANs to WANs is largely determined by the physical constraints of the DER installation. Fiber-optic cables offer fast data rates and immunity to electromagnetic interference and ground potential rise. The cost to install fiber may be prohibitive for DER installations far from utility interconnections. Point-to-point or point-to-multipoint wireless radios offer a good alternative to fiber, and 38.4 kbps data rates are available in existing technologies.

It is important to engage the IT and operational groups of both the utility and DER operators to determine the procedures for accessing and exchanging data with the DER LAN. Information exchange agreements should define standard security practices, protocol support, available data sets, and procedures for activating control strategies.

IV. Infrastructure

In order to enable flexible DER control strategies between utility operators and DER sites, the infrastructure of IEDs in the network needs to exhibit some minimum integration functionality. Advanced consideration of device capabilities during installation or upgrades by system designers minimizes rework or field upgrades at a later time.

A. Data Concentrators

PV inverters have almost exclusively used Modbus® for the small amount of integration previously available. The referenced CPUC report includes a detailed discussion about gaining greater integration of PV sites into wide-area SCADA systems by designing standard interfaces and protocols into PV systems [1]. The report authors express concern that without standard interfaces, new DER installations will begin operating with a wide variety of communications methods, none the same, creating a bottleneck and potential need for many equipment upgrades in order to make the wide-area system work harmoniously. The proposal is to create one standard integration method and encourage all equipment manufacturers and users to take that approach. Due to growing use and an active organizing body, IEC 61850 is the desired approach, and IEC 61850 logical nodes have been created as a model for the DER installations. Additionally, the DNP Users Group published an application note describing a custom profile for using DNP3 as part of PV integration projects [5]. The application note specifically uses IEEE 1815.1 naming so that protocol converters can be used to efficiently map DNP3 data from DER systems into IEC 61850 networks.

As discussed previously, inverters are not the only IEDs required for many control strategies. Microprocessor-based protective relays, revenue meters, and equipment monitors work together in order to perform the necessary feedback, control, and supervisory functions. Even though standards organizations suggest common integration methods, it is not always possible for designers to enlist a common communications mechanism between all of the IEDs in the network.

Data concentrators solve this problem by providing a means for all of these disparate devices to communicate amongst themselves while simultaneously providing a common point of DER connection to SCADA or other master systems.

As shown in Fig. 6, data concentrators support multiple communications interfaces over a variety of protocols. For simplicity, the diagram does not include Ethernet or TDM infrastructure elements. Some equipment manufacturers also provide data concentrators that not only support the protocol mapping functions but also integrate the advanced control capabilities that this paper discusses [6].

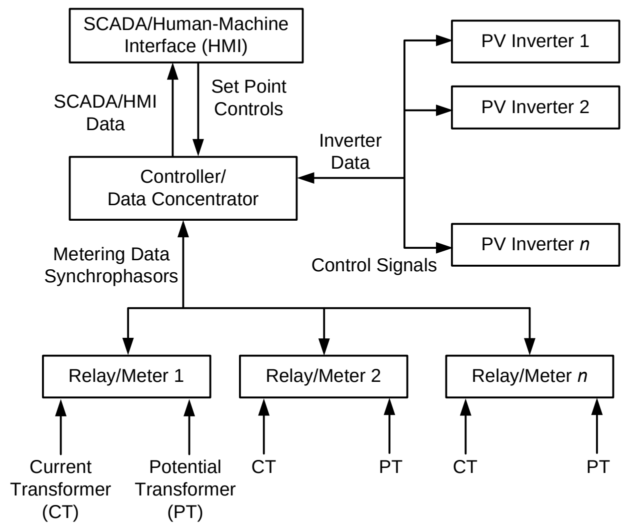

Fig. 6. DER LAN network architecture.

B. Inverters

In order to achieve more than autonomous operation, PV inverters need to be capable of integrated operation via communications protocols and networks. Inverter manufacturers have commonly implemented this service via Modbus protocol for the past few generations of devices. Contemporary models of inverters exist that include Ethernet for integration and configuration. As utility-scale PV integration becomes more prevalent, protocol and media options will likely grow.

C. Protective Relays

Even though their main function is equipment and personnel protection, modern relays are quite valuable as multifunction system monitors and controllers. Based on market feedback, relay manufacturers have deployed advanced communication, user logic, and security into many contemporary devices. Because they reside throughout the network, including at the PCC, relays can be powerful (and almost free) additions to the instrumentation network.

D. Meters and Equipment Monitors

Similar to protective relays, revenue meters and distributed equipment monitors natively include many communications and control mechanisms. Meters additionally provide a detailed feedback mechanism for many types of power system parameters and power quality. To the extent these devices exist at relevant nodes in the power system, they are ready-made for use in future PV control strategies.

E. Synchrophasor Controllers

As previously noted, DER installations are mandated to accurately identify system instability and quickly take appropriate corrective actions. In some cases, the proper response is for the inverter to disconnect; in other cases, the DER facility may be able to actively counteract the power system disturbance (i.e., watt-frequency mode or dynamic reactive current mode). Before any response initiates, the DER master controller needs to measure the dynamic power system state, categorize any disturbances, and determine the needed response.

Previous works on smart island detection describe synchrophasor-based anti-islanding schemes for synchronous generators and PV sites [7] [8]. Controllers for these types of installations need to be able to simultaneously receive synchronized phasor messages from multiple IEDs, communicate with one or more local inverters, and evaluate the smart islanding algorithm. For simplicity and cost-effectiveness, system designers gain the most benefit if the controller also performs the data concentration and protocol conversion functions previously discussed.

In order to understand the significant operational advantages inherent to smart islanding control, we need to briefly summarize the detection algorithm as presented in detail elsewhere [7]. As shown in Fig. 7, the controller receives synchrophasor messages from local and remote relays in the power system. Even though the figure only shows two for purposes of illustration, more IEDs (measuring nodes within the operating area of the DER) may be present, depending on the system topology and performance requirements. For each node of interest, the controller uses the synchronized vector messages to calculate the vector angle between the local (closest node to the inverter) and remote nodes.

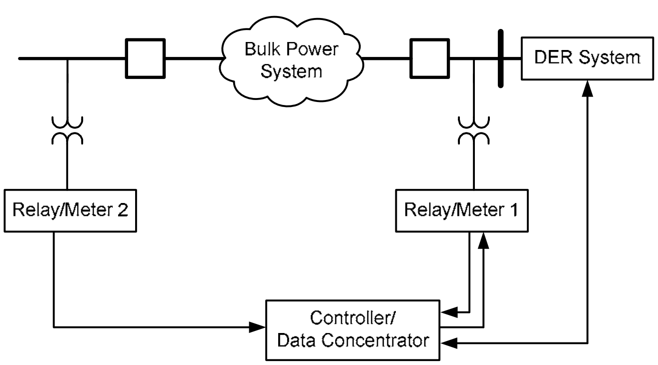

Fig. 7. Master controller connection summary.

The controller tracks the rate of change of that angle, which is labeled slip frequency. If the DER is properly synchronized with the power system, the slip frequency should be very low, with an average of zero over time. The controller also calculates slip acceleration as the rate of change of slip frequency. From the slip and acceleration calculation, the algorithm operates in two ways. First, the slip frequency is compared to the threshold. If the slip exceeds the threshold for longer than a predetermined time, then the algorithm determines that an island exists.

The second method uses both the slip and acceleration in a relationship, as shown in Fig. 8, and identifies an island more quickly than if only using slip as a detection method.

These wide-area island detection methods provide important advantages for quickly distinguishing between events that require DER separation versus transients that could be eliminated using the control mechanisms discussed previously. Synchrophasor-based algorithms also are faster and more selective than the local voltage and frequency-based methods commonly employed at modern PV sites.

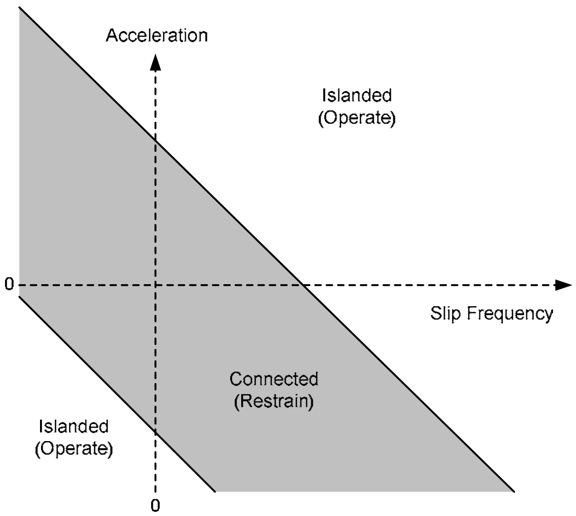

Fig. 8. Islanding detection characteristics [7].

In addition to islanded conditions, DER installations need to properly identify and mitigate negative consequences during unbalanced conditions. Either during single-line-to-ground faults or single-pole tripping on longer transmission lines, standard power control strategies for inverters introduce unacceptable overcurrent and VAR oscillations to the power system [9]. The synchrophasor-based controller that provides smart islanding supervision also has the needed phasor information to calculate symmetrical components and identify an unbalanced condition. Depending on the regional operating standards and capabilities of the inverters in operation, the controller can automatically respond during an unbalanced condition.

F. Additional Control Functions

In addition to detection for island and unbalanced conditions, DER controllers need to support a number of other supervisory and custom logic functions.

1) Priority Control Modes

As discussed in previous sections, there are multiple control strategies available for the operation of DER installations, depending on power system conditions and the standards of the DER owner and local utility. In some cases, more than one control function can be active that would simultaneously impact the same inverter parameter, such as output watts. In those cases, the master controller needs to arbitrate which control functions can remain active and which reference signals take priority. Industry groups have published guidelines for this operation that assist in implementing a common strategy between manufacturers, but the local controller device needs to be capable of processing the control mode commands and determining the appropriate configuration [5]. For example, a command for frequency-watt control takes precedence over dynamic volt-watt operation.

2) Set Point and Control Mode Management

In the simplest form, a DER unit may consist of one controller and a local inverter, but the most flexible and useful configuration is to have one master controller that can actively supervise multiple PV locations over a geographic area. In this way, all of the DER installations can operate in concert with a single command channel to the local utility and SCADA. Additionally, some control functions, such as real power smoothing, depend on a reference power measurement from a remote meter or other IED. The combined controller and data concentrator simplifies all wide-area modes.

3) Logic Engine

While many common mathematical functions and communications protocols reside in controllers and data concentrators, device manufacturers cannot predict or preconfigure the wide array of installations and operating characteristics that may be in use. Therefore, the controller device needs a simple and efficient means for users to employ their own logic and business rules. A controller that includes an IEC 61131-3 logic engine is a popular choice due to the wide variety of programmable logic controllers (PLCs) and general system controllers that use such a standard logic engine. IEC 61131 includes standard programming languages that are widely used throughout utility and industrial automation applications. Users report decreased training costs and improved development times because logic designers do not need to learn new programming languages and techniques for each device in a system.

V. Conclusion

Utilities and system operators are confronted with a new paradigm in how the electric power grid is configured and managed. The presence of variable generation in the distribution grid is a new reality, and entities operating in locations with significant DER generation (more than 15 percent) need to prepare strategies for incorporating this new set of generation in a way that increases reliability, security, and flexibility. The presented architecture comprises several technologies that cross organizational and operational boundaries. The intent of this paper is to present a holistic view of incorporating the various technologies in order to improve system performance and take advantage of emerging regulatory standards. While PV inverters are central to the control architecture, many other IEDs need to work in concert with the inverter in order to successfully implement dynamic control strategies. Additionally, the communications infrastructure needs to exhibit the necessary bandwidth, availability, and security to support the reporting and control functions.

VI. References

[1] California Energy Commission and California Public Utilities Commission, "CEC/CPUC Recommendations for Updating I-DER Technical Requirements in Rule 21," October 2013. Available: http://www.energy.ca.gov.

[2] E. O. Schweitzer, III, D. Finney, and M. Mynam, "Applying Radio Communication in Distribution Generation Teleprotection Schemes," proceedings of the 65th Annual Conference for Protective Relay Engineers, College Station, TX, April 2012.

[3] IEEE Standard 1547-2003, IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems.

[4] IEEE 1547.3-2007, IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected With Electric Power Systems.

[5] DNP Users Group, "DNP3 Profile for Advanced Photovoltaic Generation and Storage." Available: https://www.dnp.org.

[6] D. Taggart, K. Hao, R. Jenkins, and R. VanHatten, "Power Factor Control for Grid-Tied Photovoltaic Solar Farms," proceedings of the 14th Annual Western Power Delivery Automation Conference, Spokane, WA, March 2012.

[7] M. Mills-Price, M. Scharf, S. Hummel, M. Ropp, D. Joshi, G. Zweigle, K. G. Ravikumar, and B. Flerchinger, "Solar Generation Control With Time-Synchronized Phasors," proceedings of the 64th Annual Conference for Protective Relay Engineers, College Station, TX, April 2011.

[8] J. Mulhausen, J. Schaefer, M. Mynam, A. Guzmán, and M. Donolo, "Anti-Islanding Today, Successful Islanding in the Future," proceedings of the 63rd Annual Conference for Protective Relay Engineers, College Station, TX, March 2010.

[9] G. M. S. Azevedo, P. Rodriguez, M. C. Cavalcanti, G. Vazquez, and F. A. S. Neves, "New Control Strategy to Allow the Photovoltaic Systems Operation Under Grid Faults," proceedings of the 2009 Brazilian Power Electronics Conference, Bonito-Mato Grosso do Sul, Brazil, September 2009.

VII. Biographies

Michael Mills-Price is the technology development lead for the solar energy business unit at Advanced Energy Industries, Inc. Michael is the principal designer responsible for bringing new technologies to market and continues to lead teams toward advanced systems control to broaden the scope and lessen the impacts associated with widespread photovoltaic adoption. Michael received his Bachelor of Science and Masters of Science in Electrical Engineering from Oregon State University (OSU), is a registered professional engineer, and is an active member of IEEE. Michael is also an adjunct professor at OSU, teaching senior level energy storage and energy distribution systems courses.

Michael Rourke received his Bachelor of Science in Electrical Engineering and Masters of Engineering in Electrical Engineering from the University of Idaho. Michael spent ten years working on research and development of control systems for steel and aluminum facilities; he is a member of the Association of Iron and Steel Technology. He joined Schweitzer Engineering Laboratories, Inc., in 2000. Michael works on product development for automation and integration applications.

Darrin Kite received his Bachelor of Science in Renewable Energy Engineering from the Oregon Institute of Technology in 2012. Before joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2012, he worked as an engineering intern at Bonneville Power Administration. He is presently working as an associate automation engineer in SEL research and development.

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Addressing Protection Challenges Associated with Type 3 and Type 4 Wind Turbine Generators

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Abstract—**Variable-speed doubly fed asynchronous (Type 3) and full converter-based (Type 4) wind turbine generators (WTGs) have complex fault current characteristics governed by proprietary controls. The control technique of some manufacturers is to produce balanced three-phase fault current during unbalanced faults. At present, short-circuit analysis tools commonly used by protection engineers are inadequate in representing the fault current behavior of these WTGs. This paper presents the fault current characteristics of a Type 4 WTG using a detailed MATLAB® and Simulink® model that incorporates pseudo control logic for this converter type. This paper also presents a case study of a misoperation of directional overcurrent relays connected to the collector circuit in an actual wind power plant during a fault. The paper provides recommendations on protecting wind power plants with these converter-based WTGs.**

I. Introduction

Changes in governmental policies intended to expand rapidly growing renewable energy technologies have led to the increased penetration of wind turbine generators (WTGs) in the power system. Almost all new megawatt-scale wind power plants that are being developed use either variable- speed doubly fed asynchronous (Type 3) or full converter-based (Type 4) WTGs. These Type 3 and Type 4 WTGs can produce energy over a wide range of wind speeds, allow for fast and independent control of active and reactive power, limit fault current, and comply with low-voltage ride-through (LVRT) requirements set forth by industry regulatory agencies. Due to the interconnection of these wind power plants to the power grid, it is important to understand their short-circuit behavior in order to develop adequate protection systems that will make the system safer and easy to operate. Short-circuit studies allow protection engineers to selectively determine which circuit breaker ratings, relay settings, and protection methods to adopt for a particular section of the power system.

The short-circuit behavior of fixed-speed squirrel cage induction (Type 1) and variable-slip wound-rotor induction (Type 2) WTGs depends upon the physical characteristics (transient and subtransient impedances) of the WTGs and is therefore well understood [1]. For faults near the WTG terminals, the fault current can be several times the rated full-load current and is only limited by the system and the WTG impedances. The fault current characteristics for Type 1 and Type 2 WTGs are accurately represented in most commercially available short-circuit analysis tools used by protection engineers. On the other hand, Type 3 and Type 4 WTGs have much more complex fault current characteristics and are governed by the proprietary controls of the converters used in these generators. As such, they are subject to arbitrary design choices and can change with each revision of the control algorithm. For the Type 4 WTG, the fault current contribution is usually limited to 1.1 to 1.2 times the rated full-load current, following any initial transients [2]. Short-circuit characteristics of the Type 3 WTG are similar to those of the Type 4 WTG, except during severe faults when the crowbar circuit connected at the rotor is activated. This crowbar circuit is used to help force the field current to zero to avoid overvoltage. With the crowbar circuit activated, the fault current characteristics of the Type 3 WTG transition from a controlled current source to that of an induction generator.

The relatively nascent nature of the Type 3 and Type 4 WTG model development makes it very difficult to use a number of the widely available short-circuit analysis tools employed by protection engineers. This is because the existing tools do not accurately model the dynamics of the WTG control system. From a system protection perspective, it is important to have models that reflect true fault behavior. Unfortunately, such models are mostly manufacturer-specific and proprietary in nature. Even for the same manufacturer, the control technique employed in one design class can be significantly different from that of another. In order to protect the power electronic switching devices used in the converters, these WTGs limit fault current and modify the current waveform during a fault. This unconventional behavior of the Type 3 and Type 4 WTGs presents a host of challenges to the protection engineer responsible for protecting a power system with WTGs.

Over the years, the power industry has developed many standard models for various generators and their associated control systems. These models are publicly available for the study of large-scale power systems. These models are not manufacturer-specific and are widely considered acceptable for use in fault studies. A similar initiative has been organized by the Western Electricity Coordinating Council (WECC), IEEE, and IEC TC88 working groups to develop generic models for the various wind turbine types. The efforts toward these generic model developments are well documented [3] [4]. It is not the intent of this paper to discuss in detail all such developments. However, of particular interest for this paper is the model development for the Type 3 and Type 4 WTGs. The generic models, as clearly identified in [5] and [6], are not suitable for fault studies. These models are developed using a positive-sequence dynamic modeling approach. However, the complexity of the converter controls needed to depict accurate dynamic behavior of these WTGs during fault conditions continues to be a matter of discussion. The generic models for the Type 3 and Type 4 WTGs are obtained from literature describing wind turbine models [7] [8].

For this paper, a detailed GE Type 4 WTG was modeled in MATLAB®. This model was modified to include the generic current limit logic proposed by the WECC. The model was subjected to both balanced and unbalanced faults to study the response of the Type 4 WTG.

This paper is organized as follows. Section II reviews the short-circuit behavior of converter-based WTGs. Section III presents simulation results of the detailed Type 4 WTG model with WECC generic current limit logic under balanced and unbalanced faults. Section IV presents a typical wind power plant layout and common protection philosophy for a collector circuit, and Section V discusses a misoperation of the directionality of a feeder overcurrent relay located at the collector circuit of a wind power plant with Type 4 WTGs. Finally, conclusions and protection recommendations for systems with WTGs are provided in Section VI.

II. Short-Circuit Behavior of Type 3 and Type 4 WTGs

In conventional synchronous and induction generators, the fault current contribution and voltage at the terminals of the machine are determined by the physics (construction) of the machine. Under fault conditions, these generators can essentially be represented by a fixed voltage behind an impedance, even though the impedances of a synchronous generator and an induction generator are time-varying during a fault condition, transitioning from subtransient to transient and finally to steady state.

The behaviors of Type 3 and Type 4 WTGs are governed primarily by the characteristics of the control systems and not by the physical properties of the WTGs [9]. The characteristics of the control systems can be radically different between different designs and versions of firmware that run the control algorithms. Some controls are designed to introduce discontinuities in the voltage and current waveforms during fault conditions when a certain voltage or current magnitude is reached. This is done in order to protect the switching devices used in the converter circuit. Insulated-gate bipolar transistors (IGBTs) or insulated-gate commutated thyristors (IGCTs) are typically used as the switching devices and are intolerant to high current. High current levels are usually generated during fault conditions, and this current must be limited in order to protect the switching devices.

In general, the behaviors of Type 3 and Type 4 WTGs during fault conditions are very similar because both operate as current source inverters. However, for severe faults where the fault current is very high and the voltage at the terminals of the WTG is severely depressed, the behaviors of the generators diverge because of the discontinuous effect of the crowbar circuit used in the Type 3 WTG to regulate the voltage on the dc bus. For both Type 3 and Type 4 WTGs, the fault current magnitude is independent of the impedance between the WTG and fault point but is governed by the controls of the WTG.

A Type 4 WTG is interconnected to the grid via an ac-dc-ac converter. Because the WTG is isolated from the grid by the power converter, the generator type can be synchronous, permanent magnet, or induction. Fig. 1 shows a typical configuration of a Type 4 WTG with a permanent magnet synchronous generator (PMSG). The generator has very little effect on the short-circuit current characteristics of the Type 4 WTG and therefore is usually not modeled for fault studies.

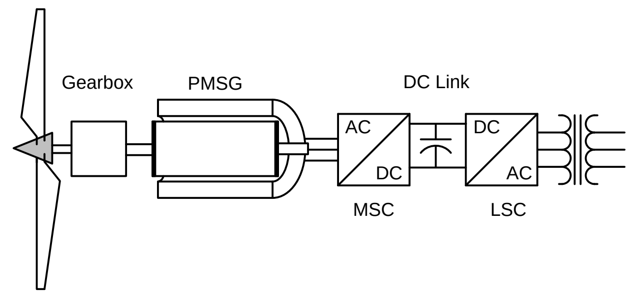

Fig. 1. Type 4 WTG with a PMSG, machine-side converter (MSC), and load-side converter (LSC).

A. Crowbar Circuits in Type 3 WTG

A crowbar circuit in a Type 3 WTG consists of a set of three phase series resistors, as shown in Fig. 2. The resistors are typically controlled by a set of thyristor switches connected back to back (bidirectional).

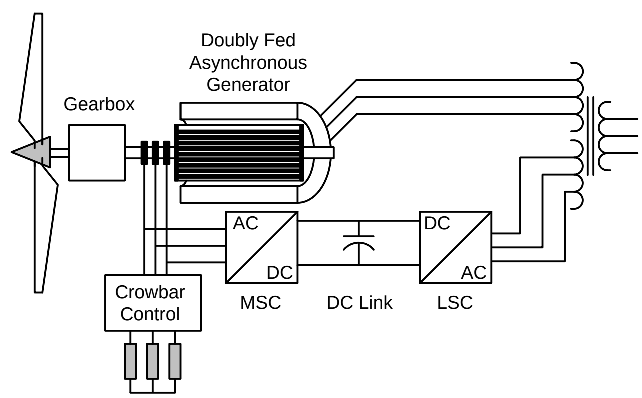

Fig. 2. Type 3 WTG showing the location of the crowbar circuit.

Fig. 2 depicts one method of implementing a crowbar circuit in a Type 3 WTG. Other methods that can be implemented are as follows [9]:

- Protective firing of the MSC to short-circuit the rotor.
- A power electronic switch that can short-circuit the dc link via a burden resistor.
- A chopper-controlled burden resistor connected across the dc link.

The crowbar system is activated when an overcurrent condition occurs on the rotor circuit or an overvoltage condition occurs on the dc link. These conditions typically occur after a fault on the power system [9] [10] [11]. Fig. 3 shows the equivalent circuit of a Type 3 WTG with the crowbar circuit included.

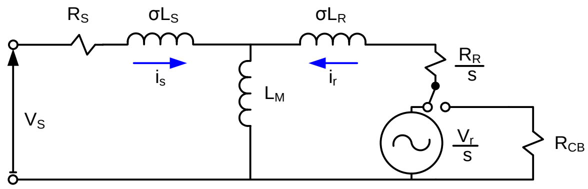

Fig. 3. A Type 3 generator equivalent circuit with the crowbar circuit included.

The rotor of a Type 3 WTG can rotate at either below or above the power system speed. When the rotor rotates above the power system speed, power is moved from the rotor of the generator to the power grid. If a three-phase fault occurs on the power system close to the generator, the voltage at the terminals of the generator collapses and power can no longer be transferred from the rotor to the grid. As a result of this, the rotor power is transferred into the dc link capacitor, increasing the voltage on the dc link. The MSC will shut down during this time, but before it shuts down, sufficient power is dumped into the dc link capacitor to significantly raise the voltage at the dc bus.

If the rotor of the Type 3 WTG rotates below the power system speed, power is transferred from the power system to the rotor and, in turn, to the stator. When a three-phase fault occurs close to the generator, the stator voltage collapses and the rotor cannot deliver this power to the stator. This causes the current in the stator and rotor circuits to rapidly increase to a large magnitude, limited only by the leakage impedance of the rotor and the stator.

The crowbar circuit is energized to protect the MSC from tripping due to high currents in the rotor circuit. By energizing the crowbar circuit, the MSC is disconnected from the rotor and the crowbar resistors are connected in series with the rotor windings. This provides a path for the high-magnitude rotor currents and helps to dissipate the power in the rotor. Once the MSC is disconnected from the rotor, the WTG behaves as a standard squirrel cage induction motor connected to the power system. Because the MSC no longer provides the current to set up the rotor flux, the current is now taken from the power system. In other words, the WTG goes from generating reactive power (VARs) to absorbing VARs from the power system. This additional absorption of VARs from the power system typically causes a further decrease in the power system voltage. This is in violation of most interconnection agreements, such as Federal Energy Regulatory Commission (FERC) Order No. 661, Appendix G, Large Generator Interconnection Agreement of 2005 [12].

B. Low-Voltage Ride Through

Historically, WTGs have made up only a small percentage of the total installed generation capacity of a power system. This was commonly referred to as low wind penetration. During a fault condition or any other system condition that was adverse to the WTGs, they were allowed to disconnect from the power system. However, as wind power penetration has increased and makes up a larger portion of the generation capacity of the power system, disconnecting the WTGs during power system disturbances severely affects the stability of the power system. This is because after the fault is cleared, a large part of the generation base is no longer available. This has led regulatory authorities, such as FERC in the United States, to propose an LVRT capability for large WTG installations.

The LVRT rule specifies the depth of the voltage sag versus the time for which a WTG is expected to remain online. Fig. 4 is a graph of the LVRT requirements per Appendix G of FERC Order No. 661.

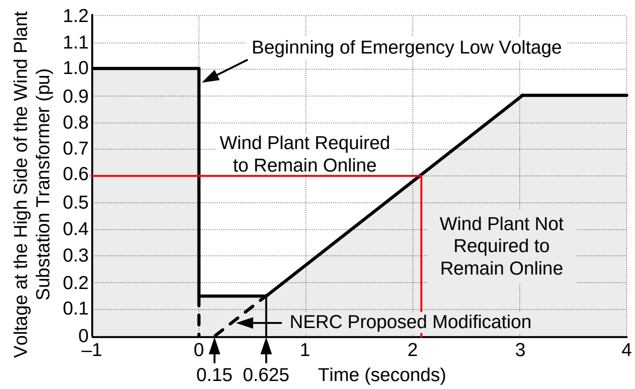

Fig. 4. LVRT requirement per Appendix G of FERC Order No. 661 (minimum required wind plant response to emergency low voltage).

From Fig. 4, it can be seen that if the terminal voltage at the WTG decreases to 60 percent of its nominal voltage, the WTG will have to remain online for a minimum of 2.1 seconds. However, as shown, there is currently a proposed modification to the LVRT curve. With this modification, the WTG has to stay online for at least 0.15 seconds, even if the voltage at the terminals of the generator is zero. Manufacturers will therefore have to provide extra ride-through capabilities for their generators. This further changes how the generator behaves during fault conditions because the MSC must not be disconnected during a fault condition so that the generator is available to support the power system once the fault is cleared. This clearly illustrates that the fault behavior of these types of WTGs will change as new design ideas or regulations are implemented.

III. Fault Study of Type 4 WTG Detailed Model

Because a voltage-behind-the-impedance model does not work for converter-based WTGs, a detailed transient time-domain model is needed to study the short-circuit characteristics during faults. A transient time-domain model can represent the power converter and its control algorithm in detail for greater accuracy. Fault current contribution from the Type 3 WTG is similar to that of a Type 4 WTG, except during severe faults when the crowbar circuit is activated. Hence, the short-circuit characteristics of only Type 4 WTGs are examined in this paper.

To study the behavior of a Type 4 WTG during a fault, the detailed model available in MATLAB and Simulink® was used as a base case [13]. The model was modified to incorporate the new current limit logic described in Appendix B of the WECC Type 4 Wind Turbine Generator Model [6]. The current limit logic defines the maximum active and reactive current output of the converter as a function of voltage. This is needed to ensure that the physical limit of the converter, which is dictated by the thermal capacity of the switching devices, is not exceeded at any point in time. The logic defines two modes of operation: active current priority mode and reactive current priority mode. For this paper, the active current (*P*) limiter has the highest priority during normal operating and post-fault conditions. This is to allow the WTGs to produce as much active power during normal power system conditions as possible. However, the priority changes during fault conditions or when the power system experiences an undervoltage condition because these times require the reactive current (*Q*) to have the highest priority. The current limit logic was added to mimic the current limitation associated with the Type 4 WTG. WECC WTG models are positive-sequence dynamic models and are primarily intended for power system stability analysis. The outputs from WECC WTG models have been validated against field data from multiple WTG manufacturers for three-phase balanced faults. Fig. 5 shows the simplified one-line diagram used for the study. The model consists of five Type 4 WTGs (rated at 2 MW each) lumped as one equivalent generator. The WTG model and control are based on the GE turbines presented in [7]. The WTG connects to the collector grid via a pad-mounted transformer, a collector circuit, and a station transformer.

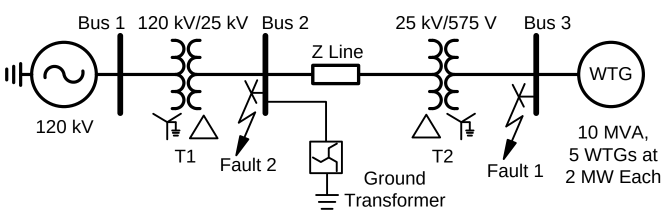

Fig. 5. One-line diagram of the simulation model.

The output current of the grid-side converter was limited by the current limit logic during faults. The piecewise curves defining the limits of the active and reactive current used in the model are shown in Fig. 6. The VDL1 curve corresponds to the reactive current limit, and the VDL2 curve corresponds to the active current limit as a function of the WTG terminal voltage. The limits on active and reactive currents (Ipmax and Iqmax) are calculated per the WECC current limit logic.

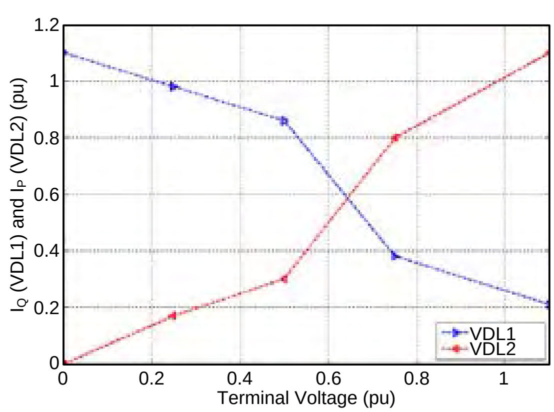

Fig. 6. Piecewise linear curves VDL1 and VDL2.

A. Case 1: Three-Phase Fault at WTG Terminal (Bus 3)

The simulation starts with the WTG set at *P* priority (i.e., supplying active power to the grid). At t = 0.3 seconds, a balanced three-phase fault is applied at the WTG terminal. Fig. 7 shows the WTG instantaneous current and voltage. The fault current following the fault hardly increases beyond 1.1 pu, as expected of a Type 4 WTG.

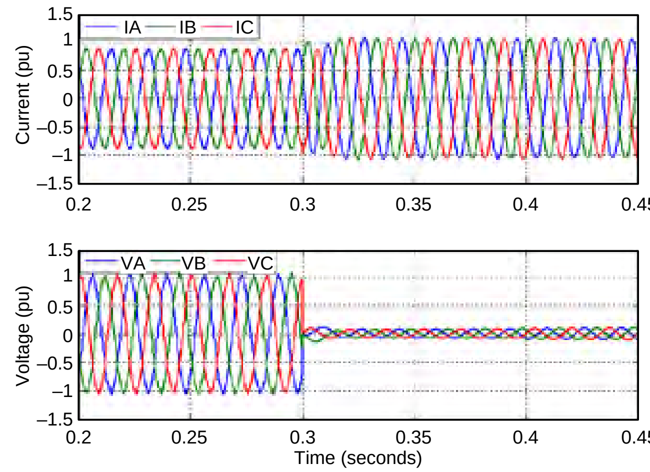

Fig. 7. WTG pu current (top) and voltage (bottom) for a three-phase fault at Bus 3.

Fig. 8 shows the output of the current limit logic as a function of the WTG terminal voltage (Vterm). It can be seen from the graphs in Fig. 8 that as the terminal voltage decreases due to the fault, Ipmax decreases and Iqmax increases to provide the needed reactive power support to the grid. Idref and Iqref are the referenced active and reactive command signals provided to the converter controller. As shown in Fig. 8, the response of the controller stabilizes in about one power system cycle following the fault.

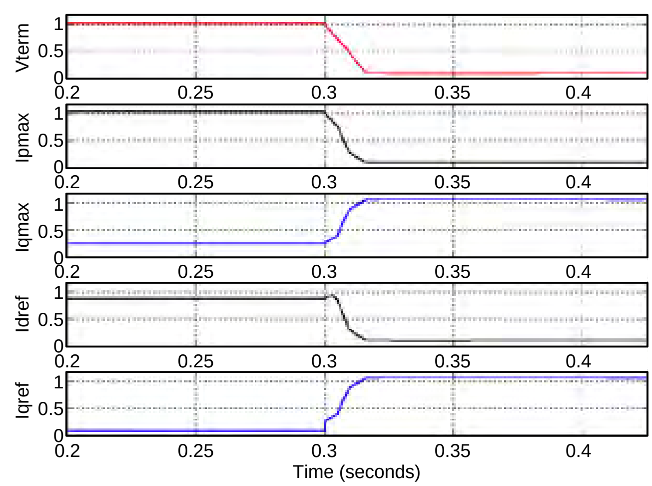

Fig. 8. Output signals from current limit logic for a three-phase fault at Bus 3.

B. Case 2: Three-Phase Fault at the Collector Bus (Bus 2)

In Case 2, a three-phase balanced fault is applied at the collector bus, Bus 2. Fig. 9 shows the fault current contribution from the WTGs and the terminal voltage before and during the fault. Regardless of the line and transformer impedances between the collector bus and WTG bus, the fault current magnitude is close to the fault current contribution observed during the three-phase balanced fault at the WTG terminals, as shown in Case 1. This illustrates the fact that Type 4 WTGs are operated as a controlled current source and the impedance between the generator and fault location has no effect on the fault current contribution. Hence, the conventional voltage-behind-the-impedance approach to calculate fault current does not apply to converter-based WTGs.

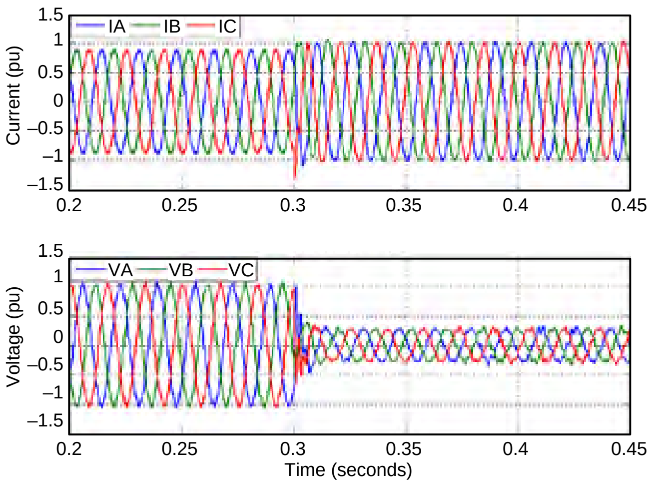

Fig. 9. WTG pu current (top) and voltage (bottom) for a three-phase fault at Bus 2.

The output of the current limit logic for the balanced three-phase fault at the collector bus is shown in Fig. 10. During the fault, Vterm decreases significantly and, as a result, Ipmax decreases and Iqmax increases. Therefore, the WTGs decrease their active power output and support the grid by supplying higher reactive power. Also, Idref and Iqref do not exceed the Ipmax and Iqmax limits.

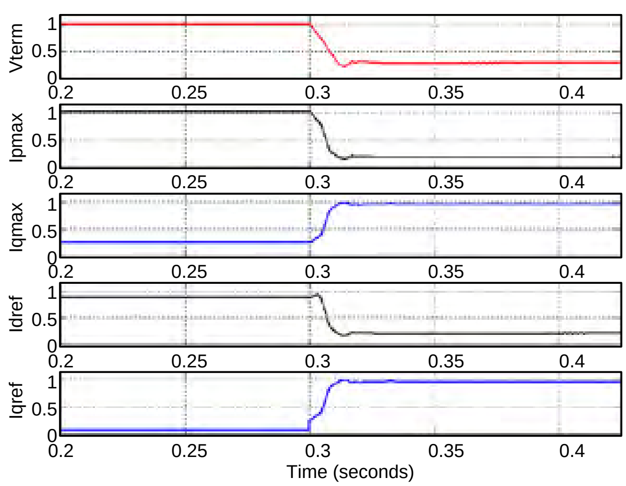

Fig. 10. Output signals from current limit logic for a three-phase fault at Bus 2.

C. Case 3: Single-Phase-to-Ground Fault at WTG Terminal (Bus 3)

The response of the Type 4 WTG to an unbalanced fault is shown in Fig. 11. A phase-to-ground fault is applied at the WTG terminal at t = 0.3 seconds. As observed, the fault current does not change significantly relative to the prefault current. Even for a line-to-ground fault, the current from the WTG remains balanced. This is because an unbalanced fault would result in a significant ripple on the dc bus and therefore would require a larger capacitor. WTG manufacturers avoid using large capacitors that can accommodate the large ripple in the dc bus by forcing the current to be balanced. This ensures that the sum of the currents leaving the WTG at all times is zero (i.e., IA + IB + IC = 0). With the balanced current, the dc bus voltage is maintained during a fault. This control approach suppresses the negative-sequence current contribution from the WTG during unbalanced fault conditions, unlike conventional generators.

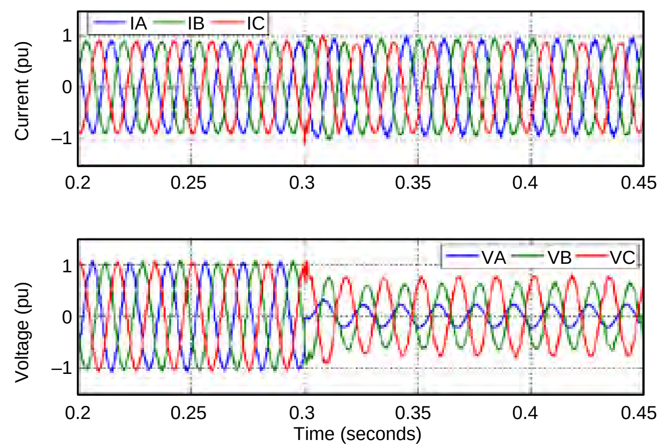

Fig. 11. WTG pu current (top) and voltage (bottom) for a single-phase-to-ground fault at Bus 3.

The output of the current limit logic is shown in Fig. 12. As shown, the WTG terminal voltage is reduced to about half its nominal value, thereby allowing for the continual supply of some amount of active and reactive power. However, the active power is reduced from its prefault state and the reactive power support to the grid is increased as expected. The fault current does not change significantly. Hence, the WTG barely contributed to the fault current.

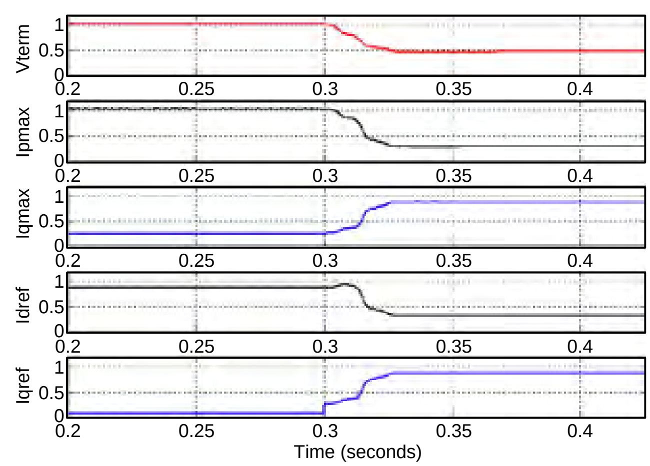

Fig. 12. Output signals from current limit logic for a single-phase-to-ground fault at Bus 3.

D. Case 4: Single-Phase-to-Ground Fault at Collector Bus (Bus 2)

For this case, a similar unbalanced fault is applied at *t* = 0.3 seconds at Bus 2. The WTG fault voltage and current as well as the outputs of the current limit logic are shown in Fig. 13 and Fig. 14, respectively. Due to the delta-wye grounded connection of the pad-mounted transformer, a single-line-to-ground fault on the collector bus appears as a line-to-line fault to the WTG. Again, the fault current barely differs from that of Case 3 and is balanced for similar reasons, as explained previously. Once again, this verifies that the fault current contribution from the Type 4 WTG is independent of the impedance between the fault point and the WTG location.

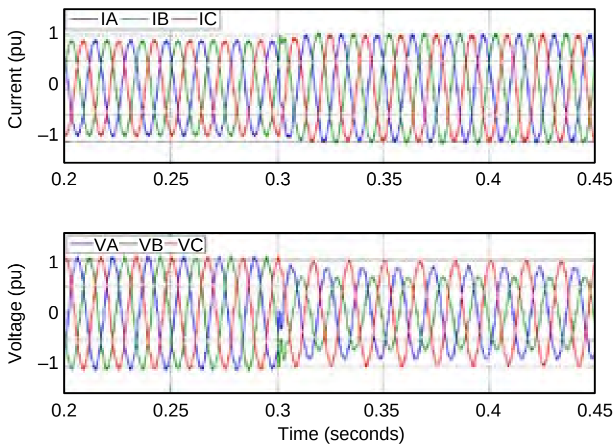

Fig. 13. WTG pu current (top) and voltage (bottom) for a single-phase-to-ground fault at Bus 2.

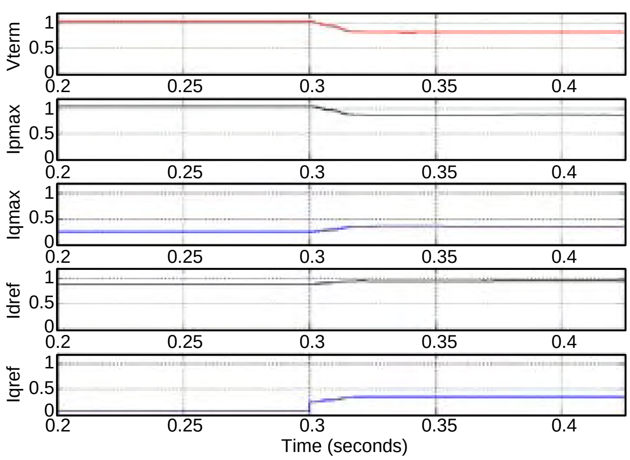

Fig. 14. Output signals from current limit logic for a single-phase-to-ground fault at Bus 2.

IV. Wind Power Plant and Collector Circuit Protection

A modern wind power plant consists of a large number of WTGs, a collector system, substation transformers, and transmission lines or cables that connect the wind power plant to the grid. Fig. 15 depicts a one-line diagram of a typical wind power plant with two collector circuits. Multiple WTGs are connected to the collector bus with the feeder circuit in a daisy-chain fashion. The WTGs are normally ungrounded and do not contribute significantly to the ground current during unbalance faults. The ground current contribution that is likely to be produced is typically from the grounding transformer connected at the collector bus. WTGs usually operate at low voltage (usually 575 to 690 V) and connect to the collector feeder via pad-mounted transformers. Pad-mounted transformers are usually protected with fuses and occasionally have low-voltage breakers. Normally, these transformers are connected in a delta-wye grounded fashion to block the flow of zero-sequence current from the collector circuit to the WTGs. The collector circuit connects a group of WTGs to the collector bus via a series of either overhead lines or underground cables. The collector circuit is usually grounded with a grounding transformer. Substation transformers step up the collector voltage (around 13.8 to 34.5 kV) to the grid voltage for interconnection.

Protection of the station transformer and collector bus in existing wind power plants is similar to that of any distribution substation. The protection schemes for the station transformer and collector bus are somewhat standardized and are not discussed here. The challenge lies in protecting the collector circuits connected to the converter-based WTGs. The protection scheme for the collector circuit should be sensitive enough to detect faults at the lateral circuit of the farthest WTG and also provide backup protection of the WTG pad-mounted transformer. The protection scheme should be secure against transformer inrush current during collector circuit energization. The protection scheme should not misoperate during normal reactive power support or during faults and should not interfere with the LVRT requirements.

Sensitive phase directional overcurrent relays are often used to protect collector circuits. These relays are set to look into the WTG from the collector bus (opposite of normal power flow direction). To provide security against transformer inrush current, harmonic blocking can be used during circuit energization. A core-balanced current transformer (CT) at the collector circuit or current flowing through the grounding transformer can also be used for sensitive ground fault detection.

V. Case Study of Misoperation of Directional Overcurrent Relay at Collector Circuit

A section of a wind power plant located in the New York region is shown in Fig. 16. Only three collector circuits are shown for simplicity. All WTGs are Type 4 generators with a rated capacity of 2.5 MW each. There are four wind turbines on Feeders 7A and 7B and six wind turbines on Feeder 8A. The wind power plant substation is interconnected to the utility through two identical power transformers. The collector Buses A and B were connected during the case study event. The 13.8 kV collector Circuits 7A, 7B, and 8A are protected using the 11F7A, 11F7B, and 11F8A feeder overcurrent relays, respectively. Bus voltage is supplied to the relays using open-delta-connected voltage transformers. Directional overcurrent elements are set to look toward the WTGs. Negative-sequence voltage-polarized directional elements are used to supervise both phase and negative-sequence overcurrent elements.

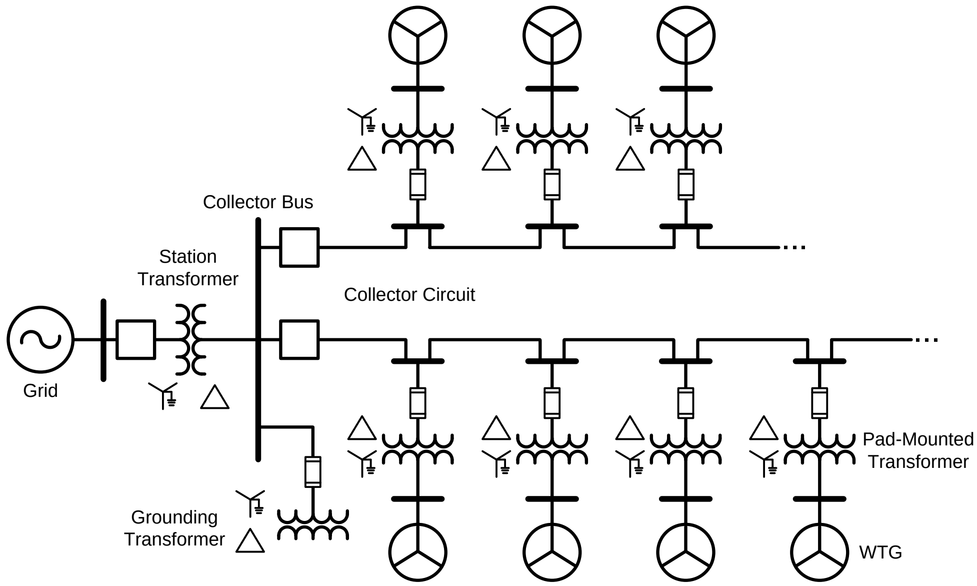

Fig. 15. Simplified one-line diagram of a typical wind power plant.

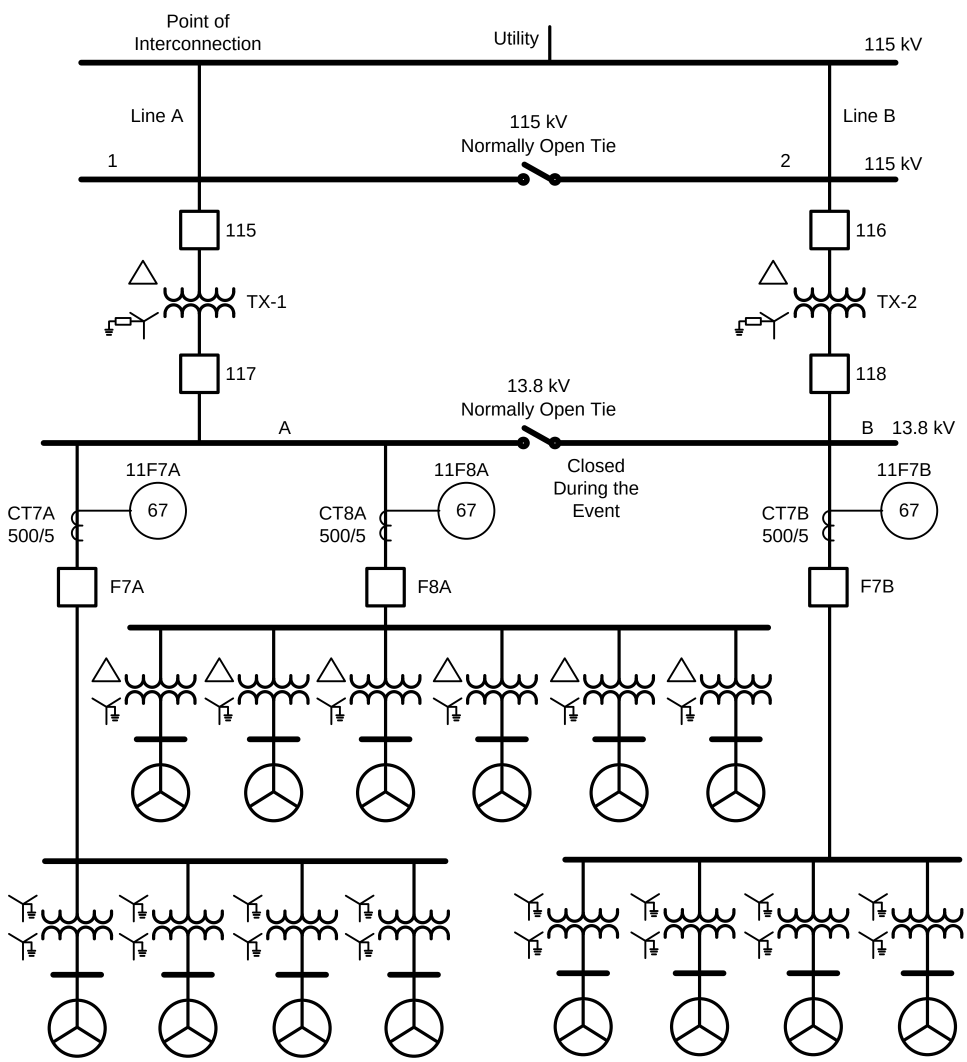

Fig. 16. One-line diagram of a section of a wind power plant installed in the New York area.

A BCG fault occurred at collector Circuit 7B. Relay 11F7B saw the fault as a normal forward fault and tripped Breaker F7B after a time delay. The instantaneous current and voltage signals and some of the protection bits that asserted during the event for Relay 11F7B are shown in Fig. 17. Because the fault was in the forward direction and due to the stiffness of the grid, large fault current flowed from the grid to the collector circuit. The relay identified the fault as a forward fault (forward directional elements 32GF, 32QF, and 32PF asserted), and the time-overcurrent element, 51P1T tripped the breaker.

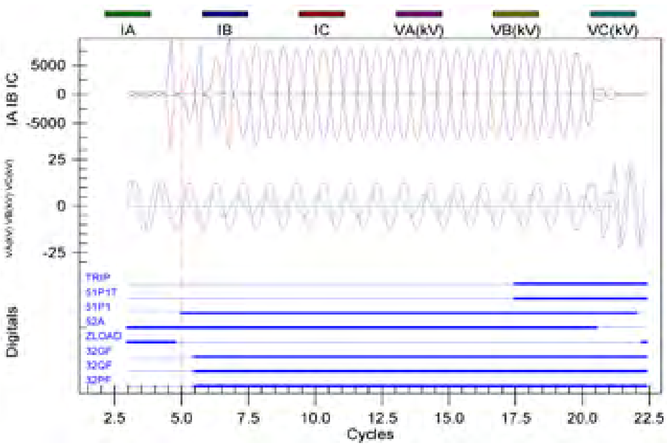

Fig. 17. Raw event report from Relay 11F7B for a BCG fault at the F7B collector circuit.

The vector diagram of the sequence components for prefault and during the fault for Relay 11F7B is shown in Fig. 18. The prefault vector diagram shows that the normal power flow direction is opposite to that of the relay set direction. Because the fault current seen by Relay 11F7B is supplied by the grid, which is highly inductive, positive-sequence current (I_1) lags positive-sequence voltage (V_1) and negative-sequence current (I_2) leads negative-sequence voltage (V_2). The negative-sequence voltage-polarized directional elements determine the fault direction by calculating negative-sequence impedance (Z_2) using (1).

$$Z_2 = \frac{\mathrm{Re}\left(V_2 \bullet \left(I_2 \bullet 1\angle Z1ANG\right)^*\right)}{\left|I_2\right|^2} \quad (1)$$

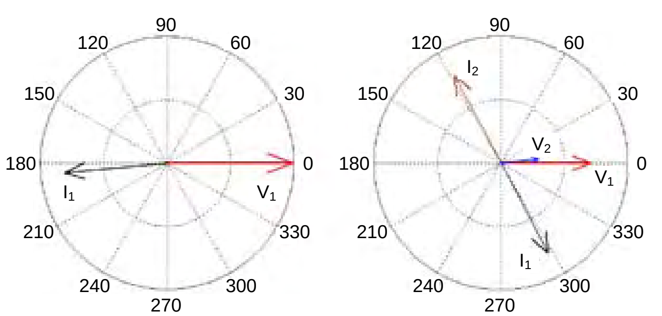

Fig. 18. Vector diagram of sequence components for Relay 11F7B (prefault on the left and during fault on the right).

A forward fault direction is declared if Z_2 is less than the forward directional threshold, and a reverse directional fault is declared if Z_2 is greater than the reverse directional threshold. If we consider the angle between V_2 and I_2, a forward fault is declared if I_2 leads V_2 and a reverse fault is declared if I_2 lags V_2 in an inductive power system.

For the same BCG fault, the oscillographic data of the current and protection bits recorded by Relay 11F7A on collector Circuit F7A are shown in Fig. 19. Only the first few cycles of data are shown in Fig. 19. From the oscillographic data, we can see that the currents supplied by the WTGs are highly distorted during the fault. The fault current contribution from the WTGs on this circuit is small and hardly changes from the prefault load current. The fault on collector Circuit F7B is in the reverse direction with respect to Relay 11F7A on collector Circuit F7A. However, during the fault, the Relay 11F7A directional elements misoperated because the relay saw the fault as forward instead of reverse.

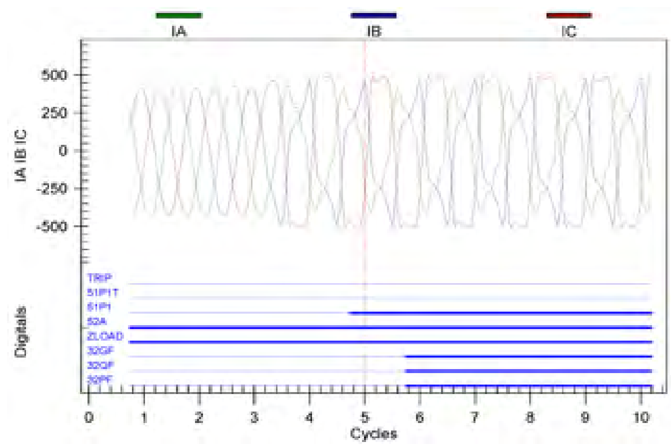

Fig. 19. Raw event report from Relay 11F7A for a BCG fault at the F7B collector circuit.

The vector diagram of the sequence components seen by Relay 11F7A for prefault and during the fault is shown in Fig. 20. During the fault, I_1 lags behind V_1 by almost 180 degrees, which indicates power is flowing in the reverse direction. Because converter-based WTGs are controlled to minimize negative-sequence current, I_2 is smaller than I_1. Also, we see I_2 leads V_2 during the fault, which is typical for a forward fault in a standard power system that has an inductive impedance between the source and fault location. Because the relay was set for a typical inductive power system, the fault was declared in the forward direction. This is corroborated by the assertion of forward directional elements 32GF and 32QF.

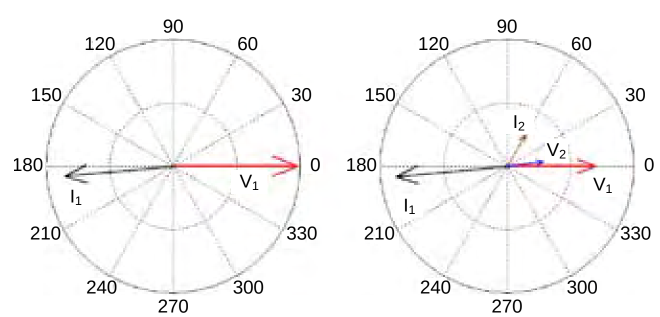

Fig. 20. Vector diagram of sequence components for Relay 11F7A (prefault on the left and during fault on the right).

This misoperation of the directional element can be attributed to the attempt of the WTG converter control to balance the output fault current in all three phases. The converter control caused the system behind the relay to become capacitive instead of inductive. Relay 11F8A directional elements also misoperated during the event as this relay also saw the fault as forward. The event report of Relay 11F8A is similar to that of Relay 11F7A and is therefore not shown.

From Fig. 20, it can be seen that the negative-sequence current (I_2) leads the voltage (V_2) by approximately 60 degrees, which is similar to a reverse resistive fault on a capacitive system. As mentioned previously, the relay was set for a conventional power system with a line angle close to 90 degrees (the impedance behind the relay was used to determine this setting; in this case, it was a power transformer). Substituting the values of V_2, I_2, and Z1ANG from Fig. 20 into (1) results in a negative Z_2 value. A negative Z_2 value translates into a forward fault direction.

To correct for the misoperation of the negative-sequence directional element in this case, the positive-sequence line angle (Z1ANG) has to be set at a low value, typically 10 degrees. If Z1ANG was set at 10 degrees for this case, the modified I_2 quantity would have led V_2 by 70 degrees, which would have resulted in a positive Z_2 value, translating into a reverse fault direction. In general, a true forward fault would result in I_2 leading V_2 by about 120 degrees because the source behind the relay for such a fault is a conventional power system. Applying a setting of Z1ANG of 10 degrees would therefore have no negative impact on the directionality of the negative-sequence directional element for an unbalanced forward fault. For a balanced fault, a positive-sequence voltage-polarized directional element is used and will not be affected by the low Z1ANG value.

A similar misoperation of the directional overcurrent elements with WTGs operated in voltage control mode is presented in [14]. Similarly, in this case, the positive-sequence line angle (Z1ANG) had been set for a normal conventional power system (70 degrees and above), and because of this, the negative-sequence directional element misoperated. A lower value of Z1ANG would have corrected this problem.

VI. Conclusion

Short-circuit characteristics of Type 3 and Type 4 WTGs are very complex and are governed by the proprietary control of the converters used by each manufacturer. A detailed GE Type 4 WTG model with WECC current limit logic was simulated in MATLAB and Simulink to study the behavior of converter-based WTGs during balanced and unbalanced faults. As verified, the Type 4 WTG behavior during these fault types is not distinct and the fault current magnitudes barely increase above the full-load current. Also, the challenges posed by converter-based WTGs to the directionality of overcurrent relays are discussed through an actual field event report. The distortion in fault signals coupled with the change in the angle difference between the fault voltage and current sometimes affects the ability of existing protective relays to identify the correct fault direction. Considering that directional elements are used to supervise a number of other protection elements, they pose a significant risk to the reliability of the power system if they misoperate. Directional overcurrent elements can be supervised with load encroachment logic to help prevent this. However, in the future, a collaborative effort should be pursued between relay manufacturers and WTG manufacturers so that better directional protection algorithms can be developed to protect systems with Type 3 and Type 4 WTGs. Line current differential relaying with pilot protection schemes should also be considered for wind power plant systems because they would be unaffected by the WTG control algorithms and inherently secure. While more expensive than overcurrent relays, the cost of such schemes is arguably insignificant when compared with the value of the lost generation and system stability as wind power plant output increases. Also, there is a need for generic models for these WTGs that can be used by protection engineers for fault analysis. This will help in the choice of relay type and settings and ultimately protect the large economic investment associated in developing wind power plants.

VII. References

[1] E. Muljadi, N. Samaan, V. Gevorgian, J. Li, and S. Pasupulati, “Short Circuit Current Contribution for Different Wind Turbine Generator Types,” proceedings of the IEEE Power and Energy Society General Meeting, Minneapolis, MN, July 2010.

[2] R. J. Nelson and H. Ma, “Short-Circuit Contributions of Full-Converter Wind Turbines,” proceedings of the IEEE Power and Energy Society General Meeting, San Diego, CA, July 2011.

[3] A. Ellis, Y. Kazachkov, E. Muljadi, P. Pourbeik, and J. J. Sanchez-Gasca, “Description and Technical Specifications for Generic WTG Models – A Status Report,” proceedings of the IEEE Power and Energy Society Power Systems Conference and Exposition, Phoenix, AZ, March 2011.

[4] WECC Renewable Energy Modeling Task Force, “WECC Wind Power Plant Dynamic Modeling Guide,” November 2010. Available: http://www.wecc.biz/.

[5] P. Pourbeik, “Proposed Changes to the WECC WT3 Generic Model for Type 3 Wind Turbine Generators,” January 2013. Available: http://www.wecc.biz/.

[6] P. Pourbeik, “Proposed Changes to the WECC WT4 Generic Model for Type 4 Wind Turbine Generators,” January 2013. Available: http://www.wecc.biz/.

[7] N. W. Miller, J. J. Sanchez-Gasca, W. W. Price, and R. W. Delmerico, “Dynamic Modeling of GE 1.5 and 3.6 MW Wind Turbine-Generators for Stability Simulations,” proceedings of the IEEE Power Engineering Society General Meeting, Toronto, Canada, July 2003.

[8] K. Clark, N. W. Miller, and J. J. Sanchez-Gasca, *Modeling of GE Wind Turbine-Generators for Grid Studies*, Version 4.5. General Electric International, Inc., Schenectady, NY, 2010.

[9] R. A. Walling, E. Gursoy, and B. English, “Current Contributions From Type 3 and Type 4 Wind Turbine Generators During Faults,” proceedings of the IEEE Power and Energy Society General Meeting, San Diego, CA, July 2011.

[10] M. B. C. Salles, K. Hameyer, J. R. Cardoso, A. P. Grilo, and C. Rahmann, “Crowbar Systems in Doubly Fed Induction Wind Generators,” *Energies*, Vol. 3, Issue 4, April 2010, pp. 738–753.

[11] J. Morren and S. W. H. de Haan, “Short-Circuit Current of Wind Turbines With Doubly Fed Induction Generator,” *IEEE Transactions on Energy Conversion*, Vol. 22, Issue 1, March 2007, pp. 174–180.

[12] United States of America Federal Energy Regulatory Commission, "Interconnection for Wind Energy," Order No. 661, 18 CFR Part 35, June 2005. Available: http://www.ferc.gov/whats-new/comm-meet/052505/E-1.pdf.

[13] MathWorks, "Wind Farm – Synchronous Generator and Full Scale Converter (Type 4) Detailed Model." Available: http://www.mathworks.com/help/physmod/powersys/examples/wind-farm-synchronous-generator-and-full-scale-converter-type-4-average-model.html.

[14] D. Jones and K. Bennett, "Wind Farm Collector Protection Using Directional Overcurrent Elements," proceedings of the 2012 IEEE Power and Energy Society Transmission and Distribution Conference and Exposition, Orlando, FL, May 2012.

VIII. Biographies

Bing Chen received his BS and MS in Electrical Engineering from Shandong University in 1994 and 1997, respectively, and earned his second MS in Electrical Engineering from the University of Toledo in 2001. He began his career working as a substation engineer at Shandong Electrical Power Consulting Institute. Following his graduate study at the University of Toledo, he served three years as an electrical engineer at GE Industrial Systems and Bechtel Power Corporation. In 2004, he joined CG Power Solutions USA Inc., formerly known as MSE Power Systems, Inc., as a protection engineer. He presently serves as the lead protection engineer for CG Power Solutions USA Inc. in the Maryland office. He has performed over 100 different power system studies and provided detailed relay settings for several dozen substation and wind farm projects. Bing is a registered Professional Engineer in the states of Maryland, Washington, Wisconsin, Maine, Minnesota, and Arizona.

Arun Shrestha received his BS in Electrical Engineering from the Institute of Engineering, Tribhuvan University, Nepal, in 2005 and his MSEE from the University of North Carolina at Charlotte in 2009. At present, he is working as a power engineer in the research and development division at Schweitzer Engineering Laboratories, Inc.. He is also actively pursuing his PhD in electrical engineering at the University of North Carolina at Charlotte. His research areas of interest include wide-area protection and control, real-time power system modeling and simulation, and power system stability.

Fred Agyekum Ituzaro received his BSc in Electrical/Electronic Engineering, with honors, from Kwame Nkrumah University of Science and Technology, Ghana, in 2008 and his MSc degree in electrical engineering from Texas A&M University in 2012. He is currently an associate power engineer at Schweitzer Engineering Laboratories, Inc. Prior to that, he was a research assistant at the Texas A&M Power System Automation Laboratory. His research interests include distributed generation integration studies, power system protection, and microprocessor-based relay design. Fred is a member of IEEE Power and Energy Society.

Normann Fischer received a Higher Diploma in Technology, with honors, from Technikon Witwatersrand, Johannesburg, South Africa, in 1988; a BSEE, with honors, from the University of Cape Town in 1993; and an MSEE from the University of Idaho in 2005. He joined Eskom as a protection technician in 1984 and was a senior design engineer in the Eskom protection design department for three years. Normann then joined IST Energy as a senior design engineer in 1996. In 1999, he joined Schweitzer Engineering Laboratories, Inc. as a power engineer in the research and development division. Normann was a registered professional engineer in South Africa and a member of the South African Institute of Electrical Engineers. He is currently a member of IEEE and ASEE.

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The Importance of Coordinated Control Systems in Solar Generation Plants

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Abstract—**Solar photovoltaic (PV) power plants are emerging across the United States to meet state and local energy portfolio requirements. Coordination of the PV plant and its intertie with the existing distribution and/or subtransmission electrical system is essential for reliable, practical operations. This paper describes a PV plant control system in the field, its operation, and the practicality of solving challenges associated with interconnecting large utility-scale PV installations with the bulk market. In its most basic form, a plant control system monitors the overall operations of the generation plant and the point of interconnection (POI) and, based on the conditions, adjusts the equipment to meet operational, performance, and local interconnection requirements. It seamlessly adjusts the equipment operational points in response not only to commanded set-point changes but also to unpredictable conditions such as a fault or extreme weather.**

In addition to providing internal plant monitoring and control functions, the system also serves as a single-point interface with external systems, where it supplies plant data and accepts control commands from the area electric power system. This single-point interface simplifies the communications burden on the electric power system while providing the necessary functionality to maintain critical voltage support features for the bulk electrical system. This paper describes how the control system can be integrated, including both the internal and external PV plant equipment and devices, with many available communications protocols involved for each. Internal equipment and devices include PV inverters, weather stations, sun trackers, protective relays, revenue meters, local generators, and alarm systems. The external equipment includes weather forecast systems, power management systems, and supervisory control and data acquisition (SCADA) interfaces, to name a few.

This paper discusses in depth the architecture of the plant control. Based on the implemented architecture, the paper demonstrates several different control schemes, including open-loop, closed-loop, sequential step, and time constraint-based controls. These schemes cover a wide range of possible applications, and as such, a section of this paper discusses a few real-world examples. In order to achieve reliable and deterministic controls using a variety of communications protocols and associated media, the status indicators internal to the field equipment are leveraged as part of a more complex scheme. In addition to the communications status provided by the protocols, this paper describes how the latency bit (also known as heartbeat) technique can aid in achieving more reliable controls.

I. Introduction

The integration of solar photovoltaic (PV) power plants into existing electrical networks has increased rapidly in recent years. This is largely driven by state and country mandates to meet renewable energy portfolio requirements. Integrating these intermittent PV plants into existing electrical networks can lead to serious impacts on power quality, reliability, and the overall stability of the electric power system.

Fig. 1 illustrates the impact of adding a solar PV generation plant into an existing electrical network. The small portion of the electrical network, which could be part of a distribution or subtransmission network, comprises several branches of customer loads. When a PV generation plant is a good distance from a conventional generation plant and injects only real power into the network, the voltage fluctuations at the point of interconnection (POI) vary widely depending on the incident radiation. If the PV penetration is high, a sudden decrease in radiation can cause the voltage to drop below the prescribed variations (5 to 10 percent) and a protective relay to open the circuit breaker at the POI due to undervoltage elements [1] [2].

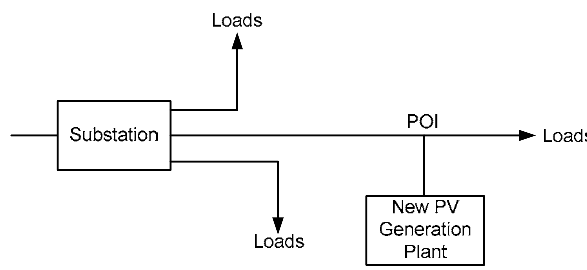

Fig. 1. PV Generation Plant Inserted Into Electrical Network

Additionally, if the network is designed and operated for unidirectional power flow (from the substation to the loads), the added PV generation can cause bidirectional power flow, resulting in issues with existing protection equipment. If the network is designed for bidirectional power flow, issues can still arise in regard to the substation bus, such as wide swings in real power flow and potential backfeeding of other parallel feeder circuits. Circuit design, coupled with electrical installation location, can potentially affect the voltage variations, grid stability, voltage regulation schemes, power quality, and protection and coordination [3].

The PV plant controller concept is to implement an aggregate control mechanism that leverages the individual PV generation inverters to match the amount of power (both real and reactive) needed and thus minimize any negative impacts on the electrical network [2] [3] [4] [5] [6]. In order to achieve this, coordination is necessary between the PV plant controller, substation, and the area electric power system. The control system of the PV generation plant needs to not only provide internal plant monitoring and control functions, but also interact directly with external systems, such as utility supervisory control and data acquisition (SCADA) systems and energy management systems (EMSs). These interactions are essential to meeting the operational, performance, and interconnection requirements of the broader coordinated control system discussed in this paper.

This paper proposes a system architecture for a coordinated control system and describes in detail the components and their interactions. The paper describes the key requirements for the communications protocols and the coordinated control system. Based on the proposed architecture, the paper demonstrates several different control schemes, including open-loop, closed-loop, sequential step, and time constraint-based control schemes that cover a wide range of possible applications. The final sections of this paper discuss several real-world examples.

II. Proposed System Architecture

The coordinated control system consists of a group of sensing devices, equipment controllers, data input devices and systems such as SCADA and human-machine interfaces (HMIs), the PV plant master controller, and communications devices and networks, as illustrated in Fig. 2. For simplicity, the communications devices and networks are omitted from the figure. Relevant details and functional descriptions of the PV inverters, microprocessor-based relays and meters, and SCADA and HMI systems can be found in [7] [8].

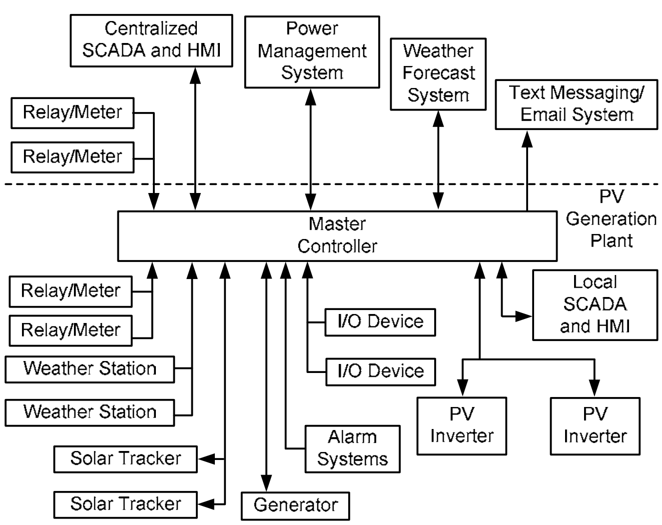

Fig. 2. System Architecture

The following subsections discuss the interactions between the control system components and the master controller.

A. Sensing Devices

Sensors in a PV generation plant include microprocessor-based protective relays, meters, input/output (I/O) devices, solar trackers, and alarm systems. The built-in support for custom logic and communications capabilities makes these devices ideal for serving as inputs to the master controller. Shifting more control logic to the sensing devices and minimizing the amount of data exchange with the master controller simplify the control interface and reduce the burden on the controller. The sensors that do not support built-in functions must have communications capabilities so that they can send the measured and observed quantities to the master controller and allow the controller to perform control functions. Although a sensing device can become a single point of failure for some applications, it is important to also consider device failure, communications failure, network throughput, and latency.

B. Equipment Controllers

The active coordinated control system requires equipment controllers such as inverters and solar trackers to support bidirectional communications. The equipment controllers must be able to accept control signals, respond to both normal and abnormal conditions, and provide their own operating status and alarming conditions so that the master controller can use them to coordinate with other equipment. This ensures the integrity of the generation system and ultimately the interconnection needs at the POI. The control signals vary widely depending on application needs. However, they can comprise set-point changes, operation modes, ride-through profiles, and on and off commands, to name a few.

C. Master Controller

The master controller acts as the coordinator of the entire control system by providing the required interfaces to ensure that all of the components are working together properly. It takes the operating statuses of the plant and the external systems and generates a set of control signals to each respective subsystem, adjusting the operation of the plant to meet operational, performance, and local interconnection requirements. In some cases, the master controller implements both coordinated control and data concentration functions. In such cases, the processing burden of the master controller must be carefully evaluated because of the vast amount of data required for the SCADA and HMI systems. In other cases, the coordinated control functions are separated from the data concentration and implemented on different controllers (monitoring on one, control on the other).

If one master controller is used in the control system, it becomes a single point of failure in the system. To increase the reliability and availability of the control system, more than one controller can be used. Either standby redundancy (also known as backup redundancy) or modular redundancy (or parallel) techniques can be implemented. The implementation of redundant controllers is beyond the scope of this paper.

D. Communications Systems and Networks

The communications systems and networks are crucial parts of the coordinated control system. Reference [7] provides details about the communications systems and networks that are essential for the control system. Security and cybersecurity are important and should be taken into serious consideration during implementation. However, for the sake of brevity, they are omitted from this paper.

Standard (open) communications protocols are preferred over proprietary communications protocols for use in the control system. Standard communications protocols offer the great advantage of interoperability among different manufacturers. Popular standard communications protocols include Modbus®, DNP3, IEC 61850, and IEEE C37.118. Experience has shown that using a single uniform communications protocol in the control system greatly facilitates and improves the maintainability and scalability of the system. In general, having interoperability among devices from different manufacturers enhances the reusability and portability of control solutions.

E. Weather Forecast Systems and Weather Stations

Due to the inherent variable, volatile, and intermittent nature of solar radiation, it is a great challenge for a utility to predict and forecast the amount of energy the PV generation plants produce at any given point in time. Accurate forecasting helps the utility and system operators better allocate resources to maintain the critical voltage and frequency support features of the bulk electric system. Weather stations and weather forecast systems are essential components to achieving an accurate forecast of power production. Weather forecast systems use diverse methods for predicting the power output of a PV generation plant, ranging from multipoint weather measurements and satellite and sky image observations and analysis to numerical weather prediction (NWP) models [9].

Local weather stations serve to provide real-time weather data to forecast systems. These data can be archived and used at a later time by forecast systems that use historical data in their models. In the proposed architecture, the master controller provides the interface between local weather stations and weather forecast systems.

Weather stations typically have a set of sensing devices that measure local weather conditions, such as ambient temperature, relative humidity, precipitation level, wind speed and direction, and barometric pressure. Other data may include solar radiation, PV panel temperature, and total sun peak hours. Most sensing devices support open communications protocols such as Modbus and provide analog values and alarm conditions such as a battery charger alarm to the master controller.

F. I/O Devices

I/O devices typically provide discrete signals that can come from transformers, uninterruptible power supplies (UPSs), circuit breakers, and fire and smoke alarms in the control building or switchgear. Some I/O devices provide the status conditions (or state) of the plant, and others provide alarm conditions for which the master controller needs to take immediate action.

G. Text Messaging and Email Systems

One of the functions supported by the control system is the dispatch of text messages and emails. Certain alarms require human intervention after an event, and the master controller is responsible for providing the necessary information about the event to the text message or email systems.

H. Power and Energy Management Systems

Power management systems and EMSs interact with PV generation plants for two major purposes: to acquire plant data and to manage plant production. Production must be effectively managed in order to match energy demand and supply. The proposed architecture is meant to support slow or low-speed data communications between the parties. In this context, when power management systems provide set-point changes from either manual or scheduled operations, the response of the PV plant is in the order of seconds to minutes. The data received from the control system lag behind the real-time data in a similar time order. The architecture is not intended to support high-speed operations between external systems and the plant (e.g., generation shedding, where the expected response time is less than 1 second).

I. Solar Trackers

PV modules can be mounted either on fixed structures, where the PV modules are tilted at a fixed angle, or on a structure with solar trackers. In the second case, the solar trackers either adjust the position of the PV modules according to the position of the sun or direct the appropriate amount of sunlight onto the PV modules as the day progresses. Studies have shown that a solar tracking system can provide an efficiency improvement of up to 60 percent [10]. Although IEC 82/618/NP specifications require that the mechanical design of the tracker support some extreme weather conditions, the control system is ultimately responsible for sending command signals to position the PV modules in a stow position (a predetermined angle or position) to minimize impact when extreme conditions arise [11]. When other unpredictable conditions occur, such as faults, outages, or certain alarm conditions, some plant operations require that the entire plant be switched into a predetermined and known state. In that case, the master controller sends signals to the tracker controllers to position the PV modules at a specific position and angle.

Two types of solar trackers are often used in a PV generation plant. Single-axis trackers have one degree of freedom that acts as an axis of rotation. Dual-axis trackers have two degrees of freedom that act as axes of rotation. In normal operations, the master controller does not send command signals to the tracker controllers. However, when such needs arise, the signals can be classified into three groups. The first group is the raw data (e.g., a specific angle in degrees for the single-axis trackers). The second group is a set of commands defined as part of the interface between the master controller and the tracker controllers. Each command is usually represented by one bit. Upon receiving the commands, the tracker controllers take a series of actions. The third group consists of discrete signals that represent operation modes and switch between on and off commands.

J. Generator

As discussed previously, one operational requirement can be to put the entire plant in a predetermined state under certain unpredictable and undesirable conditions. When an outage or a fault occurs, it can leave a big portion of the plant with no electric power. Typically, the control room of the plant has backup batteries that can last for a few hours and thus support functions of the critical devices, such as protective relays, circuit breakers, communications equipment, and the main controllers. The battery system is not designed to energize the PV inverters, solar trackers, communications network devices, and other devices in the field. This is where a generator is needed to provide sufficient, minimal electric power so that the equipment can remain powered until the control system is able to put the equipment into the predetermined state. When the generator is in operation, the main controllers must ensure all interconnect and circuit breakers at the POI (all intertied to the utility) are open and locked. Closing must be prevented because this prevents backfeed, and it must be ensured by the coordinated control system. Once the operation is complete, the generator is powered off and disconnected from the system.

The interactions between the control system and the generator include turning the generator on and off, opening and closing the disconnect or breaker of the generator, and collecting some I/O signals that monitor the status of the generator (e.g., fuel level).

III. Coordinated Control System Requirements

This section discusses some key requirements for the communications protocols and master controller for control system operations.

A. High-Speed Versus Low-Speed Communications Protocols

A high-speed communications protocol is a protocol in which a message can reach its destination in milliseconds. A well-known standard is IEC 61850, which includes a high-speed, multicast protocol: Generic Object-Oriented Substation Event (GOOSE) messaging. It is a nonroutable Ethernet Open Systems Interconnection (OSI) Layer 2 broadcast/subscription protocol [12]. Other high-speed proprietary protocols include point-to-point serial-based protocols.

Low-speed communications protocols have less-strict time constraints that can be in the order of seconds. Such protocols include DNP3 (polled data), Modbus, IEC 61850 Manufacturing Message Specification (MMS), and so on. Some applications require low latency variation in low-speed command signals from the master controller to the destinations. Large latency variation can affect the performance of the control strategies, which is discussed in Section IV.

B. Technical Requirements for Master Controller

One of the key technical requirements for the master controller is to support multiple programs and tasks, where each task has its own task cycle. This allows the coordinated control system to separate control functions for different applications and delegate tasks based on their time requirements. The automation controllers that meet the IEC 61131 standard support these features. In addition, the master controller must support both low- and high-speed communications protocols.

Although not required, using automation controllers that support libraries greatly improves the scalability, reusability, and robustness of the system. Libraries can be used to encapsulate proven control functions and strategies, and to present an application interface to the user. This helps avoid undesirable changes to the core functions due to user error or inexperience.

IV. Control Schemes

This section discusses some traditional control schemes and illustrates how these schemes can be applied in implementing a coordinated control system in a PV generation plant.

In a continuous control system, a process or plant is the system to be controlled. A process variable is the process output that can be measured by the system. A control variable is the process input that can be adjusted by the control system.

A. Open-Loop Control

Based on the proposed architecture, the set point can be changed from either the centralized SCADA and HMI system or the local SCADA and HMI system in an open-loop control scheme. Once the control system receives the set-point changes, it verifies that the set point is within the acceptable range and sends the output control signal (or control variable) to the end device via communications protocols. The control system needs to ensure which SCADA and HMI system is in control based on what the local/remote switch indicates. This local/remote switch not only avoids possible control conflicts between the two SCADA and HMI systems but also provides safety when operator personnel are working at the plant or site.

Examples of open-loop control include limiting the output power of the inverters, setting the same power factor to all inverters, and positioning all or a portion of the panel modules at specific angles (positions) for maintenance.

Open-loop control often uses low-speed communications protocols, where response time is less relevant.

B. Feed-Forward Control

PV generation plants experience disturbances from the grid when load changes and switching operations occur. Other factors that can distort a process variable (e.g., measurement at the POI) include the internal components of the plant. Such components can be the impedance and resistance of the cables, transformer impedances, and so on. If the distorted quantities are known or can be measured, the control system can take them into account, calculate the corrective set point(s) that are affected by these quantities, and send the corrective set points to the end devices. This type of control is known as feed-forward control.

Although open-loop control schemes are easier to implement than feed-forward control schemes, disturbances and internal distortions can cause the measured process variables to deviate from the set points. One solution to minimize the distortion in an open-loop control scheme is to calculate or measure the relationship between the set point and the process variable and then create a lookup table or a function and incorporate it into the control system. Although the feed-forward scheme can minimize certain known distortions, it cannot entirely eliminate the unpredictable temporal variations of the disturbances.

Feed-forward control also often uses low-speed communications protocols where response time is less critical.

C. Closed-Loop Control

A closed-loop control scheme implementation is shown in Fig. 3. A closed-loop control system consists of a controller, sensing devices to provide process variable measurements, and the process or the plant. The controller compares the desired set point with the measured process variable, calculates the control variable to maintain the desired set point, and sends the set point to the end devices. The difference between the desired set point and the process variable is also known as the error. The advantages of closed-loop control compared with open-loop control include increased speed of response, reduced error, disturbance rejection, and reduced sensitivity to modeling errors [13] [14].

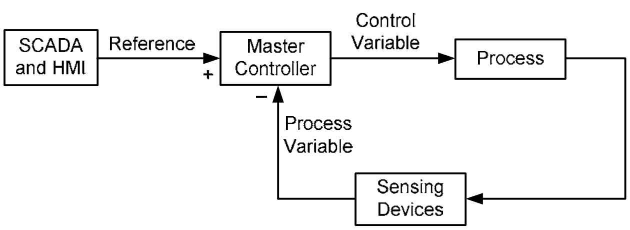

Fig. 3. Closed-Loop Control

Example use cases of closed-loop controls include measuring wind speeds from weather stations and positioning the PV modules at specific angles or maintaining a power factor at the POI. In the first example, the set point is the high wind speed and the process variables are the wind speeds measured by the weather stations. If one of the wind speeds is greater than the set point, the controller sends the commands to the solar tracker controllers and the tracker controllers position the PV modules at a predetermined angle or position. In the second example, the set point is the power factor at the POI, the process variable is the power factor measured by a meter or protective relay at the POI, and the control variable can be either the inverter power factor set point or both real and reactive power set points. Reference [8] provides a detailed discussion of the implementation and performance of the power factor controller using closed-loop control and a proportional and integral (PI) controller.

Depending on the application, a proportional integral derivative (PID) may be needed. When implementing PID control, considerations must be taken when choosing the PID control parameters. Improper selection of these parameters can cause the system to become unstable and not converge to the set point. Simulations and field parameter tuning are usually required to ensure the performance of the system.

D. Sequential Step Control

When the control algorithm follows a sequence of steps, it is considered a sequential step control scheme. A simple sequence usually has no parallel branches or operations and certain steps can be skipped depending on the status or state of the controlled system. Sequences that support parallel operations can be of two types: a selection of one sequence out of many is called exclusive divergence or branching, and multiple sequences being executed simultaneously are called simultaneous divergence or AND branching [13]. This control scheme is used in applications where a sequence of steps must be followed when a certain event occurs or when a certain condition is met (e.g., a fault).

An example usage of this control scheme applicable to a solar PV plant is when the plant experiences a power outage. Some PV plants are actually tied to two independent electric power system branches. The main branch is where the plant is connected, and it is responsible for exporting and providing power to the electronics of all components of the plant. The secondary branch is usually only used when the main branch experiences an outage. The control system uses this secondary source to put the entire generation plant into a predefined state by following a sequence of steps. Typically, the secondary source is not designed for exporting power and the control system must ensure this by turning off the inverters as one of the first steps in the control sequence. Once the entire plant is on the secondary source, the control system will be under a strict time constraint within which it must ensure that the plant does not export any power to the utility.

When a secondary source is not available or when both primary and secondary sources fail, a small local generator can be used to provide energy for the control system to put the entire plant into a known state. When the control system performs the sequential step controls, it must ensure that there are no two sources in parallel. Paralleling two sources without an appropriate synchronization mechanism can cause catastrophic consequences.

Using flow chart diagrams is a good method for designing the sequence step control. A flow chart diagram describes all of the steps that the control system performs, along with all of the associated conditions.

Fig. 4 illustrates a simple example of such a flow chart diagram. The logic first checks if the main source is available. If it is not available, the controller checks the secondary source. If the secondary source is also not available, the controller closes the generator breaker. In this example, the breaker status is used to determine the availability of the sources. In real applications, the relay determines the status of the sources and uses voltage elements as well as the breaker status to determine the availability of a source.

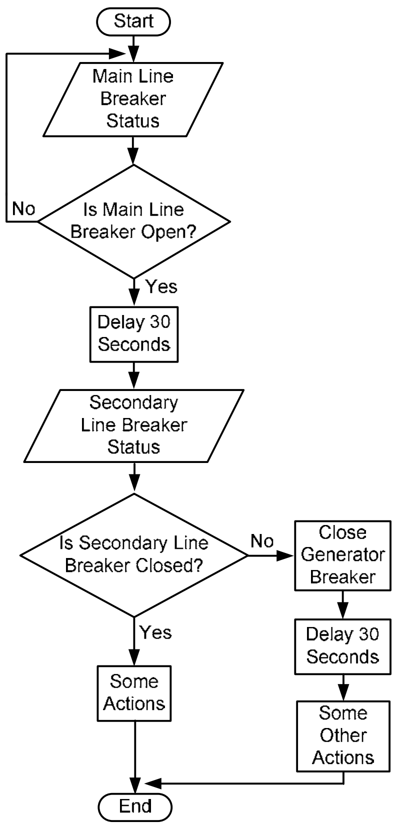

Fig. 4. Flow Chart Diagram Example

While IEC 61131 sequential function chart (SFC) language is uniquely suited for programming sequences, other programming languages can also be used.

E. Time Constraint-Based Control

A time constraint-based control scheme is one where a specific function or operation must be accomplished within a certain time limit. For instance, California Electric Rule 21 does not allow power export at the substation for more than 2 seconds. In this type of control scheme, the sensing devices must send a signal using high-speed communications protocols. As soon as the control system receives the signal, the control system must process it within a specific time limit (task cycle) and provide an output either directly or by sending a message to the end device using high-speed protocols.

Because this type of control requires high-speed communications protocols, too much data between the sending device and the controller could compromise the throughput of the network and other simultaneous control applications. To overcome this, a small set of discrete signals is recommended. This requires the sensing devices to have some processing capabilities and to be able to produce the set of signals.

V. Latency Bits

The proposed architecture and the operation of the control system rely heavily on the communications systems, networks, and protocols. In some applications, the control system or end devices are required to perform certain tasks immediately after detecting a communications failure. One approach is to rely on the status indicators internal to the equipment. Although providing the communications status by protocols has been proven successful in many applications, latency bit and watchdog methods can offer a more robust solution in detecting communications failures.

As discussed in [8], long control cycles in power factor controllers can cause the system to become unstable and unable to converge to the set point. Because large latency variation or random network latency can be larger than the control cycle, this can cause the performance of a closed-loop control system using a PI controller to deteriorate. Although heartbeat and watchdog solutions cannot prevent network latency variations, they are able to indicate whether performance has been compromised.

Latency bits (also known as heartbeats) can be implemented easily in the master controller and the end devices that support custom logic. Basically, the master controller generates a train of pulses consisting of alternating zeroes and ones. The end devices periodically check for the alternating bits in the pulses, and when the bits fail to alternate between two checks, a communications failure is considered to have occurred. Similarly, a watchdog uses a counter instead of pulses. When the end devices detect no counter increment, they declare a communications failure.

VI. Example 1: SCADA and HMI Control

In this example, consider two PV generation plants located 500 feet from each other. The rated capacity of each plant is 20 MW, and each has ten pads. Each pad has four 500 kW PV inverters. The PV modules are mounted on fixed structures at a fixed angle. The master controller is located in the main switchgear along with protective relays, utility revenue meters, and plant owner revenue meters. The backbone of the communications network is a fiber-optic cable ring, and all of the communications devices support Ethernet communications.

The internal components of the system include a local SCADA and HMI system, a master controller, 40 PV inverters, four protective relays, four revenue meters, ten transformer I/O sensors, two discrete I/O devices, and two weather stations. The external components of the system include a global SCADA and HMI system, an EMS, and an independent system operator system.

Modbus TCP/IP is used between the master controller and all internal devices, except for two utility revenue meters. These meters and all external systems use DNP3 to communicate with the master controller.

The control requirements for these two plants are to change the set points of the PV inverters and switch the individual inverters or a group of inverters on and off from either a local or global SCADA and HMI system. The EMS is only allowed to change set points. The set points include the power output, power factor, and ramp rate of the PV inverters. These set-point changes apply to all 40 plant inverters. The system does not have a local/remote switch, which means that either a global or local SCADA and HMI system or EMS can change the set points. The master controller interfaces with the independent system operator system to provide plant data.

In this application, the master controller is used to provide the interface for the described control functions and acts as a data concentrator that collects data from the devices in the field. This solution has been proven effective in meeting all of the control requirements. In this example, the two plants operate independently and their implementations are almost identical.

VII. Example 2: Power Factor Control

Consider a PV generation site with three 1 MW inverters and about 40,000 solar panels. The controller and a protective relay are located inside a switchgear cabinet at the POI. The inverters are about 600, 1,200, and 1,800 feet away from the controller. The SCADA and HMI system is located in another state.

The controller has numerous serial ports, one of which is connected directly to the protective relay that provides the system power factor. A second port communicates with the three inverters. The relay interface is EIA-232, and the inverters communicate via four-wire multidrop EIA-485 full-duplex communications networks. A DSL modem connected to a local Internet provider is used for communication between the SCADA and HMI system and the controller. The communications protocol between the controller and the protective relay is a proprietary communications protocol. The protocol between the controller and the SCADA and HMI system is Ethernet Modbus TCP/IP, and the protocol between the controller and the inverters is serial Modbus RTU. Fig. 5 illustrates the closed-loop control implementation.

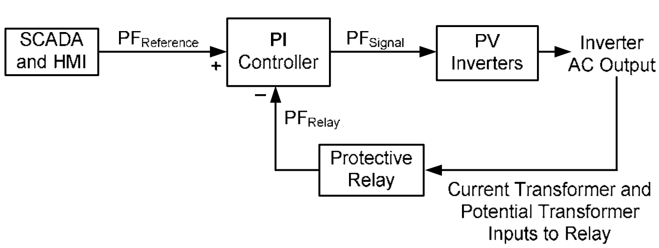

Fig. 5. Power Factor Closed-Loop Control Scheme

Fig. 6 shows the PI controller implementation, where K_p and K_i are the proportional and integral constants, respectively. The integral constant can be written as $K_i = K_p/T_i$, where T_i is the integration constant.

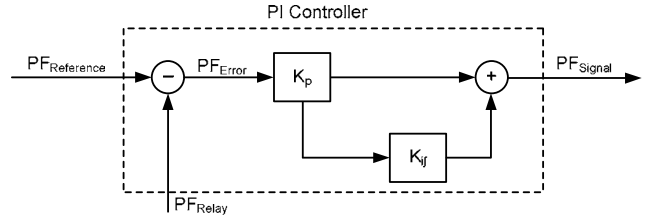

Fig. 6. PI Controller

The power factor error is $PF_{Error} = PF_{Reference} - PF_{Relay}$. The integral term is approximated by a difference equation and leads to the recursive equation in (1).

$$PF_{Integral\_New} = PF_{Integral\_Old} + \frac{K_p}{T_i} \bullet CRTL_{Cycle} \bullet PF_{Error\_New} \quad (1)$$

where:

$PF_{Integral\_Old}$ denotes the integral term up to the previous sampling instant.

$PF_{Integral\_New}$ is the new sampling instant.

$CRTL_{Cycle}$ is the sampling period.

The signal at the new sampling instant can be written as shown in (2).

$$PF_{Signal\_New} = K_p \bullet PF_{Error\_New} + PF_{Integral\_New} \quad (2)$$

Expanding this equation, the signal can be expressed in recursive form as shown in (3).

$$PF_{Signal\_New} = PF_{Signal\_Old} + K_p \left(PF_{Error\_New} - PF_{Error\_Old}\right) + \frac{K_p}{T_i} \bullet CTRL_{Cycle} \bullet PF_{Error\_New} \quad (3)$$

The controller uses this equation to update its output control signals.

The controller is implemented using IEC 61131 structured text. The main control requirement of this generation plant is to maintain a certain power factor measured at the POI. The power factor can be either leading or lagging and can be changed from the SCADA and HMI system.

The system performance shows that the power factor is kept in the range of 5 percent of the reference set point under normal conditions [8].

VIII. Example 3: Nonexport or Limited Export Power Control and Power Curtailment

Fig. 1 illustrates a simplified view of a small electrical network for a small size city. The network consists of a substation and three 12.47 kV feeders. A 3.5 MW PV generation plant is inserted into the middle section of the third feeder.

Fig. 7 shows the average daily load of the city. It shows a typical load profile of a residential city, where the load is small in the morning when most people are at work and starts to increase in the afternoon when they arrive home. Load typically reaches its peak in the evening when residents turn on air conditioners and other household appliances.

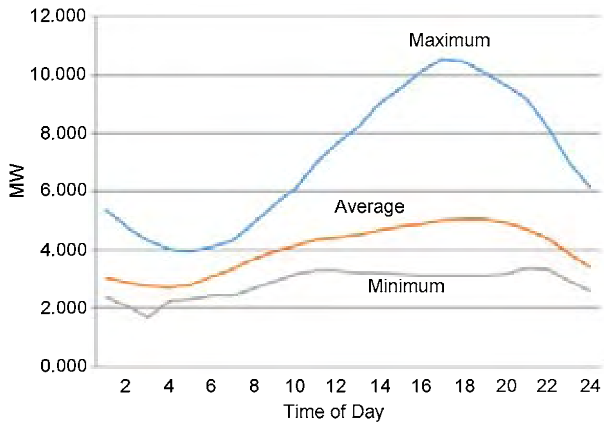

Fig. 7. Average Daily Load

Fig. 8 shows the typical load as the year progresses. Because this city is located in California, it shows the load is higher in the summer than in any other season. The repeated small dips shown in the figure represent the load on weekends. In this particular residential area, the power consumption during weekends appears to be smaller than that of weekdays.

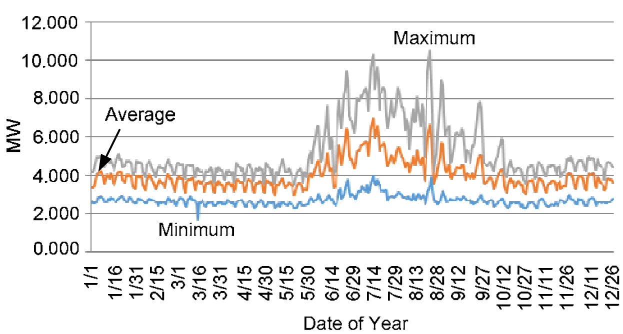

Fig. 8. Yearly Load Profile

Because the minimum daily and weekend loads can be smaller than 3.5 MW, there is a high chance that power will be exported to the utility. Due to this concern, one of the main control requirements is a nonexport condition.

The intertie of the PV generation plant to the feeder is a recloser. The PV plant is about 150 feet away from the recloser and about two miles from the substation. The main components of this system are the master controller, a recloser control, a protective relay, seven 500 kW PV inverters, and a small local SCADA and HMI system. The protective relay is located in the substation outside of the PV generation plant.

The control system requirements can be summarized as follows:

- When the relay detects a power export (power measured at the substation is less than zero), the control system must disconnect the PV generation plant from the feeder within 2 seconds.
- When the relay detects a low load condition (defined by a threshold), the control system must turn off all inverters. The reason for this requirement is that every time the PV generation is disconnected from the feeder, an operator must go to the plant and manually close the recloser. This can be time-consuming and can also depend on the availability of the operators.
- When the relay detects a load lower than a second threshold, which is known as the curtailment condition, the control system must curtail the power output of the inverters. Similarly, every time the PV inverters are switched off, they take minutes to ramp up their production. Repeated on/off operations not only degrade the performance of the plant, but also introduce behaviors similar to the cloud effect that can negatively impact the stability of the network.
- The power factor measured at the POI must be maintained at a set point, and the set point can be changed from the local SCADA and HMI system.

The system is composed of two communications media that share a common master controller. A fiber-optic network is formed among the PV inverters and the master controller. The second network is a radio link between the master controller and the substation. The master controller communicates with the inverters using Modbus TCP/IP. The radio link has three channels, one of which is used for control and another for the substation (local) SCADA and HMI system. The control channel uses a proprietary high-speed point-to-point serial communications protocol. The data collection channel uses the Modbus RTU serial communications protocol. Because the master controller and the recloser controller are in the same enclosure, they communicate via a serial copper cable using a proprietary high-speed point-to-point protocol.

The power factor control is implemented as described previously. The nonexport and power curtailment controller is implemented as shown in Fig. 9. The quantity of power *P* is measured by the relay at the substation. The relay is programmed to generate four bits of data based on the thresholds X1, X2, X3, and X4. Then the data are sent to the master controller. As soon as the controller receives the data, it sends the control signals as follows:

- In normal operation, the measured power (*P*) is above X4.
- If the measured power drops to equal or less than X3, the controller sends a curtailment command to the inverters.
- If the measured power drops to equal or less than X2, the controller sends a turn off command to the inverters.
- If the measured power drops to less than X1 (zero), the controller sends a trip command to the recloser control.
- If the measured power increases to greater than X4, the controller sends a power increase command to the inverters.

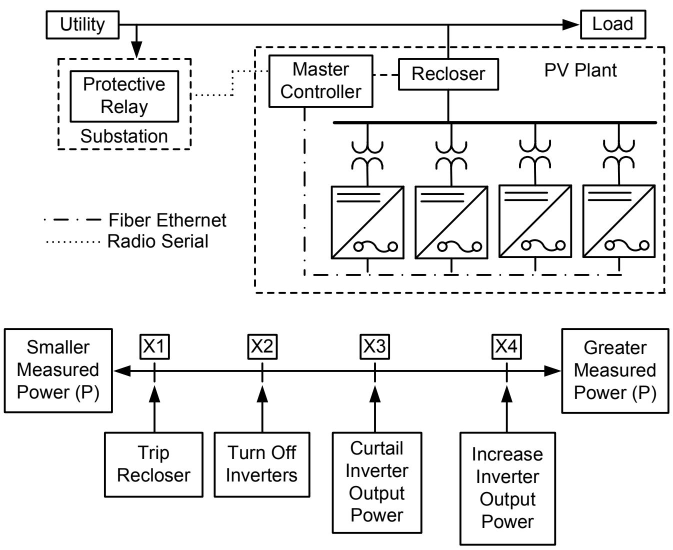

Fig. 9. Nonexport Control Scheme and Power Curtailment

In this implementation, the control system effectively enforces the nonexport condition by first attempting to curtail the output of the inverters. If that fails, it attempts to switch off the inverters. If both fail, the controller trips the recloser as a last resort. The purpose of having the thresholds X3 and X4 is to allow for dynamic adjustments to the inverter output power to match the load. Although these two thresholds, were selected by the city based on historical data, they are not optimal. The city chose to keep the selected thresholds and no optimization was conducted.

A. Power Curtailment Algorithms

1) Simple Steps

The simplest power curtailment algorithm is to immediately reduce the amount of power to a fixed number (e.g., 20 percent [or another percentage depending on the application] of the rated value when *P* drops below X3). When *P* increases to greater than X4, the controller sends the commands to raise the output to the maximum as shown in (4).

$$\begin{aligned} P_{SP} &= P_{Max} \text{ if } P > X_4 \\ P_{SP} &= P_{Min} \text{ if } P < X_3 \end{aligned} \tag{4}$$

where:

P_{SP} is the output power set point sent to the inverters.

$P_{Min} = 0.2 \bullet P_{Max}$.

This algorithm can be effective for applications where the plant needs to rapidly reduce its production to a certain amount. However, the sudden drop in the plant output power can negatively impact the local-area power system depending on the PV penetration. To avoid a sudden increase of output power, the ramp rate of the inverters can be used to limit the rate of increase. By combining the algorithm and the ramp rate, this power curtailment scheme can be applied to numerous applications.

2) Linear Curtailment

Instead of reducing the output power in one step, the output power can be reduced incrementally in multiple steps. In this implementation, the power curtailment algorithm follows a linear equation as shown in (5).

$$\begin{aligned} P_{SP} &= P_{SP} - 10\frac{\text{kW}}{\text{s}} \bullet T_i \text{ if } P < X_3 \\ P_{SP} &= P_{SP} + 10\frac{\text{kW}}{\text{s}} \bullet T_i \text{ if } P > X_4 \end{aligned} \tag{5}$$

where:

T_i is the time interval between consecutive power set-point changes.

In this example, 10 kW per second is used to either increase or decrease the output power. Because the controller sends the set point periodically, the output experiences the multiple step effects shown in Fig. 10.

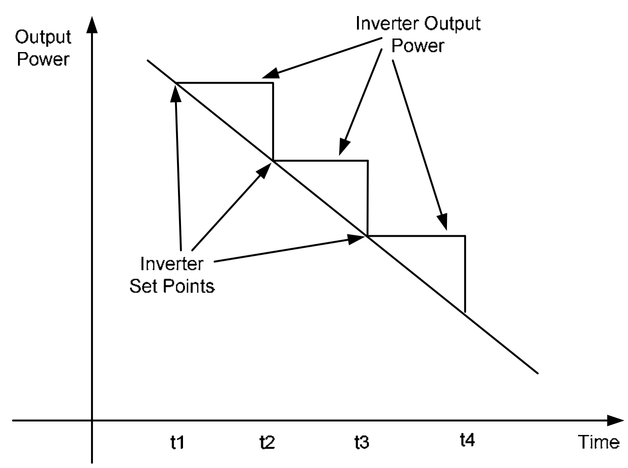

Fig. 10. Power Curtailment Using Linear Equation

In this example, the two power curtailment methods were tested, which showed that the simple step algorithm was more effective in reducing the output power rapidly.

3) Other Algorithms

Two other algorithms that can be considered are nonlinear equations for the curtailment and multiple ramp rates. The controller can use an exponential decay equation for the curtailment, where the output reduces rapidly at first and then slows down. The exponential equation can be used for the power increase. The second algorithm uses multiple ramp rates for changing power set points—one set for power increase and another set for power decrease.

B. Limited Export Power

In cases where export power is allowed but limited, the same control algorithm can be used to meet the requirement by simply changing the thresholds programmed in the protective relay. The threshold X1 is the maximum power export allowed in the system and is negative when taking the imported power as positive.

IX. Example 4: Solar Tracker Control and Sequential Step Control

Consider a 20 MW PV generation site similar to the one described in Example 1. The PV modules are mounted on a structure with single-axis solar trackers instead of a fixed structure. In addition, the plant is tied to two independent electric power system branches and has a generator on-site.

The control requirements for this site are as follows:

- Stow all trackers when high winds occur.
- Position all trackers at predefined angles. One is the angle for cleaning the PV modules.
- Turn off the PV inverter and put all of the trackers in the stowed position when the site experiences a power outage. This is the requirement to switch the entire plant into the predetermined or known state. When the inverters are turned off, they must be turned back on manually from the SCADA and HMI system.

In this application, the solar trackers are divided into ten zones, where each pad is a zone. Each zone has 26 individual controllers, and each controller manages a predetermined number of PV modules. In order for the master controller to communicate with a manageable number of devices, a programmable logic controller (PLC) is used in each zone. In this case, the master controller communicates with ten PLCs and the PLCs communicate with individual tracker controllers. However, because the master controller must be able to control individual tracker controllers as a control requirement, the master controller needs to send 26 commands to the PLCs. As discussed previously, discrete data are being exchanged between the master controller and the PLCs.

A closed-loop control scheme is used to stow the trackers when high winds occur. To position the trackers at a predefined angle, the master controller sends one bit of data to all 260 tracker controllers.

The control logic briefly described in Sections II and IV puts the entire plant in a known state after a power outage. The flow chart diagram in Fig. 11 illustrates a simplified sequence of steps. In this example, some of the logic that normally resides in the master controller has been shifted to the protective relays. As shown in the diagram, the protective relays are responsible for which secondary source is available and the master controller assumes there is always a secondary available. It could be the second branch of the electrical network or the local generator. Tests have shown that closed-loop control combined with sequential step control meets the control requirements.

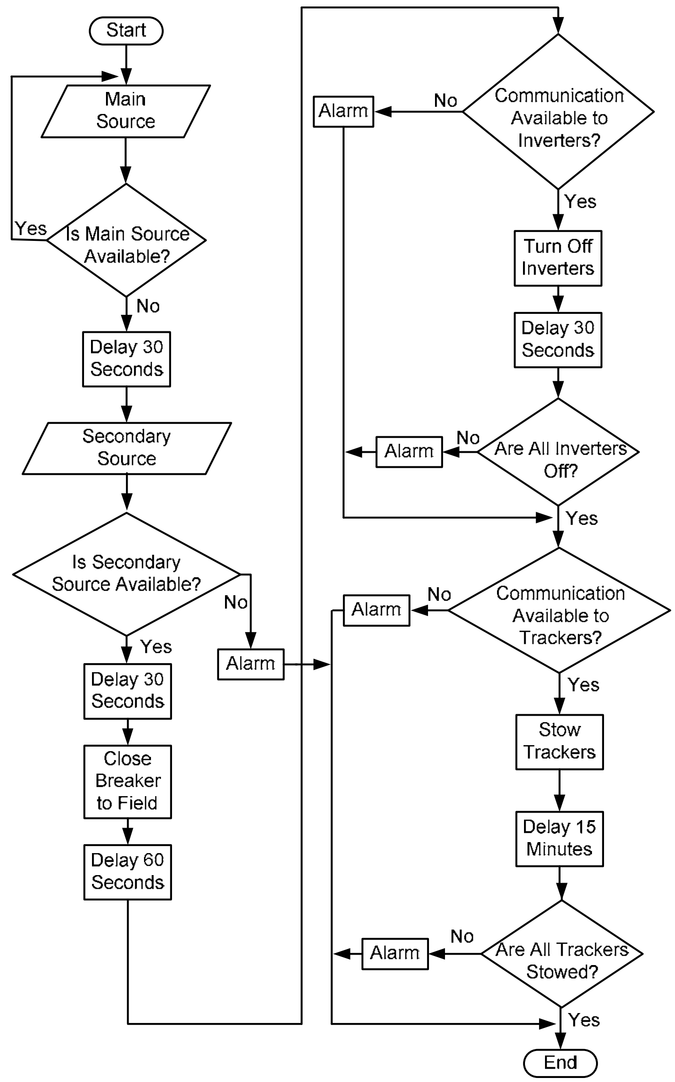

Fig. 11. Simplified Flow Chart Diagram to Turn Off Inverters and Stow Trackers

X. Conclusion

Solar PV power plants continue to emerge and can greatly impact the electrical networks into which they are being integrated. As a result, it is becoming increasingly important to employ aggregate control schemes using the proposed architecture to solve the practical challenges associated with interconnecting large utility-scale PV installations with the bulk market. Interconnection needs, plant size and location, and utility operational practices drive the need for a flexible and configurable solution set to assist in the integration of these renewable resources. The proposed control system solution serves as a single-point interface with internal and external systems, simplifying the communications burdens while providing the necessary functionality to meet a wide range of end control requirements. This paper provides a discussion of differing control techniques that leverage this flexible set of equipment, showcasing some of the capabilities of the control techniques and showing how challenges with distributed power plants can be overcome.

XI. References

[1] Y. T. Tan and D. S. Kirschen, "Impact on the Power System of a Large Penetration of Photovoltaic Generation," proceedings of the 2007 IEEE Power Engineering Society General Meeting, Tampa, FL, June 2007.

[2] K. De Brabandere, A. Woyte, R. Belmans, and J. Nijs, "Prevention of Inverter Voltage Tripping in High Density PV Grids," proceedings of the 19th Annual Photovoltaic Solar Energy Conference, Paris, France, June 2004.

[3] J. Bank, B. Mather, J. Keller, and M. Coddington, "High Penetration Photovoltaic Case Study Report," *National Renewable Energy Laboratory*, January 2013. Available: http://www.nrel.gov/docs/fy13osti/54742.pdf.

[4] R. Tonkoski, L. A. C. Lopes, and T. H. M. El-Fouly, "Coordinated Active Power Curtailment of Grid Connected PV Inverters for Overvoltage Prevention," *IEEE Transactions on Sustainable Energy*, Vol. 2, Issue 2, April 2011, pp. 139–147.

[5] K. Turitsyn, P. Sulc, S. Backhaus, and M. Chertkov, "Distributed Control of Reactive Power Flow in a Radial Distribution Circuit With High Photovoltaic Penetration," proceedings of the 2010 IEEE Power and Energy Society General Meeting, Minneapolis, MN, July 2010, pp. 1–6.

[6] S. Eftekharnejad, V. Vittal, G. T. Heydt, B. Keel, and J. Loehr, "Impact of Increased Penetration of Photovoltaic Generation on Power Systems," *IEEE Transactions on Power Systems*, Vol. 28, Issue 2, May 2013, pp. 893–901.

[7] M. Mills-Price, M. Rourke, and D. Kite, "Adaptive Control Strategies and Communications for Utility Integration of Photovoltaic Solar Sites," proceedings of the 2014 Power and Energy Automation Conference, Spokane, WA, March 2014.

[8] D. Taggart, K. Hao, R. Jenkins, and R. VanHatten, "Power Factor Control for Grid-Tied Photovoltaic Solar Farms," proceedings of the 14th Annual Western Power Delivery Automation Conference, Spokane, WA, March 2012.

[9] "Photovoltaic and Solar Forecasting: State of the Art," *IEA International Energy Agency*, October 2013. Available: http://www.iea-pvps.org.

[10] A. Kassem and M. Hamad, "A Microcontroller-Based Multi-Function Solar Tracking System," proceedings of the 2011 IEEE International Systems Conference, Montreal, QC, April 2011, pp. 13–16.

[11] IEC 82/618/NP, Specification for Solar Trackers Used for Photovoltaic Systems.

[12] N. C. Seeley, "Automation at Protection Speeds: IEC 61850 GOOSE Messaging as a Reliable, High-Speed Alternative to Serial Communications," proceedings of the 10th Annual Western Power Delivery Automation Conference, Spokane, WA, April 2008.

[13] K. T. Erickson, *Programmable Logic Controllers: An Emphasis on Design and Application*. Dogwood Valley Press, LLC, Rolla, MO, 2005.

[14] K. J. Åström and R. Murray, *Feedback Systems: An Introduction for Scientists and Engineers*. Princeton University Press, 2008.

XII. Biographies

Michael Mills-Price is the technology development lead for the solar energy business unit at Advanced Energy Industries, Inc. Michael is the principal designer responsible for bringing new technologies to market and continues to lead teams toward advanced systems control to broaden the scope and lessen the impacts associated with widespread photovoltaic adoption. Michael received his Bachelor of Science and Masters of Science in Electrical Engineering from Oregon State University (OSU), is a registered professional engineer, and is an active member of IEEE. Michael is also an adjunct professor at OSU, teaching senior level energy storage and energy distribution systems courses.

Kei Hao received his Ph.D. in Electrical Engineering from the University of Wisconsin–Madison, his M.S.E.E. from the University of Wisconsin–Milwaukee, and his B.S.E.E. from La Universidad de la Republica, Uruguay. He has experience in the fields of control and automation systems, wireless communications systems, and power system automation and protection. In 2010, he joined Schweitzer Engineering Laboratories, Inc. as an engineer in the engineering services division. He is a member of IEEE and a registered professional engineer in the state of California and has authored and presented several technical papers.

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Protection System for a Wind Generation Plant in Panama : Challenges and Solutions

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***Abstract*—The Penonomé wind power plant in Panama will have a total capacity of 337.5 MW. The first two phases currently in service provide 270 MW of generation. In this power plant, wind generators belonging to different companies are connected to a 34.5 kV system. Two transformers interconnect the 34.5 kV system to Panama's 230 kV transmission system at the El Coco substation. The 34.5 kV system is grounded through zig-zag and grounded-wye/delta banks. This paper describes the 34.5 kV system protection challenges and solutions, discusses the protection coordination requirements, and provides the coordination study results. The paper also provides recommendations for future enhancements of the protection system. Finally, the paper describes an actual event involving two cross-country faults in the 34.5 kV system.**

I. Introduction

In recent years, demand for electric power in Panama has experienced some of the fastest growth among emerging economies. To meet this growing demand, the country has prioritized investments in generation projects that reduce dependence on fossil fuels. One of these projects is the wind power plant in Penonomé—located in Coclé Department, 70 miles southeast of Panama City—which started in 2012. This is the largest wind generation project in Central America, with a future generation of 337.5 MW. The project has been divided into three phases. The first two phases are currently in service, totaling 270 MW of generation. The Penonomé power plant connects with Panama's transmission system at the El Coco 230/34.5 kV substation, which is an important node of the 230 kV network.

In this power plant, wind generators belonging to different companies are connected to a 34.5 kV system. Two delta/grounded-wye step-up transformers interconnect the 34.5 kV system to Panama's 230 kV transmission system at the El Coco substation. The 34.5 kV system is grounded through zig-zag and grounded-wye/delta banks that limit the ground fault current. This type of grounding poses a challenge for ground protection coordination in the 34.5 kV system.

This paper describes the 34.5 kV system protection challenges and solutions in detail. It discusses the protection coordination requirements and the coordination study results, and it provides recommendations for future enhancements of the protection system. Finally, the paper describes an actual event involving two cross-country faults in the 34.5 kV system.

II. Power System Description

Fig. 1 shows a single-line diagram of the power system. The El Coco substation has a breaker-and-a-half arrangement on the 230 kV bus, and it connects with the Panamá II substation through 230 kV Lines 230-12A and 230-13A. It also connects with the Llano Sánchez substation through 230 kV Lines 230-12B and 230-13B. These two pairs of lines are double-circuit lines. Two 120/140 MVA, 230/34.5 kV power transformers (T91 and T92) provide the connection to the 34.5 kV distribution system. These transformers have a grounded-wye connection on the 230 kV side and a delta connection on the 34.5 kV side. Twelve circuits (made of overhead lines and underground cables) connect to the two sections of the 34.5 kV bus, which have a normally open bus-tie circuit breaker. These circuits serve as collectors for generation from the wind power plants that comprise the El Coco generation project. The system will also include seven 9 MVAR capacitor banks and a 2 MVAR reactor as determined by load flow and harmonic distortion studies. At the time of publication, the capacitor banks and the reactor were still not in service.

Proper grounding is essential to protect wind power plant equipment from sustained and transient overvoltages on the healthy phases during ground faults [1]. Typically, wind turbine generators (WTGs) and their step-up transformers are ungrounded. The system must be grounded at the substation. In addition, if a collector circuit trips for a ground fault and the WTGs remain in operation, the system becomes an islanded ungrounded system operating with a grounded phase. The phase-to-ground voltage of the healthy phases may reach the phase-to-phase rated voltage value or more. Given the recent low-voltage ride-through requirements that system operators impose on wind generation sources, WTGs may continue to feed an islanded collector circuit for several seconds, which further compounds the overvoltage problem. Grounding the wind plant collector circuits—in addition to the substation grounding—solves this problem.

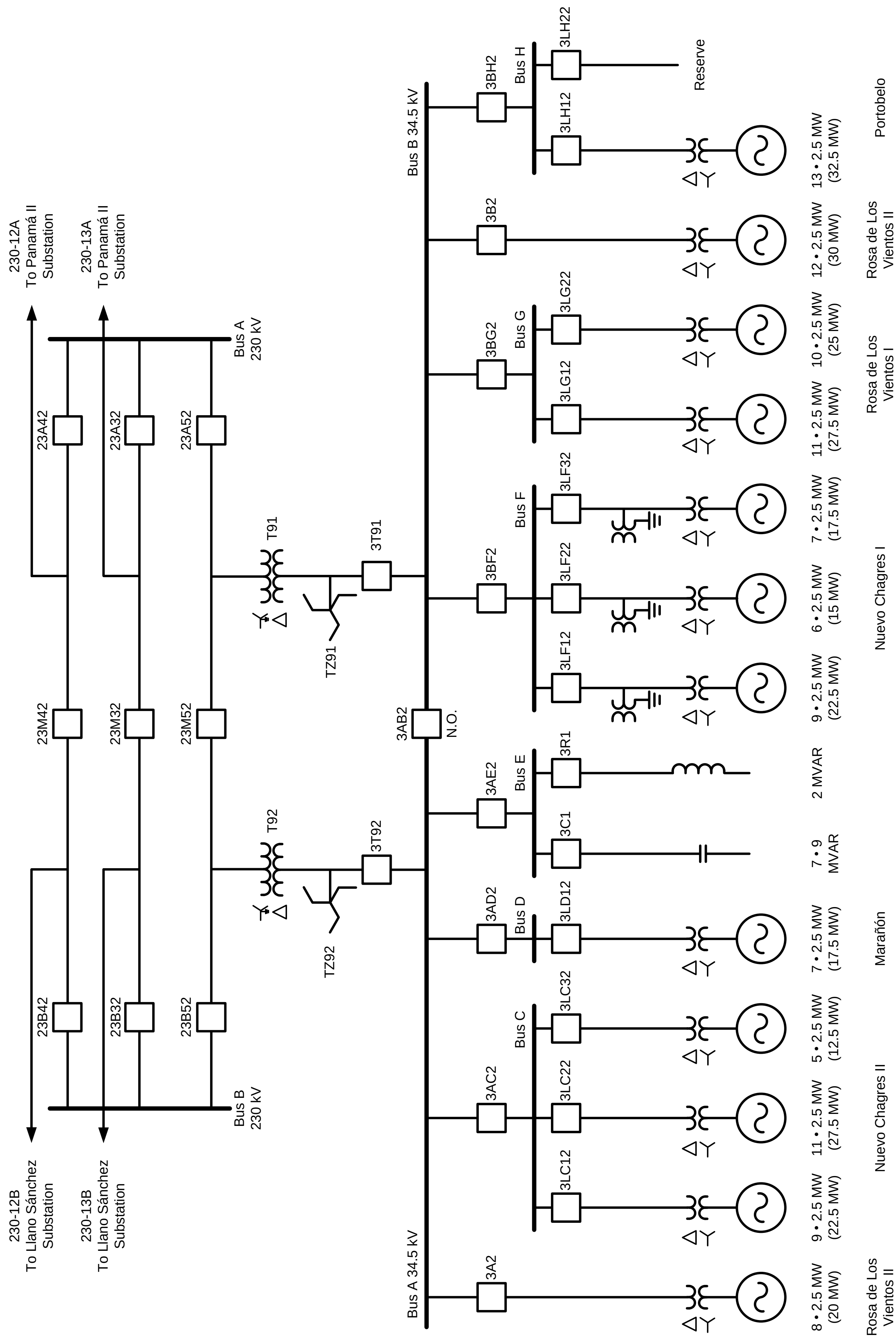

Fig. 1. System single-line diagram.

The Penonomé wind power plant 34.5 kV system is grounded through two zig-zag grounding transformers (TZ91 and TZ92) connected to the low-voltage terminals of Transformers T91 and T92. These grounding transformers limit the contribution to a bolted ground fault to approximately 1,000 A. Since the system series impedance is much smaller than the grounding transformer impedance, the ground fault current value is practically the same for any fault location on the 34.5 kV network.

In addition, three collector circuits of the Nuevo Chagres I wind power plant (Collector Circuits 3LF12, 3LF22, and 3LF32) are grounded per the wind generator manufacturer's recommendation. Three 34.5/0.48 kV grounded-wye/delta distribution transformer banks provide the circuit grounding and limit the contribution to a bolted ground fault to approximately 1,100 A. Each grounding bank is connected at equal distances from the substation and the farthest wind generator of the collector circuit. These additional grounding banks act as ground fault current sources at the collector circuits, which creates coordination problems for ground overcurrent protection.

III. Protection and Control System Description

The scope of the project described in this paper was as follows:

- Perform short-circuit and protection coordination studies for the 230 kV and 34.5 kV systems of the El Coco substation.
- Supply the protection and control (P&C) panels for the following:
  - Four 230 kV transmission lines with breaker-and-a-half bus arrangements at both ends (Lines 230-12A, 230-13A, 230-12B, and 230-13B).
  - Two 230/34.5 kV transformers with grounded-wye/delta connections (Transformers T91 and T92).
  - Two 34.5 kV zig-zag grounding transformers (Transformers TZ91 and TZ92).

A. Design Requirements

Meeting the wind generation plant demand for high service continuity requires dependable and fast phase fault protection, and sensitive and selective ground fault protection. The design requirements of the protection system include:

- Dual primary line protection, including current differential (87L) and directional-comparison protection schemes with the following characteristics:
  - Redundant fiber-optic communications channels.
  - Single-pole switching in the 87L scheme of Primary Protection 1.
- Line backup protection, including phase distance (21) and ground distance (21N) protection and ground directional overcurrent (67N) protection.
- Line circuit breaker automatic reclosing (79) with the following characteristics:
  - Reclosing enabled in Primary Protection 2 and available as hot standby in Primary Protection 1.
  - Master-follower reclosing scheme with the bus-side circuit breaker acting as the master and the middle circuit breaker acting as the follower. The follower replaces the master when the master is out of service.
- Breaker-failure (50BF) protection on 230 kV circuit breakers. The direct transfer trip of remote breakers must be supervised by Zone 3 fault detection.
- Dual transformer protection, including differential (87T), phase overcurrent (51), and ground overcurrent (51N) elements.
- Overcurrent protection for the zig-zag grounding banks using 51 elements.
- Overcurrent protection for the 34.5 kV collector circuits including 50/51 and 50N/51N elements.

B. P&C System Description

The P&C system uses multifunction relays with communications and programmable logic. These relays provide all the protection functions, as well as the control and monitoring functions required by the substation integrated system.

1) Transmission Line P&C System

Two multifunction relays provide fully redundant primary and backup line protection. Each relay provides the following functions:

- 87L protection that uses phase (87LP), negative-sequence (87LQ), and zero-sequence (87LG) differential elements to provide phase and ground fault protection.
- Directional-comparison permissive underreaching transfer trip (PUTT) scheme that uses 21 and 21N elements for directional discrimination.
- Distance protection that uses 21 mho elements polarized with memorized positive-sequence voltage and 21N quadrilateral elements.
- Ground directional overcurrent protection that uses a current-polarized zero-sequence directional element, and negative- and zero-sequence voltage-polarized directional elements that measure impedance.
- Automatic reclosing with synchronism checking (25) and undervoltage (27) supervision.

Because each multifunction relay provides 87L and directional-comparison protection, each line has dual 87L and dual directional-comparison protection.

The relays communicate over two fiber-optic channels that use optical power ground wire cables mounted on each 230 kV line. Each multifunction relay has two serial ports for 87L communication and two serial ports that support a proprietary peer-to-peer communications protocol. The relays can also monitor communications channels.

A bay controller provides the following functions:

- Breaker-failure protection.
- Local/remote switchgear control, interlocking, and circuit breaker supervision.

- Data collection from the substation switchyard and data forwarding to the supervisory control and data acquisition (SCADA) gateway.

2) Transformer Protection

Two multifunction relays provide redundant primary and backup transformer protection. Each relay provides the following functions:

- Differential protection.
- Overcurrent protection:
  - High-voltage side: 51/51N.
  - Low-voltage side: 51/51N and 51G.
- Restricted earth fault protection on the high-voltage side.
- Supervision of the sudden-pressure relay (63).

A bay controller provides the following functions:

- Breaker-failure protection.
- Local/remote switchgear control, interlocking, and circuit breaker supervision.
- Data collection from the substation switchyard and data forwarding to the SCADA gateway.

3) Zig-Zag Grounding Transformer Protection

A multifunction relay provides phase (51) overcurrent protection.

4) Distribution System Protection

One multifunction relay for each 34.5 kV collector circuit provides the following functions:

- Phase and ground overcurrent protection (50/51, 50N/51N).
- Ground directional overcurrent protection when required that uses a current-polarized zero-sequence directional element, and negative- and zero-sequence voltage-polarized directional elements that measure impedance. The relay automatically selects the best directional element for each fault.
- Underfrequency (81) alarming.
- Over- and undervoltage (59/27) alarming.

IV. Power System Digital Simulation

A. Transmission and Distribution Lines

Fig. 2 shows the pi-circuit equivalent we used to model transmission and distribution lines.

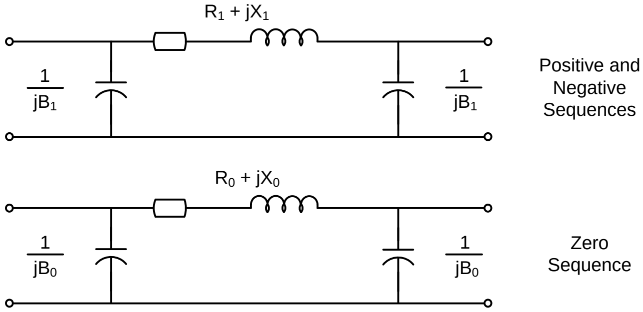

Fig. 2. Transmission line model.

In this figure, R_1+jX_1 and R_0+jX_0 are the line series impedances, and B_1 and B_0 are the shunt susceptances. Magnetic mutual coupling was included on the line models. Table III of the appendix shows the 230 kV line parameters. Table IV and Table V show the 34.5 kV overhead line and underground cable parameters respectively.

B. Transformers

We modeled the two-winding grounded-wye/delta transformers according to Fig. 3. Table VI of the appendix shows the transformer parameters. The short-circuit impedances are percent values based on the transformer rated apparent power and the tap rated voltage. Table VI also shows the parameters of the WTG step-up transformers and the grounding banks.

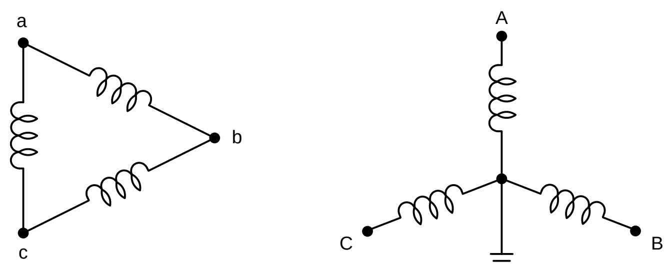

Fig. 3. Transformer winding model.

C. Wind Generators

The Penonomé wind power plant has 108 identical WTGs in its second stage, which are Type 4, 2,500 kW, 690 V units [2]. The third stage consists of the installation of 27 WTGs to reach the future planned capacity of 337.5 MW. Fig. 4 shows the WTG schematic diagram.

Each WTG consists of a variable-speed wind turbine coupled with bands to a multipole, three-phase, permanent magnet synchronous generator. The generator is connected to the network through a full-scale, back-to-back frequency converter based on insulated gate bipolar transistors and a 2,750 kVA, 0.69/34.5 kV, wye/delta step-up transformer. Table VII of the appendix shows the WTG parameters.

Type 4 WTGs offer design and operation flexibility. They can produce energy over a wide range of wind speeds, allow for fast and independent control of active and reactive power, limit fault current, and comply with the low-voltage ride-through requirements of industry regulatory agencies. The turbine rotates at its optimal aerodynamic speed (a slow speed), and the unit generates power at a frequency lower than the grid frequency. Inverters provide the frequency conversion and make it possible to supply reactive power to the grid [3] [4]. The WTG control system provides active power and frequency control, and reactive power and voltage control. Type 4 WTGs are typically designed to ride through a fault, as required by FERC Order 661 [5].

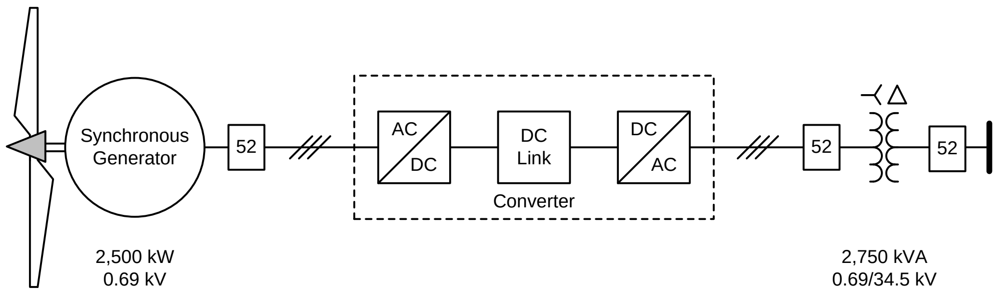

Fig. 4. WTG schematic diagram.

The behavior of Type 4 WTGs is governed entirely by the power electronics and the control algorithm. The generator response to short circuits has the following characteristics [4] [6] [7]:

- The WTG is ungrounded and contributes no zero-sequence current during a fault.
- The WTG control acts to balance the currents during unbalanced system conditions, including faults. The efficacy of this function depends on the severity of the imbalance. The WTG delivers only positive-sequence current in many cases.
- For external faults, the WTG current goes up briefly to about 2.5 times full-load current within the first half cycle. After that, the current settles back quickly to no more than 1.5 times full-load current. The WTG current response is a function of the control objective, and is not a natural generator response.

There is no consensus on whether Type 4 WTGs should be included in short-circuit studies because of their relatively low short-circuit current contributions. Some engineers recommend treating Type 4 WTGs as negative loads and ignoring them along with customer loads in short-circuit studies. In this paper, we consider WTGs as current sources for the steady-state short-circuit analysis required for overcurrent protection coordination.

V. Protection Coordination Study

A. 230 kV Line Protection Coordination

In transmission systems, synchronous generators determine the phase fault current levels. The contribution from wind power plants is typically small [4]. This is true even for the El Coco wind power plant, which is connected to a weak power system: for a three-phase fault at the 230 kV bus of the El Coco substation shown in Fig. 1, Panama's power system contributes 5,374 A under maximum generation conditions, and the wind power plant contributes 717 A (less than the plant rated current). However, the delta/grounded-wye Transformers T91 and T92 significantly contribute to ground faults on the 230 kV system.

We followed the normal coordination principles for the 230 kV line protection schemes, which are phase and ground distance, ground directional overcurrent, and PUTT schemes. In particular, we considered the following problems:

- Magnetic mutual coupling between circuits in the double-circuit Lines 230-12A and 230-13A (El Coco-Panamá II), and 230-12B and 230-13B (El Coco-Llano Sánchez) [8].
- Infeed effect for ground faults from the El Coco substation, which affects protection schemes at the Panamá II and Llano Sánchez substations.

B. 34.5 kV System Protection Coordination

1) Phase Overcurrent Protection Coordination

The transmission system contribution typically determines the phase fault current levels in wind power plant medium-voltage collector circuits. The contribution from the wind power plant to collector circuit faults is normally small. For this reason, overcurrent protection is generally suitable for collector circuits. In some cases, a significant phase fault current contribution from the wind power plant makes it necessary to use directional overcurrent elements supervised by load encroachment elements [9].

Given the weak current contribution to phase faults, we use phase overcurrent protection for the El Coco collector circuits. The protection coordination study had to consider the inrush current resulting from closing the collector circuit breaker with all of the WTG step-up transformers in service. The WTG step-up transformers have fuse protection. Fig. 5 shows an example of phase overcurrent protection coordination for phase faults on Collector Circuit 3LF12. For simplicity, the fuse curves are not shown.

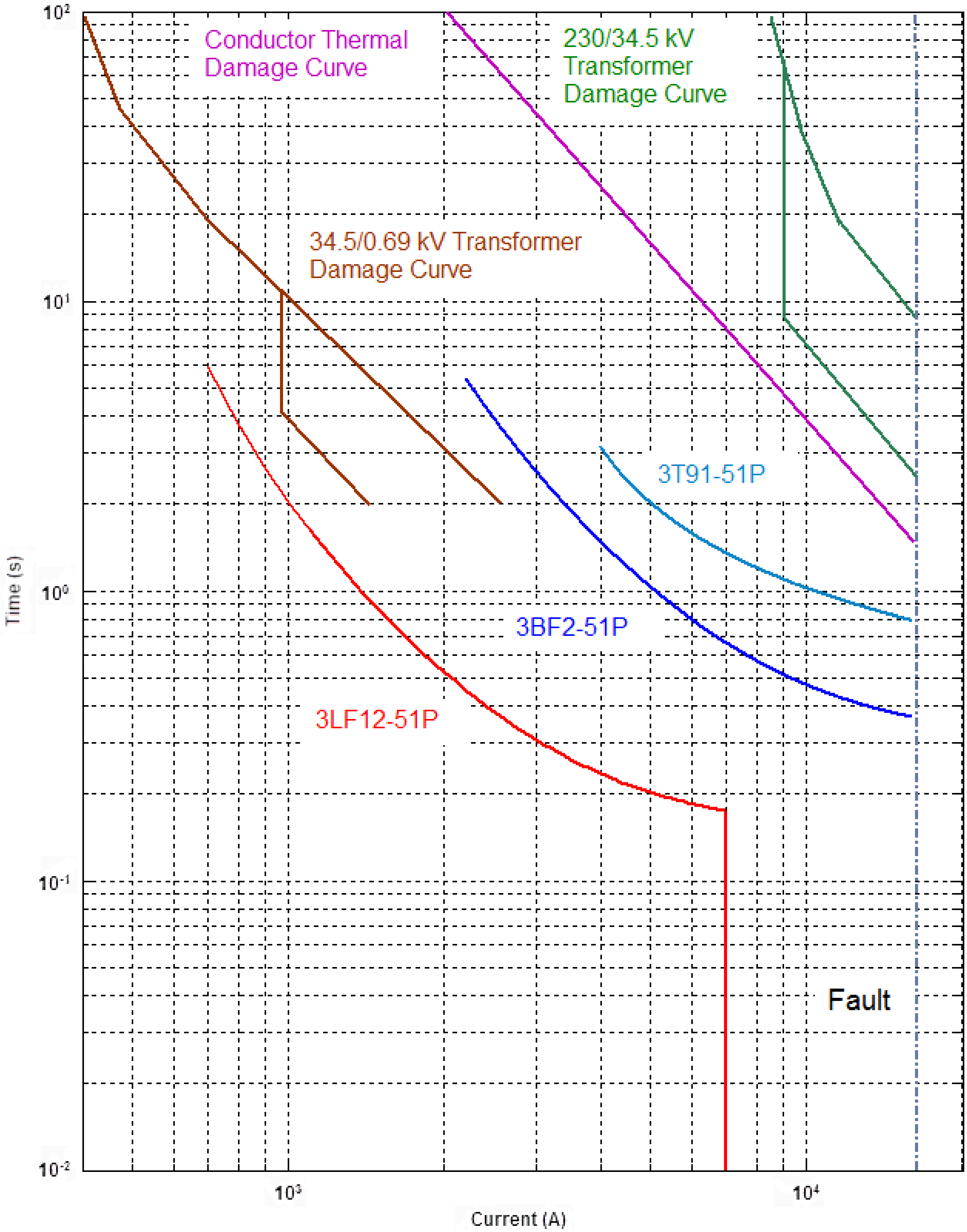

Fig. 5. Example of phase overcurrent protection coordination.

2) Ground Overcurrent Protection Coordination

As mentioned before, the El Coco 34.5 kV system is grounded through two zig-zag grounding transformers connected to the low-side terminals of Transformers T91 and T92. In addition, Collector Circuits 3LF12, 3LF22, and 3LF32 of the Nuevo Chagres I wind power plant are grounded through grounded-wye/delta distribution transformer banks. These five grounding transformers are the only sources of zero-sequence current for ground faults in the 34.5 kV system.

Fig. 6 shows the currents for a bolted single-phase-to-ground fault at the 34.5 kV Bus F of the El Coco substation. The grounding transformers of Collector Circuits 3LF12, 3LF22, and 3LF32 and the substation zig-zag grounding Transformer TZ91 contribute similar currents to the fault. The other collector circuits (not shown in Fig. 6) do not contribute to ground faults because the WTG step-up transformers are ungrounded.

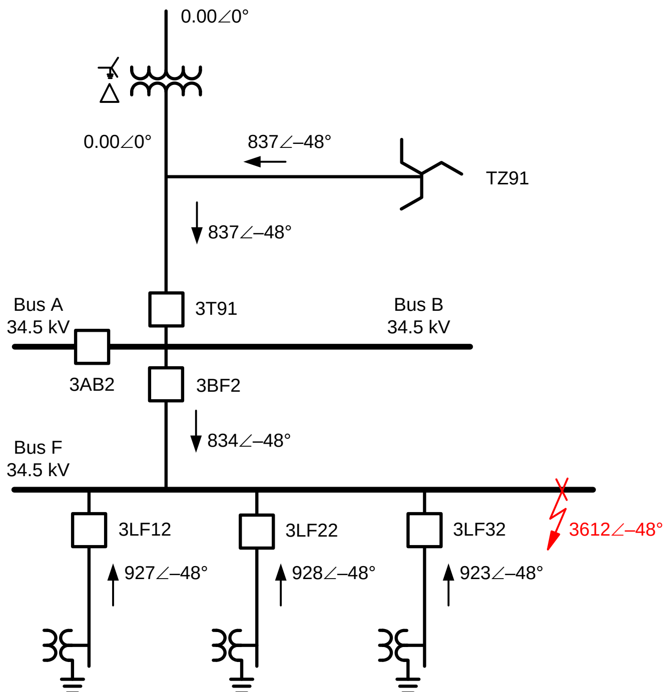

Fig. 6. Current contributions for a single-phase-to-ground fault at the 34.5 kV Bus F of the El Coco substation.

Given the ground fault current distribution, we used the following ground protection schemes for the 34.5 kV collector circuits:

- Ungrounded collector circuits have ground overcurrent protection (50N/51N).
- Collector Circuits 3LF12, 3LF22, and 3LF32 have ground directional overcurrent protection. The directional elements look into the collector circuits and supervise the 51N elements only. Our fault studies showed that the best choice for this application is a 67N element with a current-polarized zero-sequence directional element, and negative- and zero-sequence voltage-polarized directional elements that measure impedance [10]. The relay automatically selects the best directional element depending upon the fault and the system operating conditions. This 67N element provides adequate sensitivity for ground faults on the 34.5 kV system.

The 67N elements of Collector Circuits 3LF12, 3LF22, and 3LF32 provide protection for ground faults on these circuits and allow for coordination with the backup ground overcurrent elements of Circuit Breaker 3BF2. However, these 67N elements do not respond to 34.5 kV Bus B ground faults. These faults must be cleared by time-delayed operation of Relay 3BF2. We can speed-up 34.5 kV bus ground fault clearing with any of the following solutions:

- Enable a 67N element in Relay 3BF2 looking into the bus to serve as fast primary protection for bus ground faults. Enable 67N elements in Relays 3LF12, 3LF22, and 3LF32 looking into the bus to serve as time-delayed backup protection for bus ground faults.
- Add a fast bus tripping scheme at the 34.5 kV bus [11]. This scheme is currently being implemented.
- Add a bus differential protection scheme at the 34.5 kV bus.

Fig. 7 shows an example of ground overcurrent protection coordination for ground faults on Collector Circuit 3LF12.

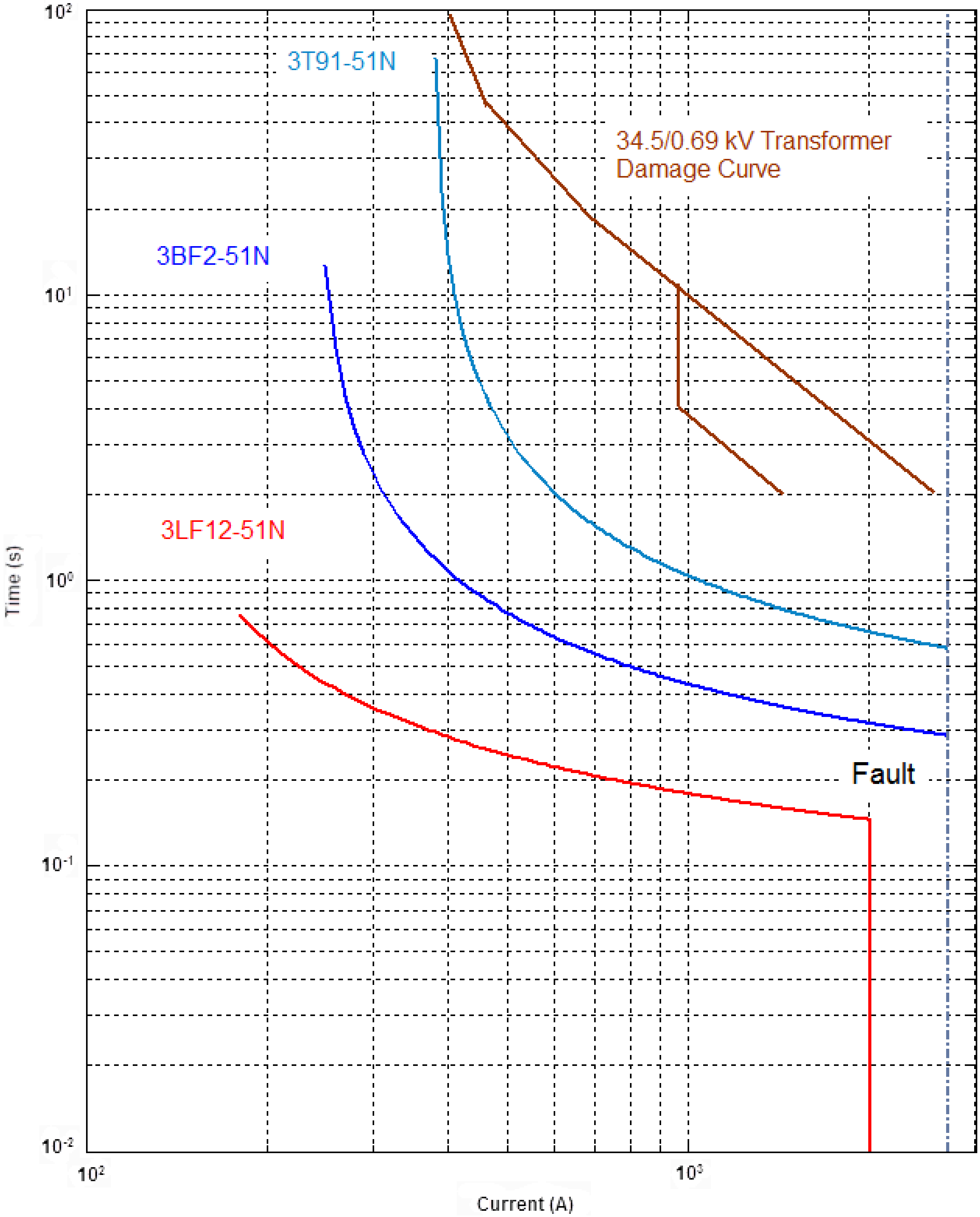

Fig. 7. Example of ground overcurrent protection coordination.

VI. Actual Fault Event

The Penonomé wind power plant protection system has operated well for almost all actual faults. This section presents a case where line insulation failures and a relay failure to operate resulted in two cross-country faults. All the other relays performed well for these complex faults.

On April 8, 2015, the section of the Penonomé wind power plant shown in Fig. 8 was operating with Collector Circuits 3LG22, 3LF12, 3LF22, and 3LF32 in service. Collector Circuit 3LG12 was out of service (Disconnect Switch 3LG11 was open and grounded). Circuit Breaker 3B2 was open and ready to be closed to energize its collector circuit for the first time.

Upon Circuit Breaker 3B2 closure, two faults occurred on two Rosa de los Vientos wind power plant collector circuits.

First, two single-phase-to-ground faults occurring on different collector circuits combined to create a phase-to-phase-to-ground cross-country fault, which evolved into a single-phase-to-ground fault and caused tripping of Circuit Breakers 3BF2 and 3T91. These circuit breaker operations caused the system to become ungrounded. With the first fault still present on one phase and the system ungrounded, a single-phase-to-ground fault on another phase of another collector circuit resulted in another phase-to-phase-to-ground cross-country fault and caused tripping of Circuit Breaker 3LG22.

Table I shows the sequence of events. Table II shows the currents measured by several relays approximately one cycle after the inception of the first fault. Because the relays are not time-synchronized, we determined these currents by manually aligning the relay time stamps.

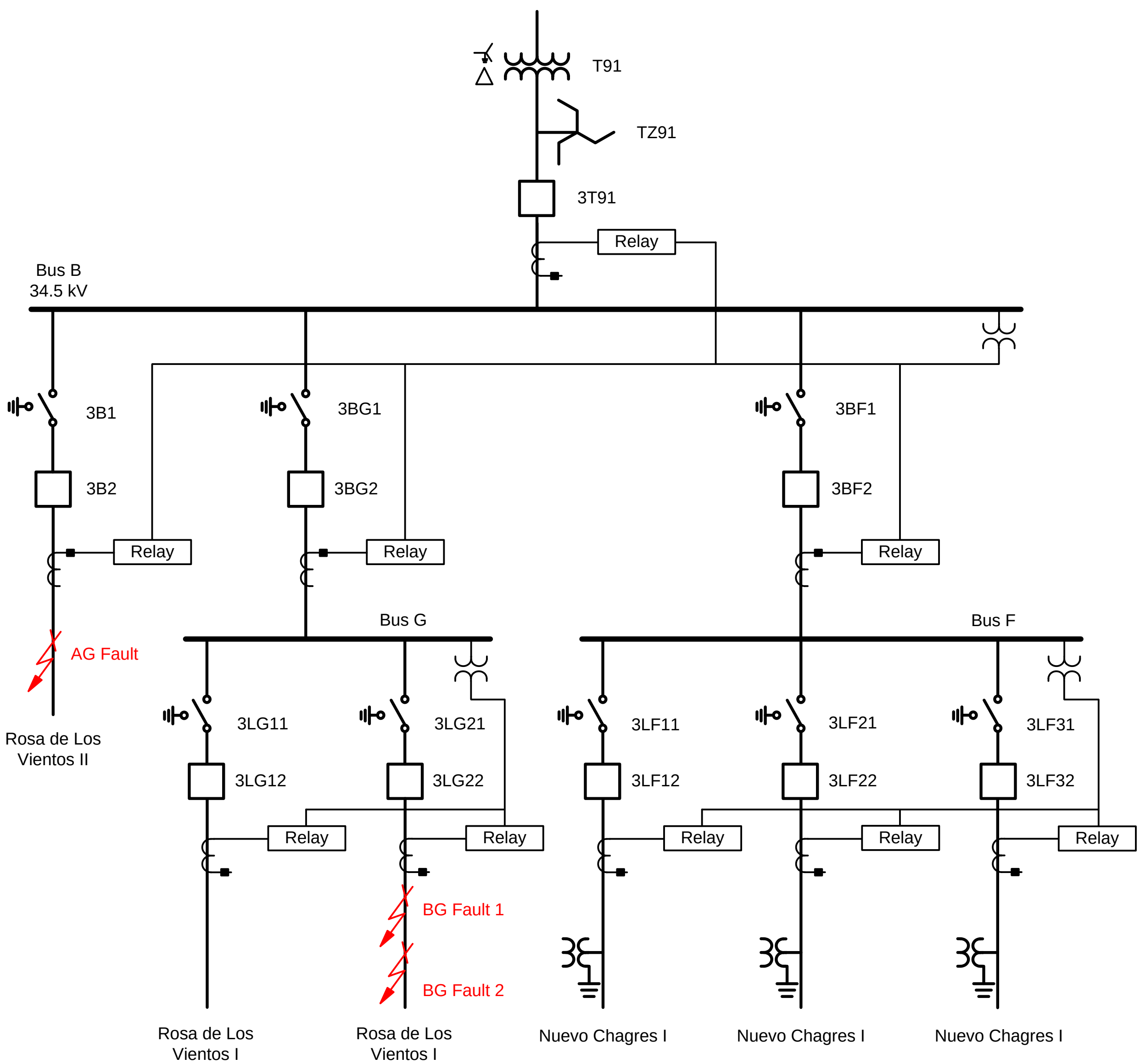

Fig. 8. Faulted power system section.

TABLE I
SEQUENCE OF EVENTS

Event	Time	Relay					
		3T91	TZ91	3BF2	3LF12, 3LF22, 3LF32	3LG22	3BG2
1	12:50:17:146	Pick up 2,163 A	Pick up 247 A	Pick up 1,519 A	Pick up 545 A		
2	12:50:17:359		Pick up 322 A	Trip 1,489 A T_{OP} = 0.213 s			
3	12:50:18:215	Trip 785 A T_{OP} = 1.069 s	Pick up 310 A			Pick up 457 A	Pick up 459 A
4	12:50:18:779					Trip 453 A T_{OP} = 0.564 s	

TABLE II
RELAY RECORDED CURRENTS ONE CYCLE AFTER INCEPTION OF THE FIRST FAULT

Current	Relay					
	3T91	TZ91	3BF2	3LF12	3LF22	3LF32
I_A	2209.2∠0°	228.7∠0°	1482.4∠0°	540.4∠0°	446.4∠0°	513.8∠0°
I_B	1819.8∠175.3°	239.4∠1.1°	1513.7∠296.8°	545.8∠291.7°	486.3∠303.7°	501.5∠301.7°
I_C	326.3∠41.2°	247.4∠–2.9°	83.1∠275.6°	28.6∠206.3°	72.2∠316.3°	26.9∠20.8°
I_1	1209.5∠327.2°	9.8∠185.1°	862.1∠30.2°	330.6∠27.4°	246.8∠34.1°	285.0∠29°
I_2	1114.9∠28.6°	3.6∠88.8°	45.9∠73.7°	22.3∠69°	13.1∠92.6°	2.9∠163.7°
I_0	245.7∠29.6°	238.4∠–0.7°	867.9∠326.6°	295.2∠324.1°	303.3∠330°	301.4∠332.5°
I_G	736.8∠29.6°	715.1∠–0.7°	2603.7∠326.6°	885.5∠324.1°	909.8∠330°	904.2∠332.5°

A. *First Fault*

Circuit Breaker 3B2 was manually closed at 12:50:17:146 to energize its collector circuit for the first time. Upon Circuit Breaker 3B2 closure, two single-phase-to-ground faults involving different phases occurred in two collector circuits of the Rosa de los Vientos wind power plant, which resulted in a phase-to-phase-to-ground fault condition. An insulation failure upon energization caused a permanent AG fault on an underground cable—approximately 3.2 km away from the substation—of Collector Circuit 3B2. At the same time, or immediately after the AG fault, a lightning arrester failed in an overhead section of Collector Circuit 3LG22—approximately 10.7 km away from the substation—resulting in a BG fault in that circuit. After some time, the lightning arrester exploded, which removed the BG fault. As a result, the fault evolved from a cross-country ABG fault to an AG fault on Collector Circuit 3B2.

Protection operation for this fault was as follows:

- Relay 3B2 failed to operate for the AG fault. Circuit Breaker 3B2 did not trip.
- Relay 3BF2 tripped in 0.213 seconds (the 51 and 51N elements detected the fault; the 51N element tripped). This relay operation is correct because the 67N elements of Relays 3LF12, 3LF22, and 3LF32 block tripping of their 51 elements for this fault. Circuit Breaker 3BF2 tripping removed the fault contribution from Nuevo Chagres I wind power plant and also removed the grounding provided by the grounding banks connected to Collector Circuits 3LF12, 3LF22, and 3LF32.
- Relay 3T91 tripped in 1.069 seconds (the 51N element tripped). This operation is correct. Circuit Breaker 3T91 tripping removed the fault contribution from Transformer T91 and also removed the grounding provided by the zig-zag Grounding Bank TZ91. As a result, the system became ungrounded.

Fig. 9 shows the currents and voltages recorded by Relay 3T91 at the start of the first cross-country fault. The currents are the traditional contributions from an ungrounded power transformer and a grounding bank and correspond to an ABG fault. The Relay 3T91 currents shown in Table II confirm the fault type. The voltages in Fig. 9 do not correspond to an ABG fault because the WTG inverter controls act to try to balance the voltages. The A-phase voltage remains low because of the permanent, probably low-resistance AG fault on the underground cable.

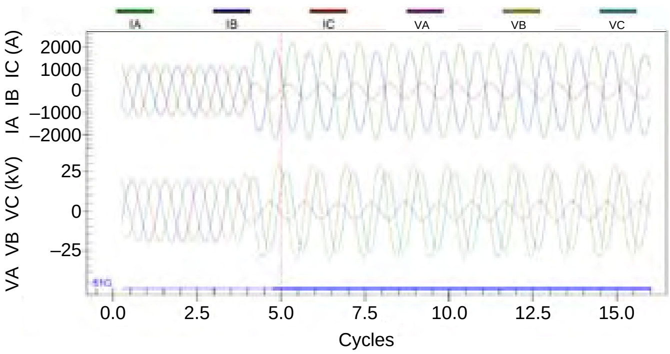

Fig. 9. Currents and voltages recorded by Relay 3T91 at the start of the first cross-country ABG fault.

Fig. 10 shows the currents recorded by Relay TZ91 (not shown in Fig. 8) at the start of the first fault. This figure and the Relay TZ91 currents shown in Table II demonstrate the typical contribution of a grounding bank to a ground fault.

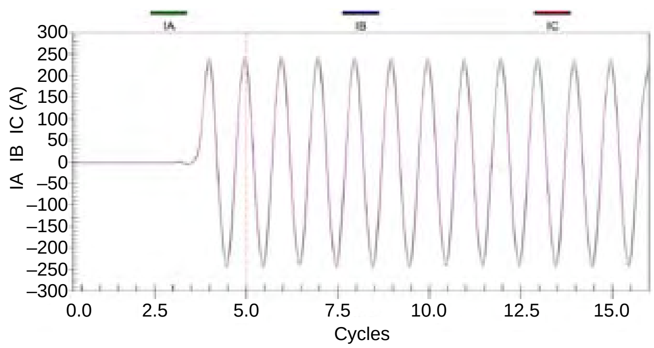

Fig. 10. Currents recorded by Relay TZ91 at the start of the first cross-country ABG fault.

Fig. 11 shows the currents recorded by Relay 3BF2 at the start of the first fault, which represent the contribution of the Nuevo Chagres I wind power plant to the cross-country fault. This figure and the Relay 3BF2 currents in Table II show that the faulted phase currents have similar magnitudes, but are less than 180° apart because of the WTG inverter controls effect. This effect and the grounding transformers connected to Collector Circuits 3LF12, 3LF22, and 3LF32 cause the zero-sequence current to be much higher than the negative-sequence current.

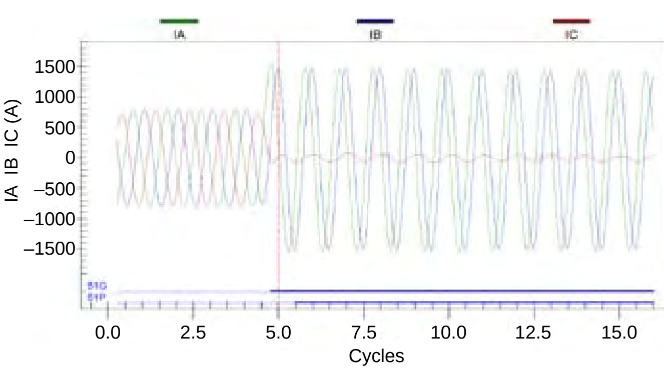

Fig. 11. Currents recorded by Relay 3BF2 at the start of the first cross-country ABG fault.

Fig. 12 shows the currents and voltages recorded by Relay 3T91 at the time of Circuit Breaker 3T91 tripping. The lightning arrester explosion removed the BG fault and the cross-country fault evolved into an AG fault on Collector Circuit 3B2. The system became ungrounded when Circuit Breaker 3T91 tripping removed the only remaining grounding source (zig-zag Grounding Transformer TZ91). With the AG fault still present, the system neutral shifted and the two healthy phase voltages took values greater than the phase-to-phase system-rated voltage, as shown in Fig. 12.

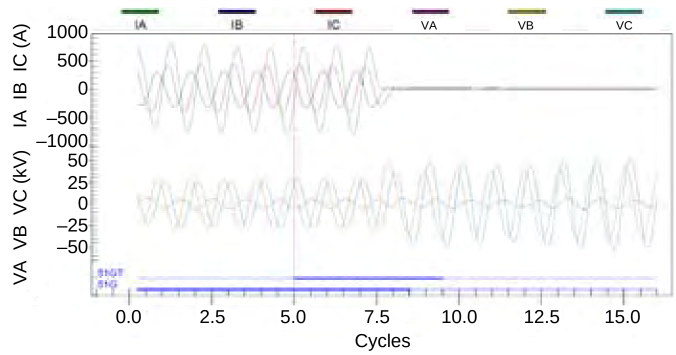

Fig. 12. Currents and voltages recorded by Relay 3T91 at the time of Circuit Breaker 3T91 tripping, when the cross-country ABG fault had evolved into an AG fault.

B. Second Fault

When the system became ungrounded, the high phase-to-ground voltages on the healthy phases shown in Fig. 12 caused the failure of another lightning arrester on the B-phase of Collector Circuit 3LG22, resulting in a new BG fault in that circuit and the evolution of the AG fault into another ABG cross-country fault in the system. Relay 3LG22 tripped in 0.564 seconds (the 51N element tripped). This relay operation is correct. Circuit Breaker 3LG22 tripping cleared the fault.

Fig. 13 depicts the currents and voltages recorded by Relay 3BG2 at the start of the second fault. The only source left in the system at this time was the Rosa de los Vientos I wind power plant. The A-phase and B-phase voltages are very low in Fig. 13, which shows the ABG type of fault. However, Relay 3BG2 measures fault current only on the A-phase. This is a result of the location of both faults. The Rosa de los Vientos I WTGs contribute to the AG fault on Collector Circuit 3B2 through Relay 3BG2, so this relay measures A-phase fault current. However, Relay 3BG2 does not measure the WTG's current contribution to the BG fault on Collector Circuit 3LG22.

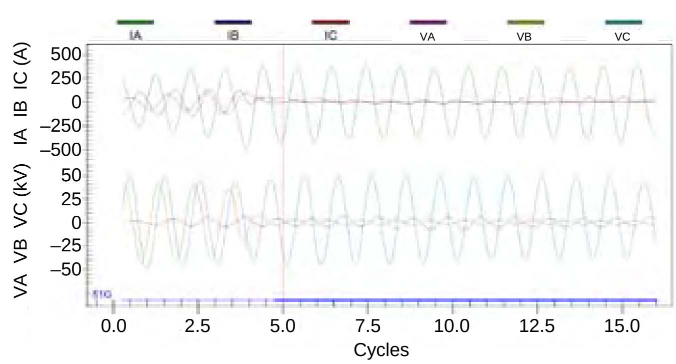

Fig. 13. Currents and voltages recorded by Relay 3BG2 at the start of the second cross-country ABG fault.

VII. Conclusion

From the results of the Penonomé wind power plant project, we can conclude the following:

- The Penonomé wind power plant is comprised of WTGs belonging to different companies connected to a 34.5 kV system. Two step-up transformers interconnect the 34.5 kV system to the 230 kV transmission system at the El Coco substation. The 34.5 kV system is grounded through zig-zag and grounded-wye/delta banks, which poses a challenge for ground protection coordination in the 34.5 kV system.
- The Penonomé wind power plant has 108 Type 4 WTGs. Each WTG consists of a variable-speed wind turbine coupled to a three-phase, permanent magnet synchronous generator, connected to the network through a frequency converter and a step-up transformer.
- Type 4 WTGs can produce energy over a wide range of wind speeds, allow for control of active and reactive power, limit fault current, and comply with FERC low-voltage ride-through requirements.
- The typical response of Type 4 WTGs to short circuits has the following characteristics:
  - The WTG contributes no zero-sequence current during ground faults.
  - The WTG control balances the currents during unbalanced system conditions including faults.
  - The WTG current contribution to external faults is not greater than 1.5 times full-load current.
- The P&C system uses multifunction relays with communications and programmable logic. These relays provide all the protection functions, as well as the control and monitoring functions required by the substation's integrated system.
- We considered WTGs as current sources for the steady-state short-circuit analysis required for overcurrent protection coordination.
- We followed the normal coordination principles for the 230 kV line protection schemes. In particular, we considered magnetic mutual coupling on the double-circuit 230 kV lines and infeed effect from the El Coco substation for ground faults.
- Given the strong contribution from the 230 kV system to phase faults on the 34.5 kV system, we applied overcurrent protection for the 34.5 kV collector circuits. The WTG step-up transformers have fuse protection.
- Given the ground fault current distribution, we used ground overcurrent protection for the ungrounded collector circuits and ground directional overcurrent protection looking into the circuit for grounded collector circuits. This protection system provides time-delayed clearing on 34.5 kV bus faults.
- The following improvements can speed-up 34.5 kV bus fault clearing:
  - Enabling 67N elements looking into the bus in Relay 3BF2 and Relays 3LF12, 3LF22, and 3LF32.
  - Adding a fast bus tripping scheme at the 34.5 kV bus, which is currently being implemented.
  - Adding differential protection at the 34.5 kV bus.
- The Penonomé wind power plant protection system has operated well for almost all actual faults. The paper presents a case where line faults and a relay failure to operate resulted in two cross-country faults. All the other relays performed well for these complex faults.

VIII. APPENDIX

This section provides the power system parameters we used for the fault analysis and protection coordination studies.

TABLE III
230 KV LINE ELECTRICAL PARAMETERS

Line	**ID**	**Length (km)**	**R_1 (pu)**	**X_1 (pu)**	**B_1 (pu)**	**R_0 (pu)**	**X_0 (pu)**	**B_0 (pu)**	**R_M (pu)**	**X_M (pu)**
El Coco-Llano Sánchez	230-12B	60	0.00606	0.05400	0.11148	0.03991	0.15191	0.16072	0.03380	0.08510
El Coco-Llano Sánchez	230-13B	60	0.00606	0.05400	0.11148	0.03991	0.15191	0.16072	0.03380	0.08510
El Coco-Panamá II	230-12A	135	0.01364	0.12150	0.25082	0.08979	0.34179	0.06888	0.07620	0.19150
El Coco-Panamá II	230-13A	135	0.01364	0.12150	0.25082	0.08979	0.34179	0.06888	0.07620	0.19150

TABLE IV
34.5 KV OVERHEAD LINE ELECTRICAL PARAMETERS

Structure Type	**Circuits**	**Conductor Size**	**Ground Wire**	**R_1 (pu/km)**	**X_1 (pu/km)**	**B_1 (pu/km)**	**R_0 (pu/km)**	**X_0 (pu/km)**	**B_0 (pu/km)**	**R_M (pu/km)**	**X_M (pu/km)**
Eagle 9000	3	ACSR 477 27/6	ACS 7 No. 8	0.01032	0.03099	0.00005	0.04038	0.13812	0.00003	0.02878	0.07828
Eagle 9000	2	ACSR 477 27/6	ACS 7 No. 8	0.01032	0.03099	0.00005	0.04036	0.13813	0.00003	0.03005	0.08322

TABLE V
34.5 KV UNDERGROUND CABLE ELECTRICAL PARAMETERS

Installation Technique	**Circuits**	**Conductor Size (mm^2)**	**Ground Wire**	**R_1 (pu/km)**	**X_1 (pu/km)**	**B_1 (pu/km)**	**R_0 (pu/km)**	**X_0 (pu/km)**	**B_0 (pu/km)**
Direct burial	1	400	NA	0.00852	0.00988	0.00114	0.01569	0.00653	0.00114
Direct burial	1	240	NA	0.01199	0.01092	0.00097	0.02068	0.00739	0.00097
Direct burial	1	95	NA	0.02654	0.01312	0.00069	0.03784	0.00945	0.00069

TABLE VI
TRANSFORMER AND GROUNDING BANK ELECTRICAL PARAMETERS

Transformer ID	**High Voltage (kV)**	**Low Voltage (kV)**	**Rated Power (MVA)**	**Vector Group**	**Impedance (%)**	**Impedance (Ohms)**
T91	230	34.5	120/140	Ynd11	10.95	-
T92	230	34.5	120/140	Ynd11	10.95	-
TZ91	-	34.5	0.5	ZN0	-	59.47
TZ92	-	34.5	0.5	ZN0	-	60.15
TU	34.5	0.69	2.75	Dyn5	6.97	-
TDG	34.5	0.48	1.25	Ynd1	5.63	-

TABLE VII
WTG ELECTRICAL PARAMETERS

Parameter	Value	Unit
Number of phases	3	-
Nominal voltage	690	V
Rated active power	2,500	kW
Rated apparent power	2,632 (power factor = 0.95)	kVA
Rated frequency	60	Hz
Rated power factor	1.0 default; controlled: from 0.95 leading to 0.95 lagging	-
Reactive power	0.0 default; controlled: from 820 inductive to 820 capacitive	kVAR
Maximum short-circuit current	2,600	A
Positive-sequence impedance	0.7530	pu
Negative-sequence impedance	0.7530	pu

IX. REFERENCES

[1] E. H. Camm, M. R. Behnke, O. Bolado, M. Bollen, M. Bradt, C. Brooks, W. Dilling, M. Edds, W. J. Hejdak, D. Houseman, S. Klein, F. Li, J. Li, P. Maibach, T. Nicolai, J. Patiño, S. V. Pasupulati, N. Samaan, S. Saylors, T. Siebert, T. Smith, M. Starke, and R. Walling, "Wind Power Plant Grounding, Overvoltage Protection, and Insulation Coordination: IEEE PES Wind Plant Collector System Design Working Group," proceedings of the IEEE Power & Energy Society General Meeting, Calgary, AB, July 2009.

[2] Goldwind, "2.5 MW PMDD Wind Turbine." Available: http://www.goldwindamerica.com/media/2012/12/Goldwind_25MW_Product_Brochure.pdf.

[3] E. H. Camm, M. R. Behnke, O. Bolado, M. Bollen, M. Bradt, C. Brooks, W. Dilling, M. Edds, W. J. Hejdak, D. Houseman, S. Klein, F. Li, J. Li, P. Maibach, T. Nicolai, J. Patiño, S. V. Pasupulati, N. Samaan, S. Sailors, T. Siebert, T. Smith, M. Starke, and R. Walling, "Characteristics of Wind Turbine Generators for Wind Power Plants," proceedings of the IEEE Power & Energy Society General Meeting, Calgary, AB, July 2009.

[4] R. A. Walling, E. Gursoy, and B. English, "Current Contributions from Type 3 and Type 4 Wind Turbine Generators During Faults," proceedings of the IEEE Power & Energy Society General Meeting, San Diego, CA, July 2011.

[5] United States of America Federal Energy Regulatory Commission, "Interconnection for Wind Energy," 18 CFR Part 35, Docket No. RM05-4-000, Order No. 661, June 2005. Available: http://www.ferc.gov/whats-new/comm-meet/052505/E-1.pdf.

[6] E. Muljadi, N. Samaan, V. Gevorgian, J. Li, and S. Pasupulati, "Short Circuit Current Contribution for Different Wind Turbine Generator Types," proceedings of the IEEE Power & Energy Society General Meeting, Minneapolis, MN, July 2010.

[7] B. Chen, A. Shrestha, F. A. Ituzaro, and N. Fischer, "Addressing Protection Challenges Associated With Type 3 and Type 4 Wind Turbine Generators," proceedings of the 68th Annual Conference for Protective Relay Engineers, College Station, TX, April 2015.

[8] D. A. Tziouvaras, H. J. Altuve, and F. Calero, "Protecting Mutually Coupled Transmission Lines: Challenges and Solutions," proceedings of the 67th Annual Conference for Protective Relay Engineers, College Station, TX, April 2014.

[9] D. Jones and K. Bennett, "Wind Farm Collector Protection Using Directional Overcurrent Elements," proceedings of the IEEE Power & Energy Society Transmission and Distribution Conference and Exposition, Orlando, FL, May 2012.

[10] J. Roberts and A. Guzmán, "Directional Element Design and Evaluation," proceedings of the 21st Annual Western Protective Relay Conference, Spokane, WA, October 1994.

[11] H. J. Altuve Ferrer and E. O. Schweitzer, III (eds.), *Modern Solutions for Protection, Control, and Monitoring of Electric Power Systems.* Schweitzer Engineering Laboratories, Inc., Pullman, WA, 2010.

X. BIOGRAPHIES

Darío Vila received his B.S. degree in industrial engineering with a specialization in electrotechnology and an emphasis in automation and electronics from the Escola Técnica Superior de Enxeñeiros Industriais of Vigo, Spain. Mr. Vila joined Instalaciones y Servicios CODEPA S.A. in 2000, where he works on projects related to distributed electric power generation, in particular, wind power plants.

Eliseo Alcázar received his B.S.E.E. degree from the Oaxaca Technological Institute in 1998 and his M.Sc. degree from the Autonomous University of San Luis Potosí in 2015. From 1999 until 2001, he was the head of the protection, control, and metering department in the Southeastern Distribution Division (SDD) of Comisión Federal de Electricidad (CFE) in Tehuantepec, Mexico. From 2001 until 2004, he was head of the protection office of the CFE SDD. During this time, he was engaged in supervision, maintenance, improvement, and commissioning of protection, control, and metering systems. In April 2004, Mr. Alcázar joined Schweitzer Engineering Laboratories, Inc. (SEL), where he is currently a protection engineering supervisor in San Luis Potosí, Mexico. His activities include protection, control, and metering system design and commissioning, as well as technical support and training on SEL products for engineers from utilities and industrial plants. His expertise includes fault analysis, short-circuit studies, protection coordination, and protection system design.

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Distributed RE Resources in India- Planning & Network Integration

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Synopsis

Climate Change Conference in Paris- 21st Session (COP 21) in 2015 and ISA (International Solar Alliance) has given fillip to the development of Non-conventional Energy Resources / Distributed Energy Resources (DER) all over the world including India by allocation of funds, setting of PPF (**Project Preparation Facilities)** to assist development partner countries towards the preparation of viable projects for concession financing under lines of credit.

This Paper discusses Planning Criteria & Status of DER in India including Solar Generation categorization (Solar Voltaic & Solar thermal) and configuration (Roof top, Solar Community Farms & Solar Mega Farms). The present share of RE in India is around 17% which will grow to 35% by 2022 with 175GW RE initiative by GoI as major boost to clean power & energy security. There is need of putting more stress on collection of actual data, load & demand curves on each transformer, each feeder with Re-closures on /off, peaking time and duration and forecast detailed study on future distribution system requirement considering reliability, resilience, security , safety, etc and particularly involvement of digital technology in distribution system and its effect on the battery capacity requirement. The large 100 GW scale deployment of Solar Projects in India to meet MNRE targets has brought to the fore urgent issues of planning, manufacturing quality, construction & integration to the Distribution Network.

3rd Party Drones deployment for speedy and timely performance of site survey,installation, monitoring, data collection of remote solar farms lagging communication facilities. Drones can be deployed for Lattice Tower corrosion inspection, Post disaster inspections, Substation surveillance against Intruders and inspection.

Key Words: DER, CEA TL Planning Guidelines, Solar Generation Categorization, Solar Configuration, Solar Generation Components, Drones, Solid State Batteries,

1.Introduction

1.1 Conventional Power System

Indian Power System (335GW) has robust Hybrid Transmission network having both EHVAC & HVDC Systems managed through five Regional Grids synchronously interconnected forming National Grid.

India has Installed Grid Interactive Renewable Power Capacity (excluding large hydropower) around 57,244 MW (Wind Power- 32,280MW, Solar Power- 12,289 MW, Biomass Power- 8,182MW, Waste-to-Power- 114MW and Small Hydro power- 4380MW).

Hydro including pump storage, Thermal (coal, gas and diesel) and Nuclear are now further augmented by Renewable Distributed Energy Resources (DER) using mainly Solar (PV &Thermal) & Wind Energy. Growth in DER is progressively brought thru improvement in manufacturing technology, efficiency, reliability, resilience and techno economic competitiveness. All these power generating resources are connected to load centers thru Transmission System (Primary and Secondary network).

Battery Energy Storage, Biogas, Geothermal and others viz. Compressed air / Heat Storage System, Fly wheel System, Fuel Cell System(at infancy stage) etc are other options being tried elsewhere in the world. Indian Power System is yet to experience major intervention in these areas.

1.2 Renewable *Distributed* Energy Resources (DER)-Solar Energy Generation

Ministry of New and Renewable Energy Resources is vigorously monitoring Renewable Energy target of 175 GW {Wind 60 GW, Solar 100 GW, Bio-Power (Biomass Power & Waste to Power Generation) 10 GW and Small Hydro 5 GW} achievement by year 2022. Additionally, MNRE communicated in May 2017 to States List of spare bays available in Power Grid S/Ss(WR/NR/SR under ISTS) advising State Govts. to prioritize setting up Solar projects matching available capacity of S/S/ Transmission system. CEA approached separately to prepare related list and maps of such ISTS in consultation with States.

CEA Guidelines in ‘Manual on Transmission Planning 2013 also include additional provisions to be made for generation covered under DER. The communiqué also mentions GOI target of setting up 100 GW solar capacity by 2022. As on date over 12 GW Solar generation has been installed.

Ladakh, remotely situated mountainous region, is not connected to National Grid and supplied power thru DGs & small hydro Sets. LREDA took initiatives including Ladakh Renewable Energy Initiative Project (LREI) - an off-grid renewable energy development program established in 2011. In 2013, LREDA was conferred with UNDP GEF's Award 2013, securing first position in capacity addition of solar water heating systems during 2013.

2.0 Clean Energy Programs in India

In compliance with Paris Agreement (COP21) and commitment under ISA, India has launched the world’s largest renewable energy expansion program of 175GW by 2022. Out of Tamil Naidu and Rajasthan having attained status of leading Indian States in Renewable Energy (Wind and Solar). MNRE Portal may be referred for more details. Indian Projects like Electrifying Rural India is also converged on using clean energy. GOI have launched several schemes for better implementation of Clean Energy Generation .

Siemens received an order in 2016 for supply of Automation Generation Control (AGC) to be run jointly by POSOCO, NLDC and NTPC's Dadri Stage-II Thermal Power Plant to control operational issues / variants arising from interconnection of DER to main grid.

U.S.-India collaboration for Smart Distribution System with Storage (UI-ASSIST)

US-India Consortium has made provision of $30million ($7.7 million by USA & balance by India) to foster reliable, resilient, and secure delivery of electricity as also further DOE's collaboration with India under the U.S.-India Partnership to Advance Clean Energy (PACE)

UI-ASSIST-New consortia for Smart Grid and Energy Storage under the U.S.-India Joint Clean Energy Research and Development Center (JCERDC), comprises of experts from academia, DOE's National Laboratories, and industry together with their counterparts in India.The Center will conduct R&D to deploy new Smart Grid and Energy Storage Technologies to modernize grids of both Nations to make them "Smarter," with increased resilience and reliability.

UI-ASSIST American team led by Washington State University, is comprised of MIT, Texas A&M University, University of Hawaii, Idaho National Laboratory, Lawrence Berkeley National Laboratory, Snohomish County (WA) Public Utility District, Avista, Burns and McDonnell, ETAP Operation Technology, ALSTOM Grid/GE Grid Solutions, Clean Energy Storage, ABB, Philadelphia Industrial Development Corporation, and the National Rural Electric Cooperative Association (NRECA). The India team is led by the Indian Institute of Technology (IIT) Kanpur and includes the partners IIIT Delhi, IIT Madras, IIT Roorkee, IIT Bhubaneshwar, and The Energy and Resources Institute (TERI) New Delhi.

International Solar Alliance (ISA) India, (founding member of ISA with Secretariat in India) and in conformance to the Directives of COP 21 inter-alia maintaining temperature rise of Earth within 2°C by 2020, is striving hard on ISA Member Countries (120)to collaborate on increasing solar energy use around the world and mobilize $1trillion in investment by 2030 on all the members of ISA.These countries to facilitate joint R&D efforts among member states and other stakeholders to develop appropriate business models, cost effective standards, innovative technical application, equipment and storage design with provision to readjust members climatic conditions and to achieve clean and low cost operation under the agenda.

GOI is to set up a $ 350 million Solar Development Fund as a contribution to ISA funding. In addition to it, nine Indian companies and banks have agreed to develop and finance various solar projects, which include a $1 billion partnership corpus of NTPC and CLP India to ISA.13 Projects worth $ 143million are funded under the line of credit provided by India. India has announced about 17 proposed projects at the founding conference of ISA which entail funding of $ 1.4 billion.

2.1 Role of Project Preparation Facilities (PPF) in ISA

India set up PPF to assist its development partner countries in preparation of viable projects that can be considered for concession financing under lines of credit.ISA, spearheaded by India in garnering support from 12 other countries, has been set up for taking up study into solar risk mitigation to help reduce cost of capital.

3.0 Distribution Network for Distributed Energy Resources

Studies Performed by International Institutions and their Recommendations gives bird eye view of Power Generation, Transmission & Distribution covering both conventional power and DER Energy Generation.

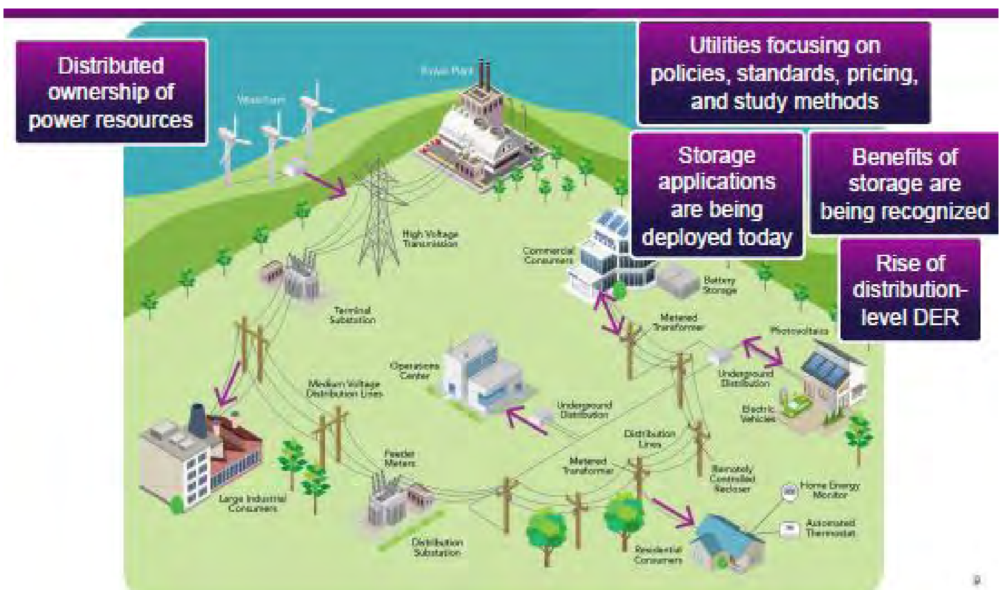

Figure-1

The aim discusses suitability of existing / new distribution system to permit two way power flow when connected with DER and Energy Storage system and pre-requisites for making connection to Conventional grid.3.1Planning CriteriaCentral Electricity Authority (CEA) Guidelines in ‘Manual on Transmission Planning 2013’ makes provisions for generation and Transmission covered under DER. Further, U.S.-India collaboration for Smart Distribution System with Storage (UI-ASSIST) and both countries committed to provide $ 30million for exchange of technology implementation (Para 2.1 & 2.2 above) in addition to taking up Pilot Project on Automatic Generation Control (AGC) (2.1 above) to control the joint operational requirement of DER and Grid are additional measures being adopted to improve the Indian System.

3.1 Two Way Power Flow on Distribution System for Connection to DER and Energy Storage Systems

DERand Battery Energy Storage System (BESS) & Electric Vehicles Charging Resources (EVs) facilitate reduction of the peak demands while filling in the valley of load demand, increasing the efficiency and load factor, and importantly reducing the need for generation expansion and Transmission lines. Unlike power stations, BESS can, without problem, be placed in proximity to Load Centers / city consumers.

Traditional planning methods and tools may no longer be adequate to identify and plan for investments that will outlast the near term changes impacting distribution systems. Increasingly, utilities shall plan for localized generation and loads while taking into account existing constraints and complex, unanticipated interactions between discrete components of the system.System planning methods -'Integrated Resource Planning (IRP)' must be expanded to address the local, more granular requirements of spatial load and multiple-scenario forecasting over and above the traditional system.

Load forecasts must now be considered at a locally discrete level, taking into consideration a broad variety of DER scenarios, customer demographics, weather, energy efficiency, customer profiles, economics and existing system performance. This may be frustrating problem due to number of variables and values to consider in a very specific spatial circumstance on the given distribution system.

3.2 Distribution System Network issues

Indian Planning Criteria does not generally include pre-requisites of network or connection issues for Distributed generation, resources, capacity. These issues, however, are important from the technical aspects as there are significant differences in the design of LV,MV and HV distribution networks namely Uni-directional and not bi-directional.Different characteristics of LV, MV & HV in Rural, Urban and Metro cities, and Non availability of communication facilities at remote transformer etc.

Thirdly, the low voltage ends of distribution systems are usually not connected to *Supervisory Control and Data Acquisition* (SCADA) systems. The data gathering required for the control of the distribution system as well as the Distributed GenerationProjects is therefore difficult.

3.3 Connection issues

The DER generation and its connection to grid can be significantly different from traditional Centralized power generation technologies. Large power units use synchronous generators and DER generation is asynchronous and is not capable of providing reactive power except where capacitors and power electronic converters are provided for this purpose.

Micro systems such as photovoltaic modules, batteries, fuel cells and micro hydro turbines have to be connected via an interface (converter) to the grid.

Modern power electronic interfaces offer different solutions to convert D.C. current to A.C. voltage and active/reactive current with the required frequency. Power electronic converters introduce also 'new control issues and new possibilities' to grid integration. Power converters could be used for voltage control in the distribution network. In some cases, a control problem might emerge if dispersed converters somehow interact via the distribution network. This may lead to power fluctuations or oscillations in the distribution networks.

The interconnection of DER with Conventional grids may cause rotor angle instability and voltage instability and as such may need installation of Phasor Measurement units. This calls SCADA/ EMS operators to be trained to understand situation awareness and take protective measures. Deployment of DER Management System (DERMS) is also essentially required to control variation in the generation from renewable sources connected to the conventional grid.

4.0 Solar PV Cells / Solar Modules

Solar PV Cells and modules technology are developing rapidly with wide variety of different technical approaches on either improving module efficiency or reducing manufacturing costs. PV cell technologies are broadly categorized as either Crystalline or Thin-film. Crystalline silicon (c-Si) cells provide high efficiency modules and are sub-divided into mono-crystalline silicon (mono-c-Si) or multi-crystalline silicon (multi-c-Si).

Mono-c-Si cells are generally the most efficient, but are costlier than multi-c-Si. Wafer-based crystalline modules composed of a mono-thin c-Si wafer surrounded by ultra-thin a-Si layers, due to reduced manufacturing costs and maturity of the technology, are expected to maintain a market share of up to 80%, Thin-film (17 percent) and high efficiency (3 percent) modules up to at least 2017.

PV modules (long-term power output) suffer annual degradation @0.3% to 1.0 %. For crystalline modules, a generic annual degradation @ 0.4 % is often considered applicable.

For a-Si and CIGS modules, a generic annual degradation @ 0.7 to1.0 % is often considered reasonable. For CdTe modules, a value of 0.4 to 0.6 % is often applicable. In general, good quality PV modules can be expected to have a useful life of 25 to 30 years. The risk of increased rates of degradation becomes higher thereafter. The performance of a PV module degrades over time depending on the environs and the technology of the module. The degradation is attributed by Potential Induced Degradation PID, Degradation of Amorphous silicon (a-Si) cells through a process called the Staebler-Wronski Effect and other factors like pollution, color degradation etc.

4.1 Mounting and Tracking Systems

PV modules are mounted on a structure to keep them oriented in the correct direction and to provide protection. Mounting structures may be fixed or tracking. Fixed tilt arrays are typically tilted away from the horizontal plane in order to maximize the annual irradiation they receive. The optimum tilt angle depends on the latitude of the site location. The direction the system is facing is referred to geographic South, and in the southern hemisphere it is geographic North. Fixed tilt mounting systems are simpler, cheaper and have lower maintenance requirements than tracking systems. In locations with a high proportion of direct irradiation, single/ dual-axis tracking systems are used to increase the average total annual irradiation. Tracking systems follow the sun as it moves across the sky. Single-axis trackers alter either the orientation or tilt angle only, while dual-axis tracking systems alter both orientation and tilt angle.

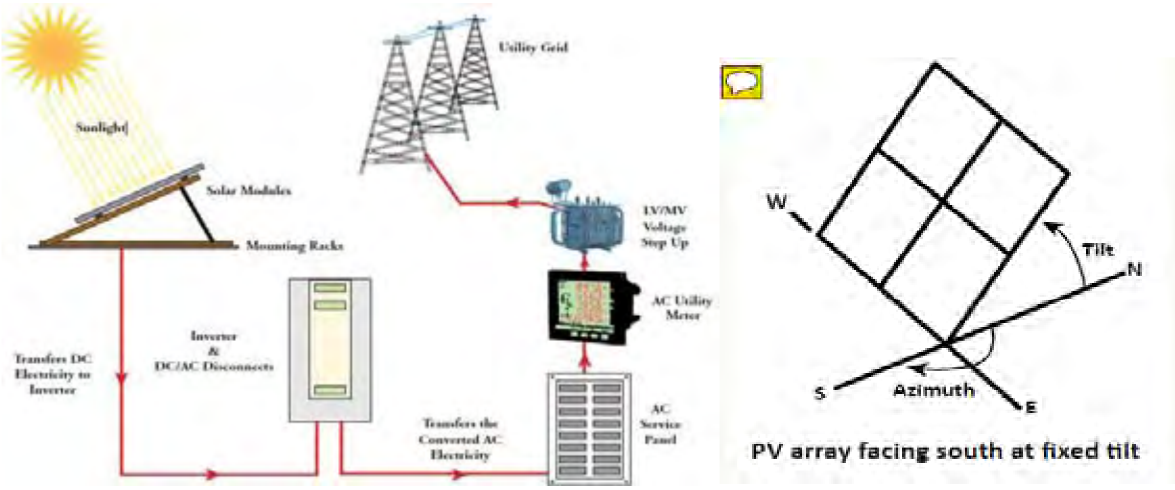

Fig-2 Module mounting (or tracking) systems: Ground Mounted at a fixed tilt angle or on sun-tracking frames.

4.2 Inverters, Layout Configuration and Electrical Arrangement

Inverters are solid state electronic devicesto convert direct current (DC) electricity generated by thePV modules into AC electricity, ideally conforming to the local grid requirements and play a crucial role in Energy Storage projects and provide the direct interface with the batteries. The inverter charges and discharges the batteries and also provides the expected grid regulation functions, complying with appropriate power quality requirements and supporting the grid during abnormal conditions with high and low frequency ride-through functions. Solar PV plants with large-scale storage projects use either large central inverters or rely on many smaller inverters. Typically, large storage inverters (500 to 2500 kW) are outdoor type and mounted on a concrete pad or skid Smaller storage inverters (50 to250 kW) are indoor type installed on the floor or a rack.

Inverters are broadly designated **String and Central** configurations. Inverters are capable of optimizing the voltage across the strings and monitoring string performance to logging data and providing protection and isolation in case of irregularitiesin the grid or with the PV modules.

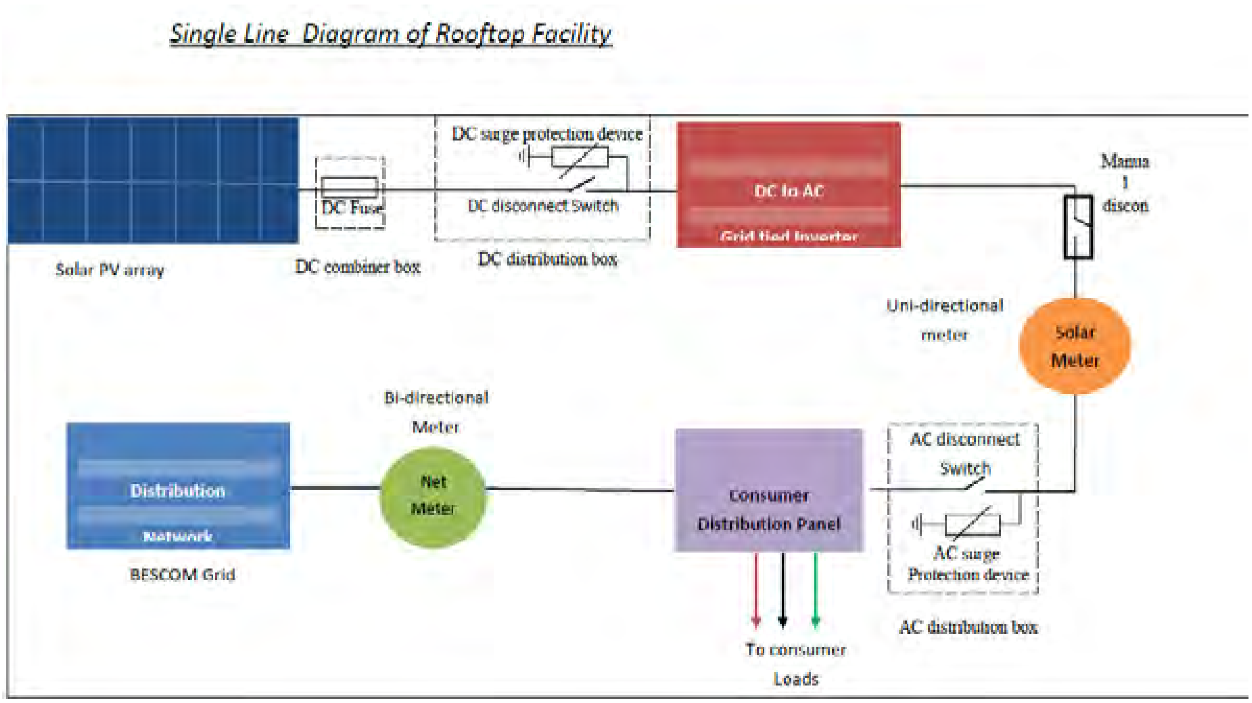

Fig-3 Single Line Diagram of Roof Top Solar PV Facility without battery

5.0 Drones deployment in RE Projects

Deployment of 3rd Party(Out sourced) Drones for speedy and timely performance of site survey, installation, monitoring , data collection of remote solar farms lagging communication facilities is gaining momentum in India also to avoid financial burden on individual facility. Drones can be deployed for Lattice Tower corrosion inspection, Post disaster inspections, Substation surveillance against Intruders and inspection. MW scale Solar farms has Solar Panels deployed over very large areas (648MW Adani Solar Plant in Southern India has 3500 acres land area) & very difficult to monitor every panel manually. Solar panels are very hot & human inspections are tedious. There is need for deployment of monitoring & imaging techniques using Drones. Many Indian Solar Plant operators have already started using Drones for their regular Operation, Maintenance & disaster inspections to save on manpower deployed.

6.0 Conclusion

Non-conventional Energy Resources / Distributed Energy Resources (DER) are making speedy penetration into Conventional Energy Resources call for modernization of existing Distribution Network's suitability for bi-directional flow, protection, modification of existing equipment and making the system operationally reliable due the variable generation (solar & wind)

Solar Photovoltaic Generation is speedily growing up all over the world in compliance of COP-21 in 2015 and ISA (conglomerate of 121 countries) commitment. India, Founding member of ISA, is following vigorously both at National and International level thru allocation of funds, setting of PPF (**Project Preparation Facilities) in ISA** to assist its development partner countries towards the preparation of viable projects that can be considered for concession financing under lines of credit. In addition to above, the Planning Criteria of DER, Status of DER in India, Solar Generation categorization and configuration (Roof top, Solar Community Farms & Solar Mega Farms), pre-requisites for connecting Solar generation to grid network etc. are briefly discussed.

Further, Technical Requirement of Solar Energy Generation Equipment / Components (Solar Cells / Panels and its Racking support structure (Fixed and motorized GPS racking system), Power Inverters, Inverter Transformers etc.) are briefly discussed. Deployment of 3rd Party(Out sourced) Drones for speedy and timely performance of site survey, installation, monitoring , data collection of remote solar farms lagging communication facilities is gaining momentum in India also to avoid financial burden on individual facility. Industrial Solar projects are providing Self monitoring & communication facilities as also tools to check health of Solar arrays, facilities for Isolation monitoring, ground fault monitoring, Remote Controlled fault monitoring, insulation monitoring un-grounded PV system, String Monitor etc. which could not be highlighted for reasons of brevity. Development of Energy Storage batteries such as solid state as also requirement of non flammable batteries and making the battery cheap using cheaper metal radicals having long life (20-25 years) with re-use of materials at the end of life. On-going development abroad does not conclude that Lithium-ion battery is the final solution as it is comparatively inferior to others for deep discharge. USA and India collaboration may take up this mutual development project.

References

1.0 India's Electricity Regulator Approves Automatic Generation Control Pilot Project, January 2, 2018 By Rasika Athawale)
2.0 OUTCOMES OF THE U.N. CLIMATE CHANGE CONFERENCE IN PARIS'- 21st Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 21); November 30 – December 12, 2015 / Energy Revolution in India 2017:

3.0 COP21 SummaryFeb 2016-Final

4.0 How A Super grid Could Make The World A Lot Smaller and Connected' by Patrick Plas 18thAug 2017)

5.0 A Project Developer's Guide prepared by IFC (World Bank Group)- 2015 In Partnership with governments of Ireland, Luxembourg, the Netherlands, Norway, and Switzerland may be referred for submitting Tech cum Financial proposal on DER to IFC (World Bank)

6.0 "Pressure Optimization of Medium-Voltage Liquid-Filled Transformers in Photovoltaic Solar Applications," Eaton Technical Data White Paper, May 2014,cooperpower.com)

7.0 Battery energy storage technology for power systems—An overview by K.C. Divya∗,1, JacobØstergaard1 *Technical University of Denmark, Kgs. Lyngby 2800, Denmar kpublished Electric Power System Research (*www.elsevier.com/locate/epsr)

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Power Factor Control for Grid-Tied Photovoltaic Solar Farms

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***Abstract*—To maintain the power quality of solar farms, the common-point power factor of multiple photovoltaic (PV) inverters needs to be maintained inside of the utility requirement range. One solution is to utilize the communications capabilities of protective relays, meters, and PV inverters to integrate an active control system. This system compares the common-point power factor to the utility requirements and calculates a control signal to adjust the inverter outputs. The scheme can be implemented in a real-time automation processor or an industrial computing platform that is integrated with the inverters, allowing the control system to meet a wide variety of needs in a simple manner.**

This paper describes how using a closed-loop feedback control scheme and a proportional and integral controller can maintain the power factor in the required range. Further, the effects of various controller parameters on steady-state performance are studied. This paper also demonstrates that only one controller is sufficient for multiple inverters, making the active control scheme simple and cost-effective. Finally, it examines the communications and data collection limitations while analyzing the benefits of using multiple controllers instead of a single controller when the number of inverters increases.

I. Introduction

Photovoltaic (PV) solar farms are one of the renewable energy sources that have recently gained widespread popularity because of their environmentally friendly nature (green or clean energy) and the cost reduction of solar PV panels [1] [2]. The main components of these systems are solar PV panels and PV inverters that convert dc power generated from the panels to ac power tied to the electric grid. This energy conversion mechanism can potentially deteriorate the power quality of the grid, especially as the number of grid-tied solar farms increases [3].

The common-point power factor at the point of common coupling (PCC) of multiple PV inverters can fluctuate unpredictably outside of the utility requirement range. The variation depends on the power quality and harmonic distortions injected by the inverters [4] [5]. Therefore, maintaining the power factor at the PCC is critical for maintaining the power quality and stability of the overall system. A power factor adjustment can improve the efficiency of the overall utility network [6]. The power factor adjustment gives the utility greater flexibility to supply the power quality required by the loads.

This paper proposes a closed-loop feedback control scheme that uses a proportional and integral (PI) controller to maintain the power factor in the required range. This control process is accomplished by utilizing the communications capabilities of protective relays, meters, and PV inverters to form an integrated active control system.

A revenue meter or protective relay is commonly installed at the PCC by the utility to monitor the energy and power quality produced by the generation facility. The protective relay also provides protection functions for the interface to the grid. The proposed controller ensures that the measured power quality given by the meter or relay meets the utility requirements by sending control signals to adjust the inverter outputs. The solution models the power factor control problem as a closed-loop feedback system utilizing existing components of PV generation sites. It demonstrates how a PI controller can be useful in maintaining the desired reference power factor for multiple inverters in a simple and cost-effective manner.

II. System Architecture

An active power factor control system, as shown in Fig. 1, can be easily implemented by using the typical components of a PV generation site.

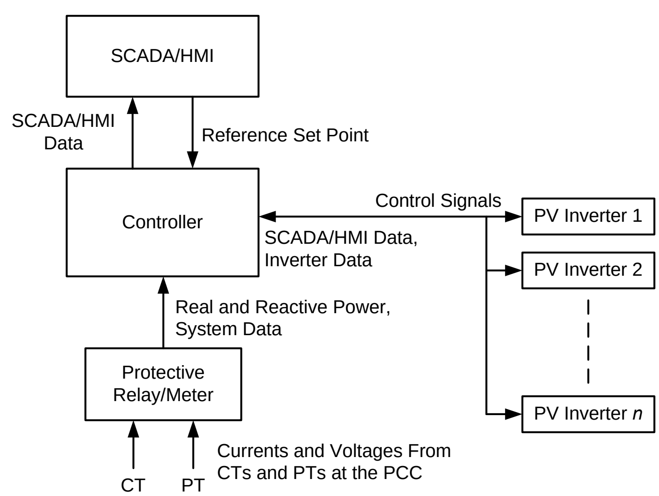

Fig. 1. Power factor control system architecture

The supervisory control and data acquisition/human-machine interface (SCADA/HMI) is responsible for displaying collected data, identifying system alarm conditions, and sending control commands to the inverters through the controller. The control commands can be to start and stop inverters and set points. One of the set points is the power factor reference set point. The power factor reference set point can be changed by sending a valid operator-entered value to the controller via the communications channel(s).

At a PV generation site, the PI controller has two main functions: it is a controller and a data concentrator. As a controller, it polls data from the protective relay or meter and the inverters and utilizes the collected data along with the SCADA/HMI set point reference to calculate control signals. It then sends the signals to the PV inverters via the communications channels to adjust the output power of each inverter. One way to adjust the output power of each inverter is by using the power factor set point. Therefore, the utilized control signal for the power factor control can be the power factor set point of each inverter. As a data concentrator, the controller polls each inverter and protective relay or meter for the required system data and then forwards the data to the SCADA/HMI. The data include inverter status, currents, voltages, power and energy values, and the power factor.

The protective relay or meter provides the controller with three-phase instantaneous real and reactive power quantities. This is accomplished by using current transformers (CTs) and potential transformers (PTs) to monitor the circuit voltages and currents that are used to calculate real and reactive power. The relay or meter updates the controller with the calculated values periodically. Besides these data, the controller polls system data periodically and sends the data to the SCADA/HMI.

A. Communications Channels and Topology

The type of communication between the components of a PV generation site is dictated by the distance and communications capability supported by each of the connected devices. Microprocessor-based relays, meters, controllers, PV inverters, and the SCADA/HMI typically support traditional EIA-232 and/or EIA-485 serial communications and/or Ethernet connections. In most cases, the controller, protective relays, and meters are located inside a switchgear cabinet or switchgear room at the PCC or the PV generation site. Copper cables are widely used in short-distance configurations because of their easy installation and low cost. Ethernet connections require an Ethernet switch for multiple devices. The devices, along with the switch, form a local network, and each device uses a Cat 5 (copper) cable to connect to the switch.

The inverters are located at the PV generation site, and their distances to the controller can be hundreds or thousands of feet. Typical communications channels include fiber-optic cables, wireless radios, or copper cables for shorter distances. Communication can be via either serial or Ethernet. Fiber-optic cables require electric-to-fiber-optic converters at both ends (for serial and Ethernet communications). For radios, converters and transceivers are required for bidirectional communication.

The SCADA/HMI can be located at the same PV generation site or at a remote site. Communications between the controller and the SCADA/HMI can be via leased T1 lines, the Internet, or a multiplexed microwave or fiber-optic backbone. In all cases, the transmitted data should be encrypted to ensure proper security.

Communication between the controller and protective relays typically utilizes point-to-point connections. Communication between the controller and the PV inverters can be via a shared channel using a bus topology or ring topology. It is also possible to have point-to-point connections to each inverter. Point-to-point connections are more efficient but can become expensive as the number of components and the distance between them increase. Shared channels, on the other hand, can be more economical but may have more limited throughput.

B. Communications Protocols

The communications protocols supported by the different devices can be proprietary or standardized and open. Open communications protocols have the advantage of interoperability among device manufacturers. Most protective relays, meters, and PV inverters support the traditional standard communications protocols Modbus® and DNP3. Other protocols supported by these devices include IEC 61850 and IEEE C37.118. Due to the nature of this application, the selected communications protocol is required to support a deterministic periodic data update.

III. Control Strategy Model

The solution described in this paper models the power factor control problem as a closed-loop control system, as shown in Fig. 2. In this closed-loop control system, the desired power factor set point reference is provided by the SCADA/HMI. The process variable is the system power factor at the PCC and is given by the protective relay or meter. The process (the plant) is the inverter, and the control signals are the set points of the inverters. These set points depend on manufacturers and can be the power factor set point or both real power and reactive power set points.

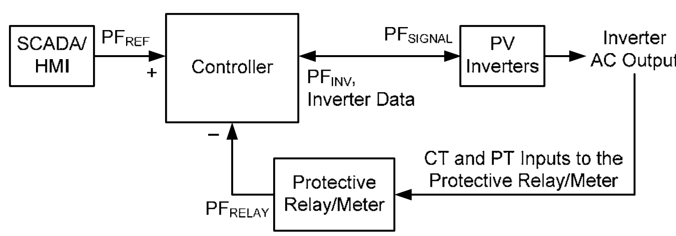

Fig. 2. Power factor closed-loop system

To implement this closed-loop control system, the controller sets up a control cycle and starts the process by polling the protective relay or meter for the instantaneous real and reactive power to calculate the system power factor at the PCC. It then polls the inverters for a set of inverter data (see Section III, Subsection D). The calculated power factor and the present SCADA/HMI power factor set point reference are used to calculate the error between the reference and the inverter outputs. Using the error and the collected inverter data, a control signal is calculated and sent to the inverters to adjust their output power. This completes the control cycle. In this dynamic system, the adjustment continues until the

SCADA/HMI reference set point is achieved. The controller continues to monitor the set point value and makes any necessary adjustments in order to maintain the set point at the reference level.

The control strategy discussed is further illustrated as follows:

- Power factor is the ratio of real power to apparent power, $Power_{Real}/Power_{App}$. Consider the following conventions:
  - Positive power factor is when current lags voltage (inductive loads).
  - Negative power factor is when current leads voltage (capacitive loads).
- The power factor reference from the SCADA/HMI is PF_{REF}.
- The inverter output power factor is PF_{INV}.
- The power factor from the protective relay is PF_{RELAY}.
- The difference between PF_{REF} and PF_{RELAY} is $PF_{ERROR} = PF_{REF} – PF_{RELAY}$.
- The output control signal from the controller is PF_{SIGNAL}.

The controller processes input values PF_{REF}, PF_{RELAY}, and PF_{INV} and inverter data and computes the PF_{SIGNAL} output, which is transmitted to the PV inverters.

In addition to the closed-loop system, which is essentially the heart of the controller, numerous limiting factors need to be considered when implementing this solution. These factors are discussed in Section III, Subsections A and B.

A. PV Inverter Limitations

The limitations of a PV inverter depend on the inverter manufacturer and the supported functions. By no means are the following limitations meant to cover all manufacturers; they are only the main limitations that need to be considered in implementing the controller.

The main limiting factors are the output power ramp rate and the maximum power limit. The output power of a PV inverter is limited by its ramp rate and maximum output limit. A ramp rate is usually defined as a percentage of the apparent power or rated power per second. To enforce this, the controller performs a sanity check and ensures that the signal sent to the inverters is always in the valid range.

B. Controller Considerations and SCADA/HMI Control

In practice, the controller can be disabled if the error between the reference and the inverter outputs is less than ΔE_{MIN}. If disabled, the controller skips certain steps or stops sending control signals to the PV inverters. When the power factor reaches the SCADA/HMI set point or is close enough due to the discretization of sampled values, sending the same control signals to the inverters does not affect the inverter output power.

It is critical that the controller check for communications failures. When communication is lost between the controller and the protective relay or meter, the controller is disabled. This prevents the controller from sending the same control signals to the inverters without knowing the power factor at the PCC. This occurs when the controller retains the last valid value before the communications loss. When communication is lost between the controller and some of (or a subset of) the inverters, the controller stops sending signals to the lost inverters and continues sending signals to those that remain online. When communication is lost between the controller and all of the inverters, the controller stops sending control signals entirely.

Data quality is taken into account by the controller. When it receives bad-quality control data or out-of-range values from some inverters, it stops sending control signals to those inverters. This prevents unexpected control signals from being sent to the inverters.

Another situation in which the controller can be disabled occurs when too little sunlight is present to generate power at utility voltages. At night or during dark, cloudy days, the output real power can be insignificant. Controlling the power factor in such low output power has no effect on power quality.

In many applications, the SCADA/HMI sends commands to the controller to request that the inverters start or stop. In addition to executing the start/stop commands, the controller also keeps track of the status of the affected inverters so that future signals are only sent to the inverters that remain active.

C. PI Control Algorithm Model

Under normal conditions, the PI controller is in charge of the power factor control and can be implemented as shown in Fig. 3.

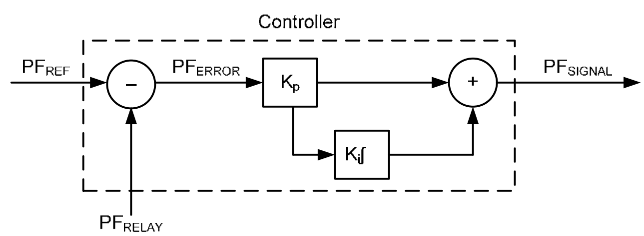

Fig. 3. PI control algorithm model

K_p and K_i are the proportional and integral constants, respectively, and are determined during the simulation and testing phase (tuning). The integral constant can be written as $K_i = K_p/T_i$, where T_i is the integration constant [7].

The power factor error is:

$$PF_{ERROR} = PF_{REF} - PF_{RELAY} \quad (1)$$

To implement the integral term in the controller, the integral term is approximated by a difference equation. This leads to the following recursive equation for the integral term:

$$PF_{INTEGRAL\_NEW} = PF_{INTEGRAL\_OLD} + \frac{K_p}{T_i} CRTL_{CYCLE} PF_{ERROR\_NEW} \quad (2)$$

where:

$PF_{INTEGRAL\_OLD}$ is the integral term up to the previous sampling instant.

$PF_{INTEGRAL\_NEW}$ is the new sampling instant.

$CRTL_{CYCLE}$ is the sampling period.

The signal at the new sampling instant can be written as:

$$PF_{SIGNAL\_NEW} = K_p PF_{ERROR\_NEW} + PF_{INTEGRAL\_NEW} \quad (3)$$

Expanding (3), the signal can be expressed in recursive form [7]:

$$\begin{aligned} PF_{SIGNAL\_NEW} &= PF_{SIGNAL\_OLD} \\ &+ K_p (PF_{ERROR\_NEW} - PF_{ERROR\_OLD}) \\ &+ \frac{K_p}{T_i} CRTL_{CYCLE} PF_{ERROR\_NEW} \end{aligned} \quad (4)$$

The controller utilizes (4) to update its output control signals.

D. Control Cycle Loop

Fig. 4 shows a simplified control cycle loop. In this loop, the controller collects the control data, checks the limiting factors, utilizes the PI control algorithm to compute the output signals, and sends the signals to the inverters. The process repeats until the SCADA/HMI reference set point is achieved.

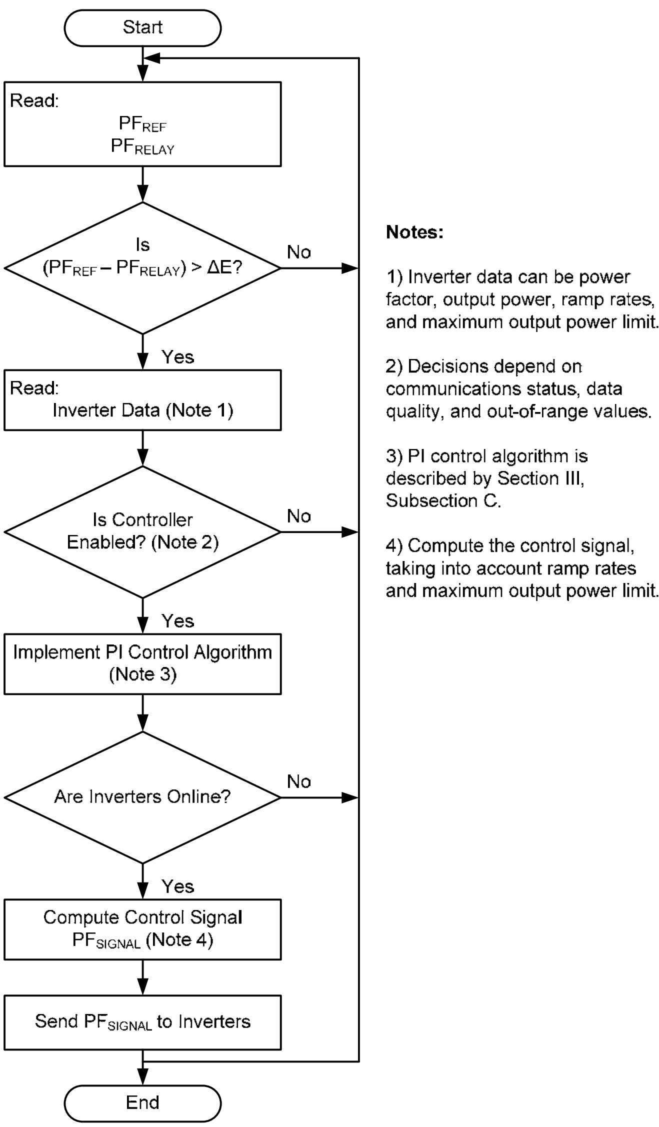

Fig. 4. Simplified control cycle loop

IV. Analysis of the Controller

Simulations are used to help understand and fine-tune the parameters of the controller in order to achieve better and more accurate performance.

One controller is sufficient for multiple PV inverters at a PV generation site. Assume that the inverters have different initial power factors and that they are turned on at the same time. The controller runs when any of the inverters are turned on. The simulation shows that the inverters first converge to a power factor and then all of the inverters with the same power factor converge to the reference set point. Fig. 5 illustrates this effect.

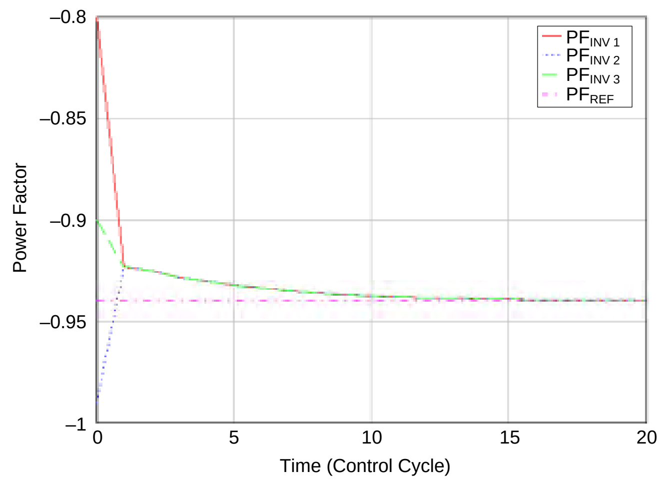

Fig. 5. Three inverter power factors converge

In this example, suppose that a PV site has three PV inverters and their initial power factors are –0.8, –0.99, and –0.9. In ideal cases, the ramp rate does not limit either power factor or output power. The inverters first converge to a synchronized point in the first control cycle, and then all three inverters with the same power factor converge to the reference set point. In cases where the ramp rate limits the inverter power factor or output power, the inverters can take a few cycles to converge to the synchronized point.

Now examine the expression of the system power factor at the PCC, and determine how each inverter affects the system power factor in different scenarios, such as when an inverter starts and stops and when system disturbances occur. Although the following analysis is theoretical, it gives some insight into such effects in practice.

Power factor is defined as the ratio of real power to apparent power (i.e., PF = P/S), where P is real power and S is apparent power. Power factor can be written as $PF = P/S = \cos\varphi$, where φ is the angle between P and S. The relation between real and reactive power is $Q = P\tan\varphi$. Using these identities, power factor as a function of real and reactive power can be written as:

$$PF = \cos\left[\tan^{-1}\left(\frac{Q}{P}\right)\right] \quad (5)$$

Equation (5) can be rearranged to express reactive power as a function of real power and power factor:

$$Q = P\tan\left[\cos^{-1}(PF)\right] \tag{6}$$

Suppose that the real and reactive power at the PCC are Q_T and P_T and:

$$\begin{aligned} Q_T &= Q_1 + Q_2 + \cdots + Q_n \\ P_T &= P_1 + P_2 + \cdots + P_n \end{aligned} \tag{7}$$

where:

$Q_1, Q_2, \cdots Q_n$ is the reactive power.

$P_1, P_2, \cdots P_n$ is the active power generated by Inverters 1, 2, and *n*.

The power factor at the PCC can be calculated by (8), (9), and (10).

$$PF = \cos\left[\tan^{-1}\left(\frac{Q_T}{P_T}\right)\right] \tag{8}$$

$$PF = \cos\left[\tan^{-1}\left(\frac{Q_1 + Q_2 + \cdots + Q_n}{P_1 + P_2 + \cdots + P_n}\right)\right] \tag{9}$$

Equation (10) expresses the system power factor in functions of the power factor and real power of each inverter. If all inverter power factors have converged to the synchronized point or the set point (i.e., $PF_1 = PF_2 = \cdots = PF_n = PF_{SP}$), then the power factor at the PCC is $PF = PF_{SP}$.

A. PV Inverter Start

Without loss of generality, assume that Inverter 1 is off and the remaining inverters are running and have converged to the set point. When Inverter 1 turns on, the power factor at the PCC is affected. According to (10), if Inverter 1 starts with the initial power factor equal to the set point, then the power factor at the PCC is affected minimally (or will not be affected in theory by the equation). If the initial power factor is different than the set point, the power factor at the PCC departs from the set point, the controller reacts to this change, and eventually the power factor converges to the set point.

To illustrate this, assume that a site has three inverters. Two of the inverters start at Time 0, and the third inverter starts at Time 40 with a power factor different than the set point. The two inverters converge to the set point before Inverter 3 starts. When Inverter 3 starts, it adds real and reactive power to the system. The added power causes the power factor to depart from the set point, forcing the controller to react. An example of such an effect is shown in Fig. 6 and Fig. 7. Fig. 6 shows the reaction of the control signals due to Inverter 3 start.

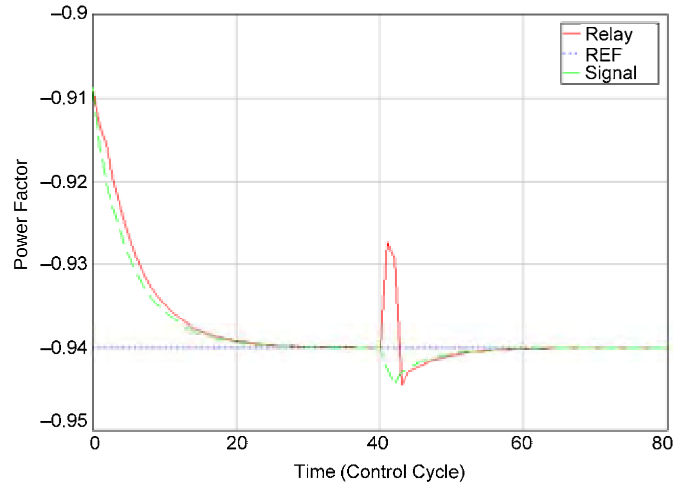

Fig. 6. System (relay) power factor and control signal reaction due to Inverter 3 start

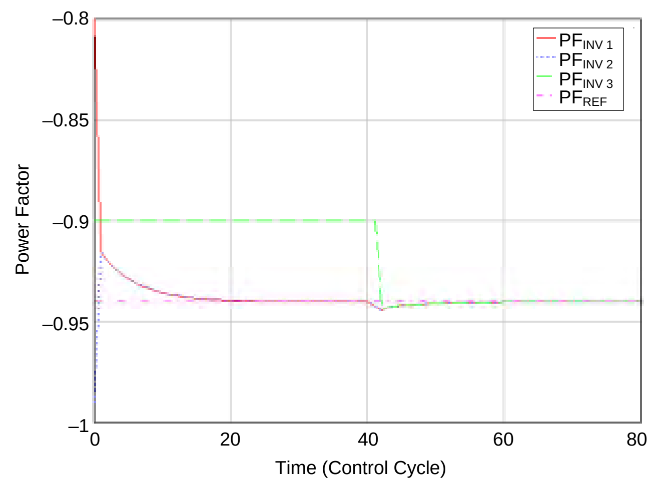

Fig. 7. Power factors of the inverters due to Inverter 3 start

B. PV Inverter Stop

Again, without loss of generality, examine the case where Inverter 1 stops contributing power to the system after all of the inverters have converged to the set point. When Inverter 1 stops, assuming its real power becomes zero immediately (i.e., $P_1 = 0$), the power factor at the PCC is not affected, according to (10). In practice, if the real power does not become zero immediately and the power factor becomes different than the set point when Inverter 1 turns off, the power factor at the PCC departs from the set point and the controller reacts to this, changes, and tries to adjust the inverter outputs.

$$PF = \cos\left[\tan^{-1}\left(\frac{P_1\tan\left[\cos^{-1}(PF_1)\right] + P_2\tan\left[\cos^{-1}(PF_2)\right] + \cdots + P_n\tan\left[\cos^{-1}(PF_n)\right]}{P_1 + P_2 + \cdots + P_n}\right)\right] \tag{10}$$

C. System Disturbances

To simulate this, an exponential decreasing disturbance is added to change the power factor at the PCC. First, assume that the power factor at the PCC has converged to the set point. The decreasing disturbance is then added to the system power factor. Fig. 8 shows the controller reactions to these changes and the corresponding inverter output adjustments that drive the system power factor back to the set point.

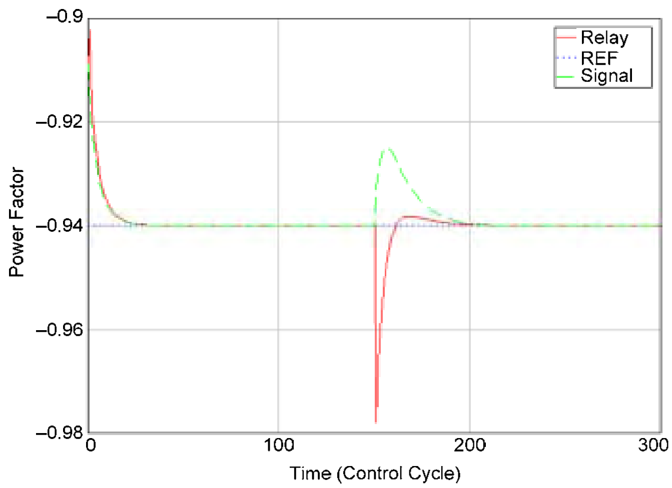

Fig. 8. System power factor and control signal reaction to the system disturbances

D. Sensitivity to Sun Radiation

Based on (10), if all of the inverters can maintain the set point power factor (i.e., all inverters keep the real and reactive power ratio constant), then the power factor at the PCC is less sensitive to the changes of the real (and reactive) power of the inverters. This suggests that as long as a set point is maintained by every inverter (i.e., $PF_1 = PF_2 = \cdots = PF_n = PF_{SP}$), the output power affects the system power factor minimally.

PV inverter output power is quite sensitive to sun radiation. The output power variation can change significantly in a very short period of time based on the amount of radiation. If every inverter can maintain a set point power factor that ensures the system power factor is maintained at the reference set point, then the system power factor is less sensitive to the amount of sun radiation.

E. Controller Parameters

In control theory, it is well known that a proportional control cannot reduce the steady-state error to zero. The error decreases with increasing gain, but the system will likely oscillate and become unstable [8]. Adding the integral, the steady-state error can be reduced to zero. A small constant time integration, T_i, causes the system to oscillate, and a large time integration reduces the strength of integral action [8].

Simulations show that large K_p and/or K_i cause the system power factor to oscillate, become unstable, and be unable to converge to the set point. Looking at (4), the third parameter is the control cycle. A large control cycle increases the integral constant, K_i. Once the proportional constant, K_p, and integration constant, T_i, are chosen, a large control cycle can cause the system to become unstable and unable to converge to the set point. A small control cycle may load the controller and restrict its ability to perform other tasks. When the controller acts as a data concentrator (its other role being a power factor controller), the control cycle can be chosen accordingly to handle both the control data and SCADA/HMI data.

F. Controller Parameter Tuning

Parameter tuning involves the selection of controller parameters K_p and T_i that are suitable for the application. Numerous tuning techniques or methods are described in literature. A simple way to tune the parameters is to assume the dynamic of the power factor at the PCC is similar to well-known processes that have tabulated values for the parameters. Although the tabulated values may not be the best choices, they can be fine-tuned during the testing phase. For instance, the well-known values for flow are $K_p = 0.3$ and $T_i = 1$ second. These values can be used as a starting point for further tuning.

One of the classic tuning methods is the closed-loop Ziegler and Nichols method [7] [8]. The procedure is as follows:

1. Set K_p as a very small value and T_i as a large value.
2. Slowly increase K_p until the process starts to oscillate.
3. Adjust K_p to make the oscillation continue with a constant amplitude.
4. Record this value of K_p as K_u and the period of oscillation as T_u.
5. The method suggests $K_p = 0.45\ K_u$ and $T_i = T_u/1.2$.

Simulations that use this method find a set of values for the parameters that can be used as the initial values during field testing and tuning. For example, K_p is set to 0.05 and T_i is set to 1,000. After adjusting the constant K_p, simulations show that $K_u = 1$ and $T_u = 2$ seconds. Therefore, $K_p = 0.45$ and $T_i = 1.67$ seconds. These values can be used as the initial values in the testing phase. In addition, simulations show that these values allow a control cycle of about 4 seconds to keep the system converging to the set point with decaying oscillations.

V. Implementation Example

The example PV generation site has three 1 MW inverters and utilizes about 40,000 solar panels. The controller and a protective relay are located inside a switchgear cabinet at the PCC. The inverters are about 600, 1,200, and 1,800 feet away from the controller. The SCADA/HMI is located in another state of the country.

The controller has numerous serial ports, one of which is connected directly to the protective relay that provides the system power factor. A second port communicates with the three inverters. The relay interface is EIA-232, and the inverters communicate via four-wire multidrop EIA-485 full-duplex communications networks. Communication between the SCADA/HMI and the controller utilizes a DSL modem connected to a local Internet provider. The communications protocol between the controller and the protective relay is a proprietary communications protocol. The protocol between the controller and the SCADA/HMI is Ethernet Modbus/TCP, and the protocol between the controller and the inverters is serial Modbus RTU.

The controller is implemented using IEC 61131 structured text. The controller includes all of the limitations discussed in Section III, Subsections A and B. The output power ramp rate is set to 10 percent, and the minimum output power to disable the controller is 50 kW. Due to the amount of the required system data from the inverters and the multidrop (shared) channel, the control cycle is selected to be 3.2 seconds.

The controller parameters are $K_p = 0.02$ and $T_i = 1.28$ seconds after field tuning and testing using a control cycle of 3.2 seconds. The system performance shows that the power factor is kept in the range of 5 percent of the reference set point under normal conditions.

VI. Single Versus Multiple Controllers

Because of the distance between the PV inverters and the controller, the inverters typically share a communications channel to the controller. The communications channel must be shared by both the control data and the SCADA/HMI data. As the number of inverters increases or the amount of data from each inverter increases, channel bandwidth becomes a critical limitation to a single automation controller.

As the number of inverters increases for a medium- to large-sized PV generation site, it may become necessary to implement multiple controllers. Each controller is then assigned to handle a unique group of inverters. The number of inverters that a controller can handle depends on the communications channel, its capacity, and the amount of data being transferred to the controller. This multiple-controller scheme is extremely scalable. Once the number of inverters is defined and tested for a single controller, the solution can be easily duplicated with the remaining inverters.

In a different system architecture configuration, two controllers can be used to separate the control data and SCADA/HMI data if the system supports two communications channels. One channel can be used for control functions and the second for SCADA/HMI data collection. As the number of inverters increases, multiple controllers may be a more practical solution.

VII. Conclusion

Utilizing the components of a typical PV generation site, an active closed-loop power factor control system can be easily implemented. This is accomplished by utilizing the communications capabilities of the components, which allow the controller to collect the required control data and make decisions to adjust the inverter outputs. The implemented solution proves to be simple and cost-effective for achieving the desired power factor reference set point.

Once the PI controller parameters are chosen appropriately after field testing and tuning, the controller can track the power factor changes at the PCC quite well. An implemented solution proves that the controller can keep the power factor within 5 percent of the reference set point.

VIII. References

[1] M. Salimi, "Low-Cost Grid Connected Photovoltaic System," proceedings of the 2nd International Conference on Environmental Science and Technology, *International Proceedings of Chemical, Biological, and Environmental Engineering*, Vol. 6, 2011.

[2] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules," *IEEE Transactions on Industry Applications*, Vol. 41, No. 5, September/October 2005, pp. 1292–1306.

[3] S. K. Khadem, M. Basu, and M. F. Conlon, "Power Quality in Grid Connected Renewable Energy Systems: Role of Custom Power Devices," proceedings of the International Conference on Renewable Energies and Power Quality, Granada, Spain, March 2010.

[4] J. H. R. Enslin and P. J. M. Heskes, "Harmonic Interaction Between a Large Number of Distributed Power Inverters and the Distribution Network," *IEEE Transactions on Power Electronics*, Vol. 19, No. 6, November 2004, pp. 1586–1593.

[5] B. Verhoeven, "Utility Aspects of Grid Connected Photovoltaic Power Systems," Report IEA PVPS T5-01:1998, December 1998.

[6] R. Ellenbogen, "Distributed Generation, Customer Premise Loads and the Utility Network: A Case Study," February 2008.

[7] K. T. Erickson, *Programmable Logic Controllers: An Emphasis on Design and Application*, Dogwood Valley Press, LLC, Rolla, MO, 2005.

[8] K. J. Åström and R. Murray, *Feedback Systems: An Introduction for Scientists and Engineers*, Princeton University Press, 2008.

IX. Biographies

David Taggart holds a B.S. in Metallurgical Engineering from California Polytechnic State University, San Luis Obispo, and an M.S. in Materials Engineering from Rensselaer Polytechnic Institute. He is the President/COO and cofounder of Belectric, Inc. His career spans 24 years across the aerospace, automotive, and renewable energy industries. At Lockheed's famous Skunk Works, he led teams producing industry firsts in advanced composite structures, manufacturing automation, and stealth technology. He cofounded Hypercar, Inc., with Amory Lovins of the Rocky Mountain Institute, where he built and led an international team to develop a full-sized sport utility vehicle integrating digital control, advanced composites, and hydrogen fuel cell propulsion to achieve 100 mpg efficiency. Over the past 8 years, he has been involved in three start-ups in the renewable energy field, focusing primarily on utility scale generation of electricity from photovoltaic technologies at costs competitive with combustive power.

Kei Hao received his Ph.D. in Electrical Engineering from the University of Wisconsin–Madison, his M.S.E.E. from the University of Wisconsin–Milwaukee, and his B.S.E.E. from La Universidad de la Republica, Uruguay. He has experience in the fields of control and automation systems, wireless communications systems, and power system automation and protection. In 2010, he joined Schweitzer Engineering Laboratories, Inc. as an engineer in the engineering services division. He is a member of IEEE and a registered professional engineer in the state of California and has authored and presented several technical papers.

Robin Jenkins has a B.S.E.T. degree from California State University, Chico. From 1984 to 1988, he was employed as a systems integration engineer for Atkinson System Technologies. From 1988 to 1999, he was with the California Department of Water Resources, where he worked as an associate and then senior control system engineer. From 1999 to 2007, he worked for Schweitzer Engineering Laboratories, Inc. (SEL) as a senior integration application engineer. From 2007 to 2009, he rejoined the California Department of Water Resources as the control systems branch chief. Since 2009, he has been employed by SEL, where he currently holds the position of integration application engineer and is responsible for technical support, application assistance, and training for SEL customers in Northern California.

Rick VanHatten received his B.S.E.E. from South Dakota State University in 1974 and is an IEEE PES member. He has broad experience in the field of power system engineering, operations, and protection. Upon graduating, he served for 32 years at Iowa Public Service, Midwest Resources, and MidAmerican Energy, where he worked in substation, distribution, and transmission engineering, system operations, and substation operations managing various engineering groups. He has led a variety of utility projects to design and build electric and gas metering shops, plan for Y2k contingencies, and consolidate utility switching practices. In 2006, he joined Schweitzer Engineering Laboratories, Inc., where he is an engineering supervisor. Previously, he worked for two years for Cooper Power Systems in the energy automation solutions group, formerly Cannon Technologies, in the area of substation automation and integration.

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Demand Response from Lift Irrigation loads to harness Renewable Energy

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***Abstract:* Maintaining Load–Generation Balance (LGB) dynamically at every instant is the most critical requirement for ensuring secure and stable grid operation. However, it would be one of the biggest challenges for the grid (system) operator with addition of huge quantum of Renewable Energy (RE) generation which is highly variable & intermittent in nature. System operator uses various options like flexing the conventional generation, using storage and Demand Response (DR) to shield the system from variable nature of renewables. DR is a valuable tool yet to be fully harnessed by Indian System Operator. Large scale Lift Irrigation (LI) projects are being established Southern Region of India, which can be ideal loads for DR.**

Lift irrigation is a method of pumping water to the high altitude terrain, where water can't go by natural gravity. This can be achieved by using power intensive synchronous motors from low lying water bodies. These loads are highly flexible and can provide instantaneous active and reactive power response, similar to hydel plants. Being distributed loads, these can be used as a part of Automatic Demand Management Systems (ADMS) to provide local grid balancing support. This paper discusses the characteristics of LI loads and elucidate how these LI loads can aid better system operation.

***Key words*-- Lift Irrigation, Flexibility, RE integration, Grid Balancing, ADMS**

I. INTRODUCTION

Indian electricity grid is one of the largest grids in the world with an installed capacity of around 344 GW [1], demarcated as five different regions based on geography. Indian power system is thermal predominant with installed capacity of around 222 GW [1]. As on 31-03-18, the share of renewable energy (RE) sources is around 20 %, with an installed capacity of more than 69 GW. In line with the "Intended Nationally Determined Contributions" (INDC) under the Paris climate agreement, Government of India has targeted a Renewable Energy (RE) capacity of 175GW by 2022. This constitutes 100GW of Solar, 60GW of Wind and 15GW of small Hydro and Biomass [2]. Of the total 160GW, states of Southern Region (SR) has been given 33% of the target with 26GW of solar and 28GW of wind [2].

II. RENEWABLE ENERGY CHARECTERISTCS

Integrating large RE into power grid comes with its challenges of variability & uncertainty and Utilities are confronted with the need to maintain the load-generation balance in real time.

Generation from RE sources have both seasonal as well as diurnal variations. Solar and wind variations specific to SR are presented in this section.

a. Solar generation characteristics:

Solar generation characteristics are derived from analysis of generation data of a 250 MW solar park located in SR. The general 3-D trend of solar generation over a sample month is plotted in Fig 1. Solar generation typically starts picking up by 06:15hrs (26th time block). From 06:15hrs (26th time block) to 12:00 (48th time block), generation increases over time and after 12:00hrs (49th time block) generation starts reducing and touches zero by around 18:00hrs (73rd time block). The generation variation in each time block of the day is shown in figure 1. The summary of approximate ramps in different blocks are given in Table1.

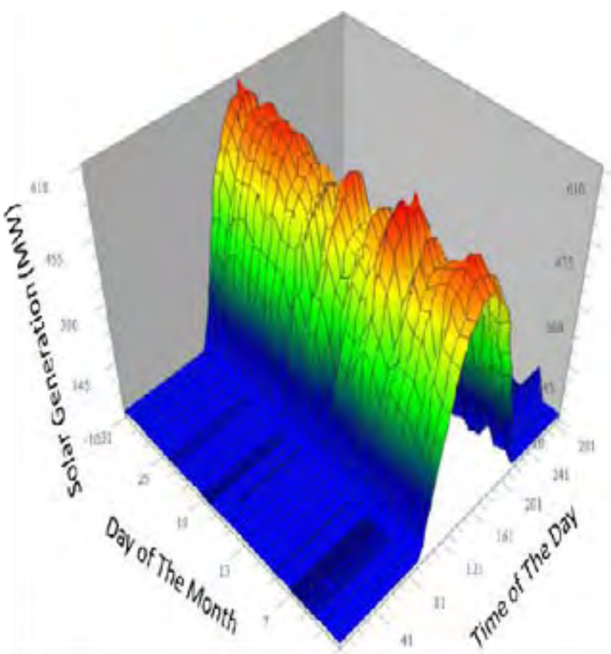

Figure 1 3-D plot of solar generation

Table 1: Approximate ramps in different blocks

Time Blocks	**Time Period**	**Average Ramp Rate as % of Installed Capacity**	**Ramp**
26-27	06:15 - 06:45	2.20%	Slow
28-38	06:46 - 09:30	5.00%	Steep
39-45	09:31 - 11:15	2.40%	Slow
46-53	11:16 - 13:15	(+/-) 1 - 1.5 %	Minimum
54-58	13:16 - 14:30	-2.20%	Slow
59-69	14:31 - 17:15	-5.00%	Steep
70-73	17:16 - 18:15	-2.50%	Slow

b. Wind generation characteristics:

Wind power generation in SR varies throughout the year. Wind generation picks up during the month of May and bottoms down by October of every year. Considerable wind generation is not observed during the remaining part of the year. The 3-Dimensional plot showing seasonal and diurnal variation of wind diversity in SR. General wind generation characteristics during high wind season, derived from the data of June & July 2017, wind generation as percentage of total installed capacity (15 GW) is as given in figure 2. Diurnal variations during high wind generation season can broadly be divided into 3 sections as shown in Table 2.

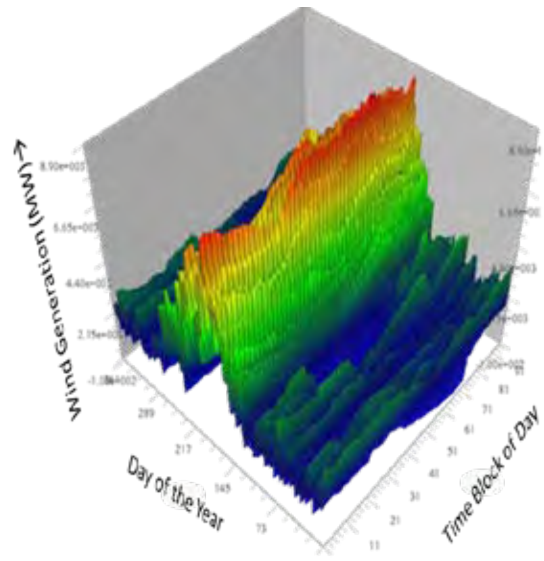

Figure 2 3-D plot of Wind diversity in SR

Table 2 Approximate ramps in different blocks

Section	Blocks	Time Period	Ramp Rate as % of Installed Capacity per Block
Section 1	01 - 28	00:00 to 07:00	-0.34 %
Section 2	29 - 73	07:01 to 18:15	+0.50 %
Section 3	74 - 96	18:16 to 24:00	-0.50%

III. RE INTEGRATION

By 2022, SR needs to integrate 28200 MW of wind & 26531 MW of Solar power, which forms 38% [3] of total generating capacity. It is expected that peak RE penetration may touch as high as 89% of total demand during July 2022[4] and ramping requirements by 2022 during high wind season goes as high as 2400MW per block [5]. Managing these load ramps on a daily basis is a herculean task for the system operator. The key to RE integration is often referred to as requirement of Flexi Watts. Flexing the conventional generation, using storage and demand response are different means a system operator resorts to while shielding the system against the variability of the Renewables. Demand response is a tool yet to be harnessed by the system operator. Lift Irrigation (LI) loads are going to be large chunk of loads that can provide fast active and reactive power response, which can be of great help to system operator. Detailed explanation on the nature of LI Loads are given in following sections.

IV. OVER VIEW OF LIFT IRRIGATION PROJECTS

The Deccan plateau of the Indian sub-continent is characterized by huge river belts with uneven altitude of land. There is abundant availability of water but limited possibility of irrigation facilities due to high altitude terrain. The state Governments of Telangana, Andhra Pradesh and Karnataka have conceived large scale LI projects to lift the water to required altitude and made a network of canals to enable the free flow via gravity. These are monsoon fed and runs depending on availability of water in the river. Typically, these schemes run between July and November [6]. They help in maximum utilization of rain water before entering sea and in some cases they help in controlling the flood in the downstream. Depending upon the altitude and terrain, these projects are made in multiple stages. At each stage, water is lifted to an altitude of around 30-35m. This arrangement is similar to a tandem hydro, where water level at each stage depends on the operation of the previous stage.

Sample schematic diagram of Handri-Neeva Phase-1 is shown in figure 3. Balancing reservoirs are provided at every 2-3 stages. Altitude/Head, availability of water and discharge requirement forms the criteria for number of motors at each stage and capacity of each motor. Quantity of water to be pumped is decided by the irrigation authorities as per the availability of water at lower reservoir and requirement of water at upper reservoir. Sample operation of a lift irrigation project in Andhra Pradesh state of SR is given in figure 4.

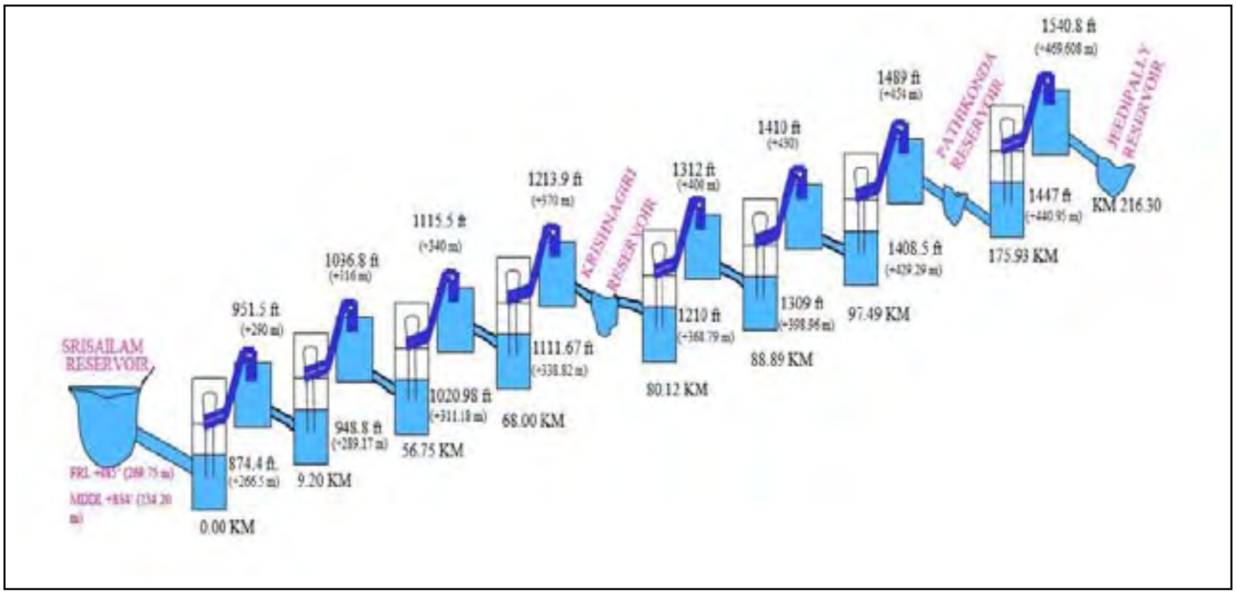

Figure 3 Schematic diagram of Handri-Neeva Ph-1 Lift Irrigation Project (Multi Stage)

Figure 4 Pattiseema Lift Irrigation project operation

As on date, capacities of these motors are in range of 1-5 MW and power requirement at each station varies from 10 to 150 MW. Details of major lift irrigation projects commissioned in different states of Southern Region is given in table-3. In the next 3-5 years, many large scale are being established in various states of South India. These projects use synchronous machines of capacities ranging from 30-150 MW. Details of power requirement of major upcoming projects are given in table 4. There are many other small scale projects proposed. A conservative estimate of the total installed lift irrigation projects could be around 10-12GW by 2022 in Southern Region of India.

Table 3 Upcoming/Ongoing LI projects in SR

Sl No	Name of the project	Power Requirement
1	Handri –Neeva Phase 1	458MW[7]
2	Kalwakurthy	450MW [8]
3	Pattiseema	113MW[9]

Table 4 List of major LI projects in SR

Sl No	Name of the project	Power Requirement
1	Kaleswaram	4300 MW[10]
2	Palamuru-Rangareddy	3635 MW [10]
3	Devadula	484 MW [11]
4	Uttarandra Sujala Sravanthi	339 MW [12]
5	Handri Neeva Ph -2	284 MW [13]

V. LIFT IRRIGATION LOADS FOR BETTER GRID

Lift irrigation projects primarily use synchronous machines owing to their efficiency & size. Some of the characteristics of LIS are discussed below.

1) Being large synchronous machines, they help in increasing the system inertia, improving the stability of the grid.
2) Immediate response and fast ramps – similar to that of a hydroelectric plant.
3) Few machines can be run under partial load using valve control. This can be used for providing secondary demand response.
4) DR can also be achieved by switching the machines on & off based on grid requirement. Theoretically, typical machine with 4-5MW capacity can be switched 2-3 times in an hour and a machine of 100MW can be switched around 5-10 times over a day.
5) Most of these machines are equipped with SCADA and can be visualized & controlled from a centralized location.
6) Being synchronous machines, these can provide reactive support, stabilizing the local voltages. These LI loads are often located at weak buses at remote areas where reactive issues exist.

Lift irrigation projects are versatile loads and can be of great help to the system operator in balancing the grid.

VI. HARNESSING THE LIFT IRRIGATION PROJECTS FOR BETTER GRID OPERATION

a) *Lift Irrigation loads for Ancillary Services*

As shown in fig-4, these projects operate at full load for very limited period of time in the whole season. This feature can be used to schedule LI loads at different parts of the day, maintaining the amount of water to be pumped as constant. As discussed in section III, many projects have balancing reservoirs at every 2-3 stage intervals, which can store water for a period of 1-1.5 days. Balancing reservoirs act as storage buffer and this feature can be exploited for providing ancillary services. Coordination with irrigation department is required for the details regarding quantity of water to be pumped on each day. System operator can schedule these loads as per grid requirements, within irrigation limits.

As on date, ancillary services are being despatched from thermal stations. Energy desptahced under ancillary services in SR would be around 70-80MU [14] per month for regulation up ancillary service and 5-10MU [14] for regulation down ancillary service. This could increase many fold with the increase in penetration of RE. Being fast acting machines, the flexibility available in LI loads can be used in despatching fast tertiary control services. This can be considered as relatively greener, since the need for thermal generation can be reduced by utilizing LI loads during contingencies. Based on availability and requirement of water, part of these can also considered in maintaining regional spinning reserves. LI loads are predominant during monsoon period of the country which is also the peak wind generation season of India. As requirement of balancing services during this period is higher than the other part of the year, effective utilization of LI projects can aid in optimum harnessing of RE.

b) *Lift Irrigation loads for ADMS*

LI loads can be used in Automatic Demand Management Systems (ADMS) for disconnecting loads during contingencies. LI loads can be shut immediately and required amount of water to be pumped can be adjusted using the flexibility available. Thus the inconvenience to the user due to load shed is thereby limited. These can be programmed to participate in Special Protection Schemes (SPS) - triggered on tripping of large generators, over loading or tripping of important transmission lines. They can also be programmed to during the operation of Automatic Under Frequency Relays (AUFR), rate of change in frequency (df/dt) etc.

VII. SCHEDULING OF LIFT IRRIGATION LOADS

Currently, LI loads operate as per the requirement of irrigation department without any schedule as a HT consumer. In order to exploit the flexibility available in the LI machines, these loads need to be despatched by a Load Despatch Centre (LDC). Most of these loads come under the jurisdiction of State Load Despatch Centre (SLDC). A robust scheduling, measurement and settlement mechanism should be in place. As on date, a full-fledged ABT mechanism is in place only at Inter-State level. As highlighted in SAMAST [15] (Scheduling, Accounting, Metering and Settlement of Transactions in Electricity) report by Forum of Load Despatch Centers of India, the same needs to be implemented at Intra-State level also.

VIII. COMMERCIAL ISSUES

Government owned LI projects are envisaged to maximize social welfare by irrigating dry lands. These projects do not aim at direct return on investment. Grid support services provided by the LI projects will be an additional outcome. The cost of services provided may be less, as these are not made with the primary objective of providing grid support services. Variable cost of thermal stations depends on fuel and variable cost of hydel storage/battery variable cost will be priced based on cycle efficiency. A typical demand response system will be priced based on the opportunity cost of rescheduling the loads. LI loads have neither fuel cost nor loss due to cycle inefficiencies. Flexing of LI loads owing to irrigation constraints can top merit order despatch since they don't have opportunity cost. However, a suitable pricing needs to be determined which can incentivize the owner for providing the grid support services.

IX. CONCLUSIONS

LI loads have the characteristics required for providing ideal Demand Response. These schemes are being established in a big way in SR. Harnessing DR from these loads will facilitate smooth operation of electricity grid with high penetration of RE.

X. CHALLENGES AND WAY FARWORD

1. Scheduling and dispatch of LI loads needs to be done in coordination with the irrigation department.
2. Even though these machines are capable of high on & off duty cycles, the impact on life and performance of the machines needs to be studied in long run.
3. In order to have a centralized operation, SCADA that is available in local sites of these projects need to be extended to load despatch centre.

If all the above technical constraints are addressed at design stage, better operation could be achieved.

XI. REFERENCES

[1] CEA Executive Summary for the Month of Mar 2018. http://www.cea.nic.in/reports/monthly/executivesummary/2018/exe_summary-08.pdf
[2] MNRE Tentative State-wise break-up of Renewable Power target to be achieved by the year 2022.

http://mnre.gov.in/file-manager/UserFiles/Tentative-State-wise-break-up-of-Renewable-Power-by-2022.pdf

[3] Advance National Transmission Plan for 2021-22 http://www.cea.nic.in/reports/others/ps/pspa2/ptp.pdf

[4] GREENING THE GRID: Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid, Vol. II—Regional Study. https://www.nrel.gov/docs/fy18osti/68744.pdf

[5] A Janardhan Et al; Net Load Ramping Requirements of Southern Region by 2022.; published at International Conference on Large-Scale Grid Integration of Renewable Energy in India

[6] *"Power for All"* MoU of Govt of Telangana with Govt of India. http://powermin.nic.in/sites/default/files/uploads/Power_For_All_4_12_Final_Telangana_Signed.pdf

[7] http://irrigationap.cgg.gov.in/wrd/static/approjects/hnss_1.html

[8] http://www.irrigation.telangana.gov.in/icad/static/projects/MGKLIS.html

[9] http://irrigationap.cgg.gov.in/wrd/projects

[10] http://www.cea.nic.in/reports/committee/scm/sr/minutes_meeting/40th.pdf

[11] http://irrigation.telangana.gov.in/icad/static/projects/jcrdlis.html

[12] http://irrigationap.cgg.gov.in/wrd/static/approjects/babujagjeevana.html

[13] http://irrigationap.cgg.gov.in/wrd/static/approjects/hnss_2.html

[14] Ancillary Services – Monthly Reports -2017-18 https://posoco.in/reports/ancillary-services-monthly-reports/ancillary-services-monthly-reports-2017-18/

[15] Scheduling, Accounting, Metering and Settlement of Transactions in Electricity (SAMAST) Report http://www.forumofregulators.gov.in/Data/WhatsNew/SAMAST.pdf

Remote / Rural Area Lighting Through Green Energy

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INTRODUCTION

Energy has become the basic necessity of life and all people weather they live in urban area or rural area they need energy. Many of the rural area are still not connected by the grid, the main source of energy for rural people who constitute the majority of population of our country are switching towards the non conventional energy resources i.e green energy. The total installed power generation capacity in India is about 340526.58 MW. Having so much of power generated, still there are about 1, 00,000 villages / remote areas / hamlets, which are not connected to grid and many are there in north-east states.

India's electricity sector consumes about 72% of the coal produced in the country. The high ash content in India's coal affects the thermal power plant's potential emissions. Therefore, India's Ministry of Environment and Forests has mandated the use of beneficiated coals whose ash content has been reduced to 34% (or lower) in power plants in urban, ecologically sensitive and other critically polluted areas, and ecologically sensitive areas. Coal benefaction industry has rapidly grown in India, with current capacity topping 90 MT.

India's renewable energy sector is amongst the world's most active players in renewable energy utilization, especially solar and wind electricity generation. As of 31, March 2018, India has grid connected installed capacity of about 62.85 GW non-conventional renewable technologies.

India is endowed with vast solar energy. The solar radiation of about 5,000 trillion kWh per year is incident over its land mass with average daily solar power potential of 0.25 kWh per m^2 of used land area with the available commercially proven technologies. As of 31 January 2018, the installed capacity is about 9 GW meeting 1% of the utility electricity generation.

India has the fourth largest installed wind power capacity in the world. The development of wind power in India began in the 1990s in Tamil Nadu and has significantly increased in the last decade. As of 28 February 2018, the installed capacity of wind power is 32.38 GW, spread across many states of India. The largest wind power generating state is Tamil Nadu accounting for nearly 23% of installed capacity, followed in decreasing order by Gujarat, Maharashtra, Rajasthan and Karnataka.

<u>Problems with India's Power Sector:</u>

Inadequate last mile connectivity: This is the main problem to supply electricity for all users. The country already has adequate generation and transmission capacity to meet the full demand temporally and spatially. However, due to lack of last-mile link-up with all electricity consumers and reliable power supply, many consumers depend on DG sets using costly diesel oil for meeting unavoidable power requirements. Also more than 10 million households are using battery storage UPS as back-up in case of shedding. India imports nearly US$2 billion worth of battery storage UPS every year. Nearly 80 billion KWh electricity is generated annually in India by DG sets which are consuming nearly 15 million tons of diesel oil. As the overhead lines availability is low during rains and wind storms, separate buried cables are to be laid from the distribution low voltage substations to supply cheaper emergency power to the needy consumers in cities and towns to drastically reduce diesel oil consumption by DG sets and installation of UPS systems.

Demand build up measures: It can be initiated to consume the cheaper electricity (average price Rs 2.5 per kWhr) available from the grid instead of running the coal/gas/oil fired captive power plants in various electricity intensive industries. The captive power generation capacity by coal/gas/oil fired plants is nearly 47,000 MW mainly established in steel, fertilizer, aluminum, cement, etc. industries. These bulk captive electricity producers can draw cheaper electricity from the grid on short term open access (STOA) basis and avoid the costly imported coal/RLNG/natural gas or utilize these fuels for process purposes instead of electricity generation. Some of these idling captive power plants can be used for grid reserve service for earning extra revenue. At present substantial diesel oil is consumed by railways for rail traffic on its non electrified rail lines. To eliminate the substantial cost of imported diesel fuel, power ministry is funding the electrification of these lines and achieving additional power demand of 7 billion units.

No access to electricity: There are over 300 million people in India or 60 million households which have any access to electricity.

A system of cross-subsidization: It is practiced based on the principle of 'the consumer's ability to pay'. In general, the industrial and commercial consumers subsidize the domestic and agricultural consumers. Further, Government giveaways such as free electricity for farmers, partly to curry political favor. This has financially crippled the distribution network, and its ability to pay for purchasing power to meet the demand in the absence of subsidy reimbursement from state governments. This situation has been worsened by state government departments that do not pay their electricity bills.

Name plate/declared capacity: Many of the coal fired plants owned by IPPs are overrated above the actual maximum continuous rating (MCR) capacity. The reason for overrating the capacity is to over-invoice the plant cost. These plants operate 15 to 10% below their declared capacity on daily basis and operate rarely at declared capacity. Thus these units are not effectively contributing to the on line spinning reserves to maintain power system / grid stabilization.

Intraday load and demand: The proper graphs are not made in India at every 15 minutes or less intervals to understand power grid nature and its short comings with respect to grid frequency. These graphs should be plotted with comprehensive data collected from SCADA / on line for all grid connected generating stations ($\geq$ 100 KW) and load data from all substations to impart authenticity to the data presented. Comprehensive list of grid connected power stations along with declared capacity should be prepared.

Coal supply: Despite abundant reserves of coal, the country isn't producing enough to feed its power plants. India's monopoly coal producer, state-controlled Coal India, is constrained by primitive mining techniques and is rife with theft and corruption. Poor coal transport infrastructure has worsened these problems. To expand its coal production capacity, Coal India needs to mine new deposits. However, most of India's coal lies under protected forests or designated tribal lands. Any mining activity or land acquisition for infrastructure in these coal-rich areas of India, has been rife with political demonstrations, social activism and public interest litigations.

Average transmission, distribution and consumer-level losses: This is exceeding 30% which includes auxiliary power consumption of thermal power stations, fictitious electricity generation by wind generators, solar power plants & independent power producers (IPPs), etc.

The residential building sector: This is one of the largest consumers of electricity in India. Continuous urbanization and the growth of population result in increasing power consumption in buildings. Thus, while experts express the huge potential for energy conservation in this sector, the belief still predominates among stakeholders that energy-efficient buildings are more expensive than conventional buildings, which adversely affects the "greening" of the building sector.

Key implementation challenges: The India's electricity sector include new project management and execution, ensuring availability of fuel quantities and qualities, lack of initiative to develop large coal and natural gas resources available in India, land acquisition, environmental clearances at state and central government level, and training of skilled manpower to prevent talent shortages for operating latest technology plants.

Hydroelectric power projects: In India's mountainous of north and north east regions the hydroelectric power projects have been slowed down by ecological, environmental and rehabilitation controversies, coupled with public interest litigations.

Theft of power: In India, financial loss due to theft of electricity may be around $16 billion yearly. Populist pro-free power measures also bleed the power companies. Some power companies continue to bleed and lead to bankruptcy due to one of these factors. This also leads to pay more by legal users. This creates a scenario where villages have huge cut of power and simultaneously availability of power in the grid with no purchase by DISCOMs. It has become menace in India. In a recent case, an engineer from a discom team died as his car lead to crash, as a mob gathered and attacked his team during their attempt to block the theft.

Lack of clean and reliable energy sources: There is a lack of clean and reliable energy source in north east parts and tribal area of india such as electricity is, causing about 500 million people in India to continue depending on traditional biomass energy sources – namely fuel wood, agricultural waste and livestock dung – for cooking and other domestic needs. Traditional fuel combustion is the primary source of indoor air pollution in India, causes between 300,000 and 400,000 deaths per year and other chronic health issues.

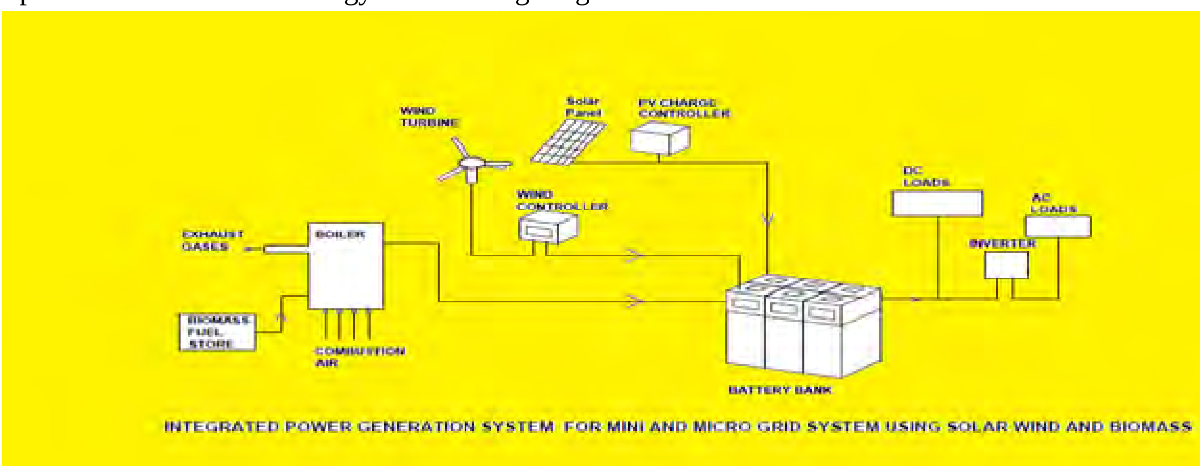
For the villages with electric connection power availability is erratic and much of the time power is not available for number of days. Whatever the power is generated out of that 14 to 16 percent of it is lost in transmission and distribution as the generating stations are placed very far away from the load centers. Taking all these factors into considerations the energy industry is increasingly realizing that it does not make sense to generate all electricity in one place and then transmit it across miles of expensive cabling. So realizing all these facts the energy industry should now switch towards the green energy and decentralized energy generating centers in particularly in north-eastern states using the solar, wind, bio-mass which can be set up at any place including remote areas.

Purpose: The fossil fuels i.e coal is of finite resource, which is available for a definite period of time. So before they start to diminish we have to switch to green energy.

Methods: Realizing the facts and importance of green energy, the energy industry should go for small and medium decentralized energy producing centers using solar, wind and bio-mass in villages, remote area and tribal jungles by using the naturally available non-conventional energy resources.

Results: By integrating the different decentralized energy producing centers with non-conventional energy resources we can permanently reduce the demand on the grid system and also we can reduce the peak load demand gap.

Conclusion: With the installation of mini and micro decentralized energy producing centers in rural areas and tribal jungles, farmers can use the power for agriculture purpose and improve their economic conditions. Students are able to continue their studies at night. Women's in rural areas can participate in other economic activities in night such as weaving and sewing apart from daily house hold work with the help of non-conventional energy resources lighting.



INTEGRATED POWER GENERATION SYSTEM FOR MINI AND MICRO GRID SYSTEM USING SOLAR WIND AND BIOMASS

References:

1. Annual report 2017-18 Ministry of Power.
2. Annual report 2017-18 Ministry of NRES.
3. Rijul Dhingra, Abhinav Jain, Abhishek Pandey, and Srishti Mahajan "Assessment of Renewable Energy in India" International Journal of Environmental Science and Development, Vol. 5, No. 5, October 2014.
4. Atul Sharma "A comprehensive study of solar power in India and World" Renewable and Sustainable Energy Reviews 15 (2011) 1767–1776.
5. S. N. Singh, Bharat Singh & Jacob Østergaard "Renewable Energy Generation in India: Present Scenario and Future Prospects. IEEE Xplore.
6. Naveen Kumar Sharma∗ , Prashant Kumar Tiwari, Yog Raj Sood Solar energy in India: Strategies, policies, perspectives and future potential, Renewable and Sustainable Energy Reviews 16 (2012) 933– 941.

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Renewable Energy Integration & Pumped Storage Plants

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Abstract

Hydro power plants are most reliable and flexible conventional energy source in grid. This flexibility has contributed in managing the imbalance between demand and supply in grid and has ensured secure operation of grid. Large scale integration of renewable energy brings new challenges to system operators and demands for inclusion of flexible power reserves which can take care of variable renewable. Pumped Storage plants are the best option to meet these challenges of power integration. Pumped-storage hydro plants provides a flexible, dynamic and efficient way to store and deliver large quantities of electricity by moving water between two reservoirs at different elevations. Variable speed operation has further enhanced the flexibility and performance of pump turbine units. THDCIL is constructing India's largest pumped storage scheme of 1000 MW Tehri PSP, comprising of pump turbine units of 250 MW each. The main feature of the project is the large head variation of about 90 m, under which the reversible units shall operate. The operation of Tehri PSP is based on the concept of recycling of water discharged between upper reservoir (Tehri Dam) to lower reservoir (Koteshwar HEP). Various aspects of Tehri PSP such as variable speed selection have been elaborated.

Keywords: Pump storage project, Power converters, Variable Speed, Optimal efficiency point

Introduction

Government of India has launched "Power for All" programme with an objective of ensuring uninterrupted power supply to all. Other development programmes such as House for all, smart cities etc have also been launched. These programmes with other social & economic growth factors would substantially increase the power requirements of the country. Also To have sustainable growth, to minimize environmental damages by fulfilling the Paris agreement convention on climate change that came into force on 4 November 2016, holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, worldwide the shift is now towards use of renewable energy. In order to cater the future energy/power requirements in coordination with fulfilment of climate change commitments, India has set a target to generate 175 GW of renewable energy by 2022 comprising solar and wind energy. Further in future the integration of renewable in grid is set to increase for contributing towards the global efforts in climate change mitigations. But this large scale variable renewable generation integration would have implications on reliability & stability of power sector. Therefore for balancing these variable renewable generations, sufficient flexible resources must be available for ensuring stability of the grid. Hydropower is ideally suited to cater all these demands/requirements of Indian power sector. Thus in future there is a need to focus on accelerated development of hydro power.

Renewable Energy Integration

Economic, environmental and energy security issues are key enablers for promoting the development of renewable energy. However, renewable generation is marked with various inherent issues like variability, intermittency and fast ramps etc which are needed to be addressed for secure grid operation. With the continual increase in share of renewable energy in the grid these issues have become prominent and impose a threat to effective grid operation and management. Developed countries such as U.S. etc have devised mechanisms to accommodate increasing the share of renewable energy. Research on various aspects of effective grid management and storage technologies is underway throughout the world.

Issues/challenges with Renewable Energy Integration

Renewable sources such as wind, solar etc solely depend on external environmental factors such as wind speed, weather etc. Larger integration of renewable sources adds fluctuations to the grid and is also difficult to manage. The current conventional sources of generation and methodologies available are incapable in responding to the sudden ramp up/down emerging from renewable generation. Therefore it is important to build flexibility in existing fleet of conventional power plants and as well as develop gas, hydro, pump storage plants etc which can quickly respond to the fluctuations in renewable generation.

With the larger integration of variable renewable into the grid, forecasting has essential requirement for grid security. For ensuring the safe /secure grid operation, it is important for system operator to foresee what is expected to happen a few hours ahead, in order to be able to take appropriate measures. Thus having an efficient forecasting system has now become essential requirement for reliable grid operation. On the basis of historical data, wind speed, humidity, air pressure etc it has become possible to forecast the weather. Forecasting techniques have gradually improved over the years and forecasting error has narrowed down however still significant is yet to be done.

Present power system includes traditional rotating synchronous generators such as hydro, thermal & nuclear generators. All these generating units have one crucial property of rotational inertias which is important for power system frequency dynamics & stability and helps in damping fluctuations in case of frequency deviations. Maintaining grid frequency within acceptable range is essential requirement for stable power system operation. Higher proportional of renewable integration will cause deactivation of traditional power plants and would consequently lower overall grid inertia which has implications on frequency dynamics. Lower grid inertia leads to faster frequency dynamics and also exposes grid to associated operational risks. Thus with higher integration of renewable in grid, whole frequency response methodology is needed to be redefined/ revised and new methods must be developed for maintaining grid frequency.

Hydropower & Renewable Integration

Hydropower is one of the most flexible power sources of electricity. Hydropower not only contributes to renewable energy generation but also balances variable renewable generation. Power system with considerable amount of hydro stations offer easier integration of variable renewable generation by balancing renewable variability while storing water/energy in reservoirs. Hydro stations particularly large reservoir based and pumped storage plants have substantial potential of flexibility.

In PGCIL report on “Renewable Energy Integration- Transmission and Enabler” it has been mentioned that due to higher integration of renewable, grid would witness higher ramp up and ramp down requirements. Thermal & nuclear generators are generally considered as base load stations and storage hydro & gas are utilized as balancing (Flexible) resources. The comparison of ramp rates of different sources is as under:

Generation Technology	Min Load (%)	Ramp Rate (%/ min)
Coal	55-60	1-2
Super Critical Power Plant	40	3
Nuclear	55-60	1-5
Gas Combustion Technology	50	22-25
Combined Cycle Gas Turbine	50	2.5-3
Hydro Storage	33	50
Battery Energy Storage	0	20

From above it can easily be concluded that Hydro (Especially Storage projects) and Gas turbines are two most fast ramping balancing resources. Hydro apart from being a source of low cost energy, it has over years contributed to reliable & secure operation of grid by means of its inherent flexibility viz peaking support, overload and part load operation capacity, fast ramping etc. Several hydro stations have facility to black start & synchronous condenser operation which is of added advantage to grid.

Energy Storage Systems: Pumped Storage Plants

Renewable energy generation is characterised by features such as variability, intermittency etc. Thus it is essential to have sufficient amount of flexible power reserves/energy storage systems which can take care of such variations. Energy storage systems due to tremendous range of uses and configuration may assist renewable energy integration in number of ways. Conventional storage system like Pumped storage system is most advanced electricity storage technologies (in terms of commercial & technical maturity). Other non conventional storage systems like battery energy storage are also available. In world over various energy storage projects have been commissioned or are under implementation and majority of this capacity is based on the pumped storage technology.

Pumped storage plants harnesses water potential using two reservoirs built at different heights. Off-peak/excess electricity in grid is utilised to pump water from the lower to the upper reservoir, turning electrical energy into gravitational potential energy and vice versa when power is needed to be generated by releasing water to lower reservoir. Large hydro projects having significant storage capacity play role similar to pumped-storage plants by deferring output until needed fulfilling energy requirements. However pumped storage plants not only provide short term power & intermittent storage but also balance the variable renewable energy.

Pumped storage technology is the most mature energy storage technology in today's market. Worldwide most pumped storage plant is of fixed speed type. The only way to control pump output in fixed speed plants is to start/stop individual pump turbine units. With the advent of highly efficient variable speed technology, machines can be operated with higher efficiency especially at part loads. For this reason variable speed technology is well suited to integration of variable renewable. The trend of power supply system is depicted as below:

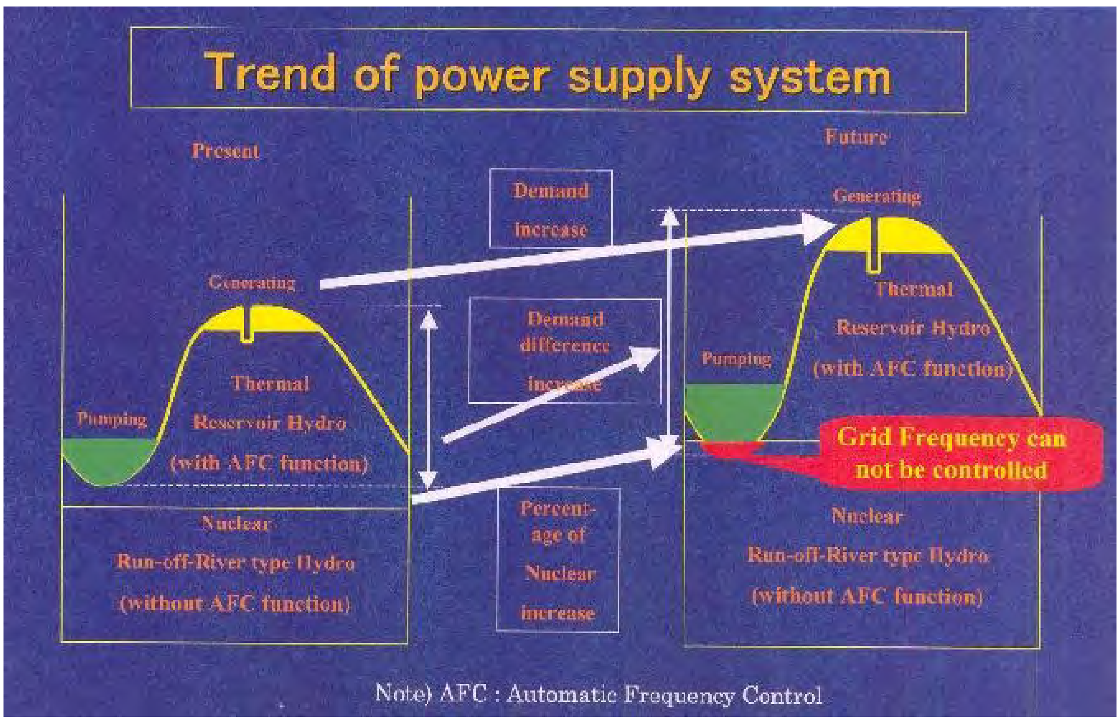

Fig.1 Power supply system trend

Variable Speed Generation

Efficiency of turbine working at variable head can be significantly increased by operating the turbine at different speeds depending upon the head & load conditions. Whenever machine is being operated in pump mode, then the maximum efficiency speed would be different from that of when machine is operated in turbine mode. So therefore two different speeds are available for optimum/ efficient of same unit for turbine and pump mode of operation. Further when there is exceptionally high head variation this speed variation technique results in optimal/ efficient operation in both turbine as well as in pump mode. With variable speed operation at each operating head, optimum of machine performance could be achieved in terms of efficiency and cavitations limit. Various PSP running worldwide with variable speed technology are Okhawachi PSP (2x400 MW), Goldisthal PSP (2x350 MW) etc. Key additional benefits of variable speed machines are as under:

- Regulation of energy consumption during pumping mode depending on quantity of excess power in grid thereby reducing number of starts and stops and also regulating grid frequency/ voltage
- Operating pump turbine close to the optimal efficiency point
- Elimination of operation modes/points prone to hydraulic instability or cavitations thus resulting in improved reliability, reduced maintenance, and increased lifetime
- Operating units in a wider head variation range thereby ensuring the increased availability of unit.

Pumped Storage Capacity in India

India has a huge potential for pumped storage plants. Assessment studies carried out by CEA during 1978-87 has identified 63 sites for pumped storage plants with total capacity of about 96500 MW. At present 9 pumped storage plants with aggregate installed capacity of 4785.6 MW are in operation. However due to various reasons, only 5 no. of plants with aggregate installed capacity of 2600 MW are being operated in pumping mode. THDCIL Tehri Pumped Storage Project (4x250 MW) which is presently in construction stage would be equipped with variable speed technology. It would be the first pumped storage power plant in India to use variable speed pump turbine technology.

Tehri Pumped Storage Plant

Tehri Pumped Storage Plant (4x250 MW) is located in State of Uttarakhand is an integral part of Tehri Hydro Power Complex (2400 MW). Tehri Hydro Power Complex comprises of following:

1. Tehri Hydro Power Plant (4 x 250 MW)- Under Operation
2. Koteshwar Hydro Electric Project (4 x 100 MW)- Under Operation
3. Tehri Pumped Storage Plant (4 x 250 MW)- Under Construction

The reservoir of Tehri dam will operate as upper reservoir and Koteshwar reservoir as the lower reservoir. The availability of water for Tehri PSP would therefore be governed by mode of operation of Tehri Power complex. Tehri dam reservoir storage has live storage capacity of 2615 million m3 which allows inter seasonal regulations. In Tehri dam water can be stored upto max elevation of EL 830 mtr. The stored water is released as per peak demand of grid besides fulfilling the irrigation requirements and is bought down to MDDL EL 740 meter before onset of monsoon of next season i.e. by end of June. During monsoon season (July to September) reservoir level increases rapidly to reach its maximum in September end. Thus during a year the head variation in reservoir shall be approx 130 to 230 mtr.

This main characteristics of exceptional wide head variation (Approx. from 130 to 230 mtr) which means that the conventional configuration/ solution with single speed reversible turbine would have lead to major drawbacks such as Loss in efficiency in both pump & turbine mode in large portion of head range, cavitations risk etc. Therefore two options were available with THDCIL:

- First option consisted of installing two speed synchronous generator motor coupled to conventional pump turbine. With this arrangement, same synchronous generator motor would run at most suitable speed depending upon the available head with highest possible efficiency. However issues with this option were significant increase in cost of the machine which can mainly be attributed to appreciable increase in weight of the machine's rotor which would substantially affect other aspects of the plant such as load bearing capacity of thrust bearings, increase in capacity of crane at power house etc.

Further fixed speed PSP suffers from major inherent drawbacks such as inability to generate power over wide range of variable water head, less efficiency at part load generation, inability to operate in partial pumping mode etc.

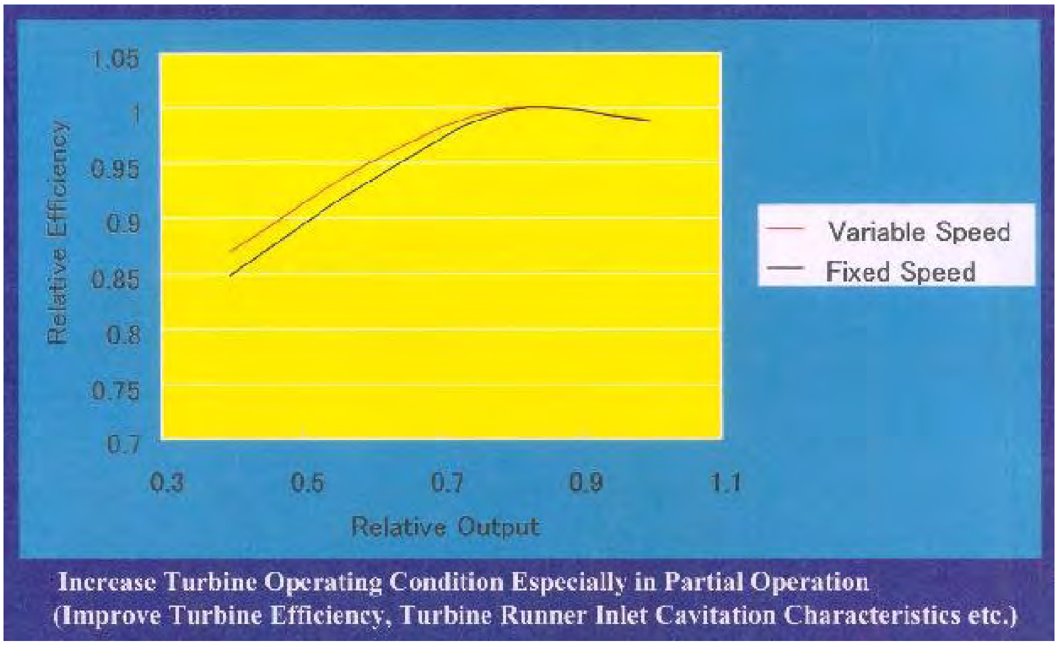

Fig.2 Relative efficiency v/s relative output for fixed and variable speed machine

- Second option consisted of installing variable speed asynchronous generator motor coupled to pump turbine. Variable speed applied to reversible pump turbines finds their principal and foremost application in hydropower schemes with large head variations. The decision for opting a variable speed reversible unit over a dual speed reversible unit takes into account maximum to minimum head ratio however the final decision has been based on the economics and efficiency gain analysis. It is also claimed by various experts that the threshold point for choosing variable speed in preference to dual speed machines is when the maximum to minimum head ratio is above 1.25. Tehri pumped storage (4 X 250 MW) project has the world record for head variation. The range of the head variation throughout the year is exceptional: between 130 meters and 230 meters.

Variable speed reversible units also offers other extremely interesting features such as usage of modern VSI type of speed control. Power converters based Doubly fed asynchronous machine (DFAM) fed variable speed PSP facilitates variable speed operation, smooth starting, braking (regenerative & dynamic), reactive power compensation and also acts as a active power filters. Moreover, the converters are also responsible for achieving real & reactive power control in generation mode and speed & reactive power control in the pumping mode. Due to change in machine technology from two speed to variable speed, the submergence required for the pump turbine reduces from 57mtr to 40 mtr without compromising in efficiency and other performance parameter of the machine resulting in reduce the cost of civil excavation that cannot be ignored.

It may also be noted that variable speed machine gives an overall increase of 5-10% in energy generation for whole year. The contractor (M/s. GE Power AG, Formerly Alstom Ltd.) of Tehri PSP have claimed that the guaranteed conversion loss for Tehri PSP is ≤ 20.33% which was calculated from hydraulic studies of pump turbine model test results.

Due to detailed analysis of various factors many of which have been mentioned above, variable speed reversible units were opted out for Tehri PSP.

Conclusion

The transmission corridors for evacuation of renewable power is being firmed up for the plan of having 175 GW of RE power in next 5 years, it is imperative to develop more PSPs and initiatives must be taken for accelerated development of PSPs. The development of pumped storage would significantly improve the grid reliability and it would act as best balancing option for large scale Renewable Energy integration. While benefits of having pumped storage hydro power are but current market structures and regulatory frameworks etc do not encourage pumped storage development. Policy/regulatory-level guidelines must therefore be revised for harnessing the pumped hydro potential to the maximum and suitable incentive mechanisms must be introduced that would encourage the development of pumped hydro plants.

Technical Issues and Challenges in Grid Connected Solar Pv Power Plants: A Utility Prospective

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ABOUT TATA POWER

Tata Power, India's largest integrated power company has installed generation capacity of 10,757MW supported through Thermal, Hydel, Wind, Solar power plants and contributes to 4% of country's power generation requirements. With intent of achieving 40-50% of generation capacity by 2025 through green and clean source of energy, Tata Power has a strong portfolio of 2168MW of operating capacity under renewable energy. Alignment to the intent, the RE generation is steadily rising. 64 grid-connected solar PV sites with operating capacity of 1237MW at 68 locations in 10 states.

INTRODUCTION

Currently, India is aggressively pushing for solar power with a 100GW target for 2021-22. The installed capacity crossed 20GW in 2017, with 18.4GW in the form of ground-mounted projects and 1.6GW on rooftops. In view of huge capital investment in Solar Photovoltaic Power Project, it is vital aspect to maintain and operate these plants economically till plant useful life. Addressing technical issues and challenges like Solar module degradation, Fire hazards, Power Quality issues, LVRT compliance & Reactive Power management, Upkeep & maintenance of outdated Inverter system, Module recycling & disposal will be a herculean task in front of utility engineers; thereby concerned about the safe, efficient, and reliable operation of the theses power plant.

In this technical paper, current as well as emerging technical issues and challenges and its impact are discussed. After recognizing these pain areas, need for new strategies / resolutions at various levels like Govt. polices / Regulation, Standards / Certifications, Grid operation SOPs, Adoption of Design & engineering and Operation and Maintenance practices are highlighted to mitigate these risks and to maintain or even to improve the plant reliability and life.

Key words: Solar PV, Solar module, Degradation, Power Quality, Solar Inverter, Grid operation

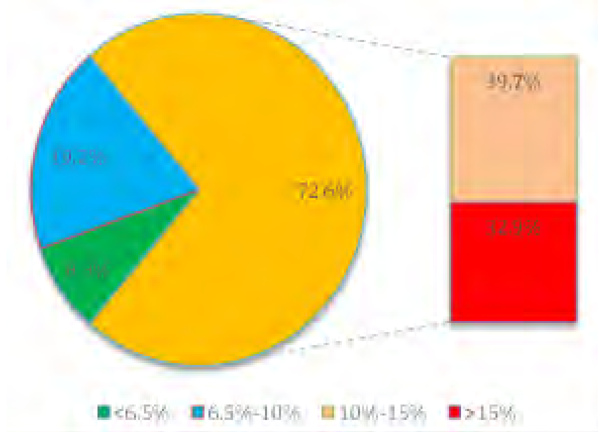
SOLAR MODULE DEGRADATION

Solar module degradation is complex phenomenon, which is resultant of multiple factors such as manufacturing defects, transportation damage, and wrong O&M practices & last but not the least harsh site conditions.

Different type of degradations is seen at our operational sites, which can be categorized as below:

a) System design induced degradation - Wrongly designed Inverter system, Hot spot generation due to shadow effect, Wrong selection of solar modules etc.
b) Manufacturing Induced degradations – Poor quality of material used in solar module manufacturing (like EVA, Back sheet, ARC, glass etc.), defective solar modules (diode failure, busbar corrosion, metal grid corrosion, delamination, snail tracks, discoloration of glass, junction box related problems and soldering issues)
c) Upkeep and Maintenance induced degradations – Moisture ingress, mechanical stress, harsh site condition leading to corrosion and thermal stress, high total dissolved solids (TDS) in water used for module cleaning leading to scaling

Recently, detailed degradation study was carried out in some solar power plants, which are commissioning in year 2010-11. Various tools like I-V curve tracer, EL Imaging camera, PV sys software, visual inspection etc. were used as part of diagnostic study. Following key findings / observations were made on Multi-crystalline solar modules in 8MW solar power plant:



- Sample size: 33792 nos. of 235 / 240 Wp
- Expected degradation: 6.5%
- Avg. module level degradation: 13.4%
- Fraction of modules with >15% degradation: 33%
- Fraction of modules with high PID: 9.7%
- Fraction of modules with moderate PID: 19.3%
- Fraction of modules with diode faults & severe corrosion: 0.9%
- Approx. loss from expected power: 7.1%
- Approx. revenue loss = 1.405 Cr/year

Similar exercise is being carried out / planned for other old solar power plants, which are posing degradation issues or showing reduction of overall plant performance. In some cases, solar module manufactures are honoring warranty claims on case to case basis. However, the above case study, OEM denied warranty claims and attributed degradation to system design & harsh environmental conditions.

Following corrective / Preventive actions are being planned to mitigate degradation effect. However, the same may be varying on case basis and depends on findings from detailed degradation study:

a) Implementing / ensuring negative grounding system in DC circuit

b) Replacement of high PID modules by new modules

c) Rebinning strategy to segregate PID affected solar modules

d) Use of PID offset boxes or PID reversal devices to recover lightly / moderately PID affected solar modules

e) Flipping the polarity of string so that then the PID affected modules are subjected to positive voltage during the day and recover slowly in due course

f) Cleaning of modules by mopping to reduce dust deposition and scaling

As per 'All-India Survey of Photovoltaic Module Reliability: 2016' report, one important observation was made that there is wide variability in the module quality and degradation rates. Many modules show excellent performance, but there are some sites (especially installation in Hot & Dry, Warm & Humid climates) are showing alarmingly high degradation rates, which is cause for concern. Some key recommendations like module certifications for guarantee confirmation, proper packaging and handling of the modules, Installation procedures and protocols, field EL testing, PG requirements need to be incorporated in relevant standards and technical specifications to mitigate degradation related risks.

FIRE HAZARDS IN SOLAR POWER PLANTS

Solar PV systems are subject to electrical faults like any other electrical installation such as arc faults, short circuits and ground faults due to cable insulation breakdowns, rupture of a module, faulty / loose electrical connections, ageing, corrosion, rodent bites etc. In the worst case, faulty conditions on the PV system will not only result in a hot spot, but also a DC arc. Any electric installation is exposed to the risk of arcs, but solar installations are particularly sensitive to this exposure because of the continuous DC current and the high currents (>10 A) and voltages (300-1000 V) involved. DC arcs does not get self-extinguished and can reach temperatures as high as 3000°C. Arcs at this temperature can melt metal, which can fall as slag and ignite nearby combustible materials.

As per research papers on 'Failure Mode and Effect Analysis (FMEA) on solar PV system', inverter is most likely component to fail. In most of cases, faulty designed inverter system and installation error are root causes of electrical fire. Well-designed ventilation system, Ground fault detection system and Insulation Resistance monitoring and Arc fault detection can provide effective protection against electrical faults that may aggravate and further result in fires.

A common method of assessing the health of PV system is by Thermography technique, visual inspection and adoption of best maintenance practices can provide good control over these fire hazards. Protecting PV systems from high voltage DC arcing faults appears to be a promising mitigation plan However, reliable detection of arc faults is a severe challenge and determination of the appropriate corrective action is difficult. Arcs must be reliably detected, without causing false alarms. Different techniques can be applied, such as voltage, current, radiated energy or a combination of these. Taking corrective actions once the arc has been detected is next challenge. Thereby, use of Arc Fault Circuit Interrupters (AFCI) on the DC side of PV installations need to be further evaluated for preventing fire.

Grass fire in solar power plant is one of threat which is pose by uncontrolled wild growth as average size of solar power plant is on rise. Even though, there is periodic removal of grass during pre and post monsoon season. There is need to deploy advanced method to control wild growth and best practices like availability of fire protection and fighting equipment, provision of fire barriers, awareness training on fire related subjects.

POWER QUALITY ISSUES

In Grid connected solar power plant, Solar PV arrays are connected to Inverter (DC-AC converter) and then interconnected to the nearby power system network through power transformers. Theses power electronic components are responsible for current harmonic distortion and injecting the same into the grid. Moreover, there is a voltage fluctuation at the output of the solar PV system due to irradiation, partial shading effect (cloud) etc., which may pose a threat to power system network in terms of Power Quality (PQ) issues, voltage regulation and grid stability. Solar PV Generating stations are required to comply with prevailing technical and regularity frameworks to ensure safe, reliable and efficient operation of overall network.

Generally, Grid Tie Inverters (GIT) are designed for maintaining the power factor, reactive power as well as limiting the harmonics injection to grid and tuned properly. These inverters are provided with inbuilt harmonic filters and smoothing reactors for maintaining the reactive power and harmonics control. Moreover, these inverters are having automatic synchronization and de-synchronization (Isolator) with grid under various conditions such as failure of grid mains supply or exceeding/decreased grid voltage level or frequency than limits and tracking of maximum power generation (MPPT).

As per CEA Guidelines, Harmonic current injections from a generating station shall not exceed the limits specified in IEEE 519-2014 as per voltage level. it also states that maximum harmonic current distortion depends I_{sc} /I_L and measured with Class A compliance instrument at Point of Common Coupling (PCC). All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc} /I_L i.e. limit of 5% for TDD & 4% for individual odd harmonic components with orders less than 11. The DC injection shall be not more than 5% of full load rated current. Moreover, Total Demand Distortion (TDD) is recommended in place of THD for current quantities as the fundamental of the peak demand load current rather than the fundamental of the present sample (refer table 2 of IEEE 519); this creates point of confusion. Some STUs are demanding THD method for hormonic measurement.

The difference between the two is that TDD expresses harmonics as a percent of maximum demand load current (I_L) and THD expresses harmonics as a percent of fundamental current (I_1) at the time of the measurement. With THD, it may difficult to comply with harmonic limits during non-peak time. Moreover, application of these limits to Inverter level may be overkill as harmonic voltages and currents at these locations could be found to be significantly greater and get cancelled due to network configuration.

For flicker measurement, Pst - Perception of light flicker in the short term shall not be greater than 1 and observed over 10 minutes intervals and Plt - Perception of light flicker in the long term shall not be greater than 0.65 and observed over 12 Pst samples, as per IEC 61000-3-3 standards. However, in few cases, flicker more than the above limits are observed, which primary due to disturbance in connected grid.

Therefore, TDD need to be calculated based on fundamental component of maximum demand load current (IL) at PCC level and compare with limits specified in IEEE 519. For peak demand load current, max full load generated (recorder by Tariff energy meter) in the year may be taken for calculation.

LVRT COMPLIANCE & REACTIVE POWER MANAGEMENT

GTI are generally configured to operate in grid ‘voltage-following’ mode and to disconnect Distributed generation when the grid voltage moves outside set parameters, this is both to help ensure they contribute suitable power quality as well as help to protect against unintentional islanding. Where there are large numbers of Distributed generation systems or large distributed generation systems on a feeder, their automatic disconnection due to the grid voltage being out of range (Transient condition) can be problematic because other generators on the network will suddenly have to provide additional power.

To avoid this happening, voltage sag tolerances could be broadened and where possible, Low Voltage Ride-through Techniques (LVRT) and High Voltage Ride Through Technic (HVRT) could be incorporated into inverter design. LVRT or HVRT allows inverters to continue to operate for a defined period (Transient condition) if the grid voltage is moderately low or High but they will still disconnect rapidly if the grid voltage drops below a set level. In addition to the LVRT and HVRT function, grid support is also available. This means a possibility to support the grid by feeding capacitive reactive current to the grid, when the grid voltage stays below a defined area and feeding Inductive reactive current helps to reduce grid overvoltage, when the grid voltage stays above a defined area. Thus, connection standards need to be developed to incorporate and allow inverters to provide reactive power where appropriate, in a manner that did not interfere with any islanding detection systems.

On LVRT feature, Inverter manufactures claims that their inverters are evaluated and certified accordingly relevant IEC / local standard, to reveal the behavior of the generation unit during voltage dips and compliance with the corresponding grid codes. However, actual performance at field is not known and there are no standards to conduct such field test to verify site performance.

For reactive power management, a case study from one of our solar site is discussed. A typical PV solar plant operates on unity power factor during generation period. Small amount of reactive power injected/absorbed based on grid condition for stabilization. During night time, when the PV plant is down, small auxiliary power is drawn over the EHV transmission line. Tariff meter at Remote substation is installed for billing purpose towards import of power from grid to plant. During night time lightly loaded transmission line and HT cabling inside plant generates significant capacitive charging MVAR (PF varies between 0.1 to 0.3). Low power factor during night time attracts penalty and may result in high import bill.

Various solutions were brainstormed to reduce MD at non-generating hours like installation of shunt reactor or Battery storage system. However, these high capital-intensive schemes are under discussions for project viability. Re-programming of ABT meter for lagging PF only and not for leading PF was proposed, as is being followed in some states. But, concurrence / acceptance of STU is required. It was also noticed that different criteria are practiced for MD calculation by STU / DISCOM. Standardization of these practices across the country is the need of the hour as the country has ambitious plans for exponential growth in renewables in the future

UPKEEP & MAINTENANCE OF OUTDATED INVERTER SYSTEM:

Generally, GTIs come with 5 years warranty with full load efficiency of around 98%. However, utilities must be careful while selecting right inverter partner for their solar plant as reliability of inverters for solar generation is utterly important. As per OEMs, GTI can operate fault-free for 10 to 12 years (avg.) before major repairs or replacements become necessary. Despite of regular upkeep and maintenance at solar power plant sites, following issues are encountered leading frequent breakdown of Inverter system:

a) Frequent failures of components due to wrong scheme design and limited / sluggish protection devices
b) Non-availability of service / spares support
c) Close-down of parent company or discontinuation of product range
d) Harsh environment conditions (dusty, hot, saline & humid), poor ventilation system
e) Undetected / unattended ground faults on DC circuit
f) Non-availability of -ve grounding scheme and LVRT feature
g) Non-competency of site team to maintain outdated inverter system

Retrofitting / replacement of outdated inverter system by new and advanced inverter system complying with latest CEA regulations is only option left in such cases. Choosing right inverters and maintaining them by O&M team is extremely important for overall plant performance.

SOLAR MODULE RECYCLING / DISPOSAL:

One of key issue / challenge with Solar PV power plant to deal with defective solar modules which have been removed from service after physical damage, high degradation levels, diode failures, affected by lightning stocks / storm as well as after expiry of service life. As most of Solar PV power plants are commissioned 5-10 years, this e-waste issue may pose serious threat after 15-20 years. However, some of utilities are facing this problem due to high reject of defective solar modules.

Assuming that an average panel is sized 250 watt, 100 GW will generate almost 400 million nos. waste panels. It will generate tonnes of e-waste at the end of a lifetime (25 years) of a solar plant. The Ministry of Environment, Forest & Climate Change (MoEF & CC) notified the E-Waste Management Rules, 2016 in March this year. The rules were developed from the E-Wastes (Management and Handling) Rules, 2011. However, none of these policies include the methodology for proper disposal of solar cells.

Most of Indian manufacturers do not make solar cells but just assemble them. Very few companies are providing recycling of solar modules. Moreover, the solar PV recycling industry is capital intensive. Solar recycling is a cumbersome process because of the involvement of various elements like glass, aluminum, silicon, Copper, lead and polymer material and extracting these elements individually is an expensive and tedious process. In western part of world like US and EU, PV recycling industry is well established and best practices can be adopted to define necessary standards and process at our end.

CONCLUSION

In the recent past, substantial growth recorded in construction / commissioning of grid connected solar PV power plants. Moreover, Government as well as Utilities / developers will put more thrust to develop such solar power in future to meet India's solar mission. In this paper, various technical issues and challenges are discussed to represent utility prospective along with some mitigation plans. However, new strategies / resolutions at various levels like Govt. polices / Regulation, Standards / Certifications, Grid operation SOPs, Adoption of Design & engineering and Operation and Maintenance practices need to be developed collective to mitigate these risks effectively.

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The authors gratefully thank Ms. Anajali Kulkarni, Mr. Mahesh and Mr. Praveen Chorghade, Tata Power Company Limited for their guidance and encouraging us to write the above paper. We are also thankful to other colleagues, who have directly / indirectly contributed in the above compilation.

REFERENCES

[1] National / International standards (IS, IEEE, IEC) & CEA regulation on DG and connectively to grid

[2] Tata Power's CFT reports, Degradation study reports & Power Quality test reports

[3] Fire and solar PV systems – Literature Review by BRE National Solar Centre July'17

[4] White paper by Waaree Energies Limited and AE Solar Energy, USA on Solar degradation

[5] Report on "All-India Survey of Photovoltaic Module Reliability: 2013, 14 & 16

[6] Articles from Solar Power World magazine on solar plant fire hazards

[7] Websites of Solar Panel Manufactures and other information available in public domain

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Market Experience of White Certificates in India

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ABSTRACT – Amidst the global concerns of climate change, energy security and reduction of energy intensity, the governments all over the world have emphasised the use of renewable energy and adopted the policies for energy conservation for sustainable development. To provide legal framework and institutional arrangements for enhancing energy efficiency, Energy Conservation Act was enacted by Government of India in 2001. Further, Government of India has launched National Action Plan on Climate Change (NAPCC) to address the impact of climate change. Under NAPCC, National Mission on Enhanced Energy Efficiency (NMEEE) was launched and one of the identified components of the NMEEE is Perform, Achieve and Trade (PAT) scheme. Under PAT Scheme, targets are assigned to energy intensive industries. The industries that save energy over and above their assigned targets – are issued Energy Saving Certificates (ESCerts) and those having shortfall are obligated to purchase ESCerts from Power Exchanges. In the international context, ESCerts is also referred as 'White Certificate', Energy Efficiency Credit (EEC), or white tag. White Certificate is considered to be an instrument issued by an authorized body guaranteeing that a specified amount of energy savings has been achieved. Each certificate is a unique and tradable commodity carrying an ownership right over a certain amount of additional energy savings and guaranteeing that the benefit of these savings has not been accounted for elsewhere. This paper discusses about the Policy framework and Regulatory framework for transaction of the 'white certificates' i.e. ESCerts as per Central Electricity Regulatory Commission (CERC) Regulations through Power Exchanges. Further, this paper discusses about the experience of trading of ESCerts, challenges and way forward in subsequent cycles.

KEY WORDS: Perform Achieve and Trade (PAT), Cycle, Specific Energy Consumption, White Certificates, Energy Saving Certificates (ESCerts), Designated Consumers (DCs), Eligible Entity, Market Regulator, Registry, Administrator, Power Exchanges, Banking, Extinguishment.

1. INTRODUCTION – The development of every country on account of industrial development, office automation, population explosion and evolving lifestyle aspirations, etc. are inevitable and demand of energy will be ever increasing to supplement the same. The important challenge of meeting the demand of energy, in this world of depleting conventional resources, can be addressed traditionally by boosting supply side on one hand i.e. adding conventional, non-conventional (renewable) sources of generation and effective demand management i.e. exploration of innovative technologies for energy saving and energy efficiency etc. It is rightly said that energy saved is energy generated, therefore efficient use of energy in the various processes from input to output to save the energy are being emphasised by the stakeholders. The limitation on the addition of conventional sources of energy has been governed by limited stocks in the world store of fossil energy. Solution lies in tapping and increasing penetration of renewable sources of energy, increasing energy efficiency, effective demand management in the demand side.

To improve the energy conservation, the Energy Conservation (EC) [1] Act was enacted in 2001 enjoining the Government of India and the Bureau of Energy Efficiency (BEE) [2] with the goal of reducing energy intensity and to promote the energy efficiency through innovative policies, market instruments, without compromising the pace of development of the Indian economy.

National Mission on Enhanced Energy Efficiency (NMEEE)[3] was undertaken by the Indian government to promote the energy efficiency in all sectors of the economy. One of the identified components of the NMEEE is Perform, Achieve and Trade (PAT) [4] Scheme. PAT scheme is designed to reduce Specific Energy Consumption (SEC) of designated consumers (DCs) across energy intensive industries. PAT is a compliance-based scheme under which targets are assigned to energy intensive industries. The industries that save energy over and above their assigned targets – are issued Energy Saving Certificates (ESCerts) and those having shortfall are obligated to purchase the ESCerts from Power Exchanges.

In PAT Cycle – I (2012-15), 478 notified designated consumers (DCs) from 8 energy intensive sectors, were mandated to save energy equivalent to 6.7 million tonne equivalent of energy. At the end of the cycle, an energy saving of 8.7 million tonne equivalent of energy (about 30% over achievement) was achieved, equivalent to 31 million tonnes of CO_2 emission reduction, avoidance of generation of about 5,635 MW and resultant monetary savings of INR 95,000 Million (~1,410 Million USD) which encouraged investment of INR 245,170 Million (~3638 Million USD) in energy intensive sectors. [INR 1 ~ 0.015 USD]

Perform Achieve and Trade (PAT) scheme has also been included in India's Intended Nationally Determined Contribution (INDC) as a market mechanism along with other instruments to address the impact of the climate change.

2. POLICY AND REGULATORY FRAMEWORK FOR TRANSACTION OF ESCerts

2.1. PAT Rules:

The Government of India has notified the Energy Conservation (Energy Consumption Norms and Standards for DCs, Form, Time within which, and Manner of Preparation and Implementation of Scheme, Procedure for Issue of ESCerts and Value of Per Metric Ton of Oil Equivalent of Energy Consumed) Rules, 2012 also referred as the PAT Rules, 2012 [5].

In the PAT Scheme, the Ministry of Power [6], Government of India is involved in notification of statutory orders and issuance of ESCerts. The Central Electricity Regulatory Commission (CERC) [7] is involved in regulatory framework and acts as Power market regulator. Further BEE, the statutory body established by the Government of India, for energy efficiency implementation is also referred as Administrator. Under PAT scheme, National Load Dispatch Centre (NLDC) operating under Power System Operation Corporation Limited (POSOCO) has been notified by the Government of India, to function as Registry for ESCerts [8].

The ESCerts are to be transacted on CERC approved Power Exchanges (PXs) i.e. Indian Energy Exchange (IEX) [9] and Power Exchange India of Limited (PXIL) [10]. Any consumer notified a Specific Energy Consumption target under the statutory orders issued by the Government of India, from time to time is referred as Designated Consumers (DCs). Any DC registered successfully with Registry, for securing eligibility to transact (buy / sell) ESCerts at the notified PX(s) is referred as Eligible Entity (EE).

PAT scheme is implemented by BEE under overall supervision of Ministry of Power. PAT Scheme has been implemented in stages called Cycles covering a three-year period for implementation, followed by assessment and compliance of energy efficiency achieved by the DCs, in various identified sectors of the energy intensive industry.

The ESCert Issuance Scheme design involves three stages:

Target Setting Stage involving the setting of SEC target for each DC on the basis of their current energy intensity. The target specifies the percentage reduction of current SEC, by which a DC has to reduce its energy intensity in a 3-year period.

Reduction/ Implementation and Assessment Stage wherein the DC(s) tries to reduce its energy intensity through adoption of energy efficiency measures/ technologies/ process amendments / improvisation, according to the set target. This is called Perform and Achieve phase. The quantified energy savings / shortfall is converted into Energy Saving Certificates (ESCerts). Each ESCert is equivalent to one metric ton of oil equivalent of energy (mtoe). [1ESCert≈1 mtoe≈11,630 KWh≈11.63 MWh] [11]. Monitoring and verification of energy savings i.e. achieved SEC, is conducted by empanelled Accredited Energy Auditors(AEAs) firms through a transparent process as prescribed under PAT Rules.

The above stated design of the scheme and implications on the entities is depicted in the following figures.

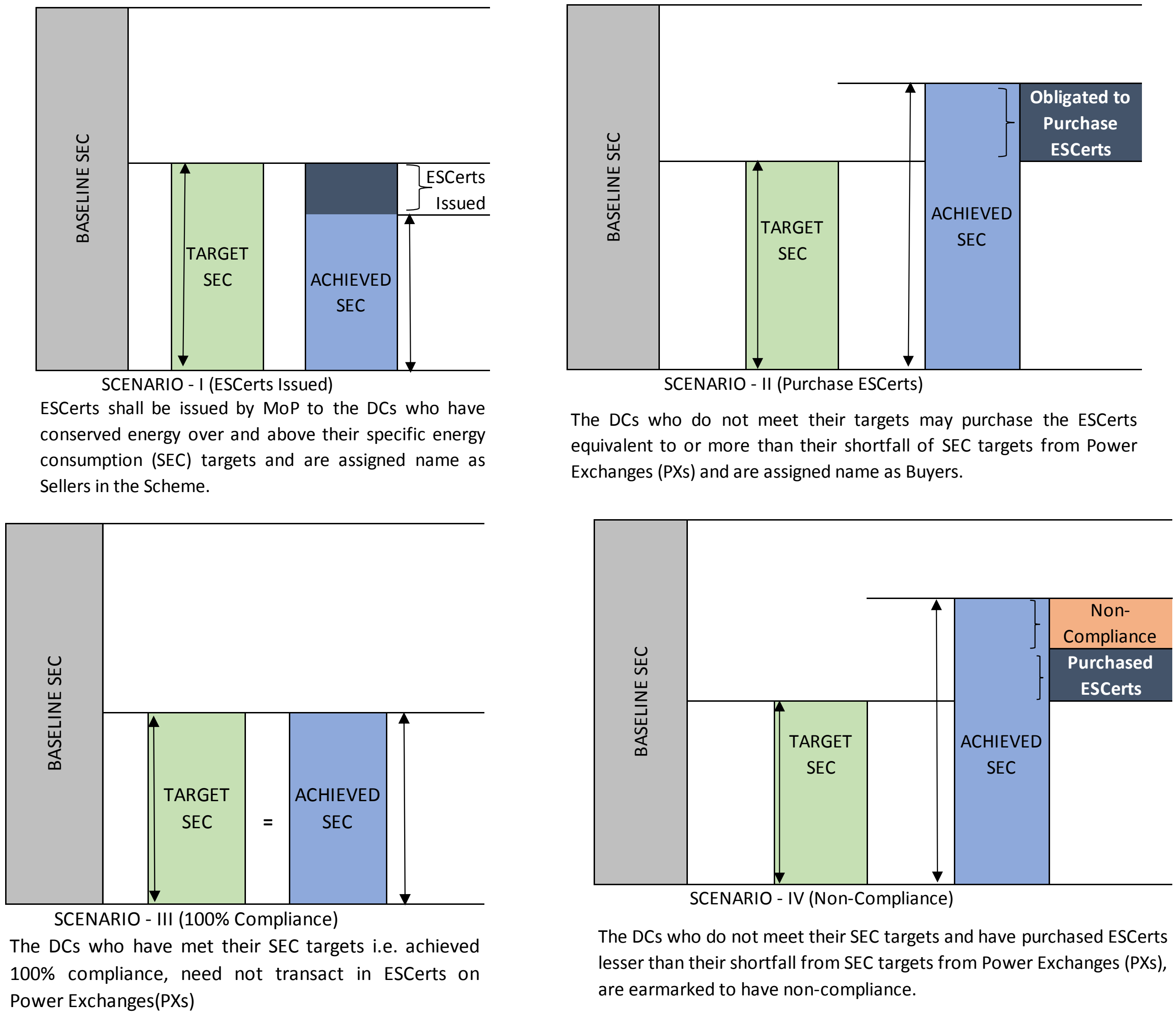

Fig. 1: Illustration of scenarios for ESCert Issuance / Obligation to purchase

Transaction (Trading) Stage is the final phase where the DC(s) who have saved over and above their target and registered with Registry, may trade their ESCerts through PXs. On the other hand, those DC(s) who have shortfall of mandated SEC, in lieu of the energy savings, can get registered with Registry and purchase of ESCerts through PX(s) to comply with their SEC in terms of mandated number of ESCerts. In case the DC(s) fail to comply with their mandated SEC, a penalty will be levied on the DC(s) as per provisions of the EC Act, 2001.

2.2. CERC Regulations and Procedures for transaction of ESCerts:

CERC has been assigned the function of market regulator by the Ministry of Power. Accordingly, CERC has notified the Regulations and Approved procedures submitted by BEE in consultation with Registry.

2.2.1 ***CERC Regulations and Orders***:

CERC has notified the Central Electricity Regulatory Commission (Terms and Conditions for Dealing in Energy Saving Certificates) Regulations, 2016 [12], also known as Energy Savings Certificates Regulations, 2016, for the development of market in energy for exchange of transferable and saleable ESCerts.

Further, CERC has notified the Determination of Fee and Charges payable to Registry by the DCs to become Eligible Entity (EE) for trading of ESCerts through PXs [13] [14].

2.2.2 ***CERC approved procedures:***

CERC has approved the detailed procedures prepared by POSOCO as a Registry and BEE for (i) Registration *of a DC; (ii) Interface activities among PXs, Registry and Administrator and (iii) Dealing of ESCerts, Transfer and Other residual matters* [15]. Important provisions of the procedures are given below:

a) Registration of a DC with Registry as Eligible Entity

The DCs have to register successfully with the Registry i.e. NLDC operating under POSOCO, as Eligible Entities (EE), through a web portal [16] for eligibility to trade ESCerts at the PX(s). Procedure for application, fee and charges to be paid by DCs and various timelines for each specified and involved activities have been spelled clearly in CERC approved procedures. However, the registration of DCs with Registry is not mandatory.

b) ***Interface activities between PXs and Registry, Administrator and Registry and Registry and DCs***

The various activities among PXs, Registry, Administrator and DCs have been represented in the Fig. 2. Two interlinked web portals have been implemented – one portal known by name of 'PATNet' meant for Administrator's interface with DCs and the other independent portal for interface among the three agencies i.e. Administrator, Registry and Power Exchange(s).

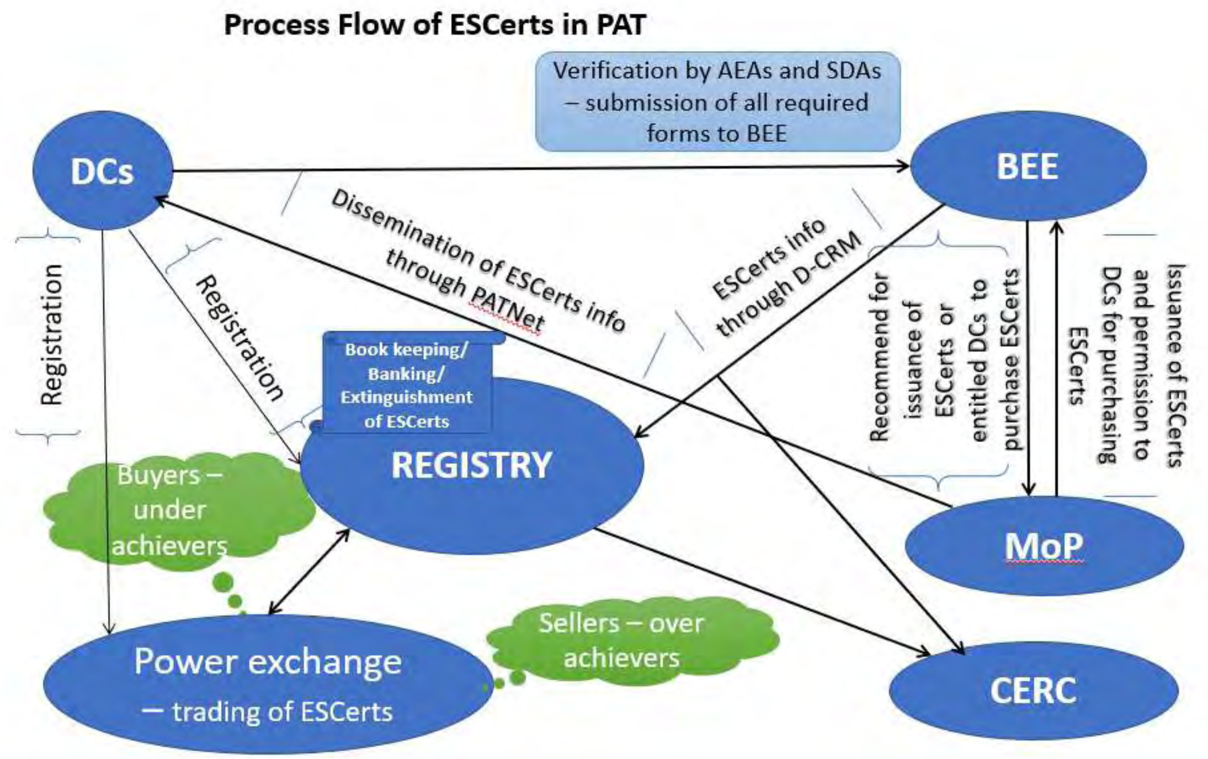

Fig. 2: Flow of various processes of ESCerts between different stakeholders in PAT

c. Dealing of ESCerts, Transfer and Other residual matters

Transaction of ESCerts on PX(s):

ESCerts shall be available for dealing in accordance with the rules and bylaws of the PX(s). In any trading session, the Registry cross-checks the sale bids placed on PX(s), validity of ESCerts with the availability of ESCerts in respective Registry account(s) of the respective entity. In case of any violation, during the particular trading session, Registry intimates the same to PX(s) and such bids become void and ineffective. Such entities are notified as 'Defaulters'. In cases of repeat of such instances on three cases of default, the entity is barred from transaction of ESCerts for next six months, notwithstanding any penalty due to be imposed as per the provisions of the EC Act, 2001.

Salient points of transaction of ESCerts on Power Exchanges:

a. Each ESCert has a unique ESCert serial number
b. The unique serial number assigned once for an ESCert to particular Eligible Entity shall remain same throughout the validity of the ESCert.
c. The validity of the ESCert is up to the compliance cycle of the next PAT Cycle.
d. The ESCerts once purchased can't be resold i.e. an ESCert can be traded only once, in the life cycle.
e. Bilateral trading of ESCerts is not permitted under the Regulations.
f. The frequency of transaction of ESCerts through Power Exchanges was notified to be on weekly basis, on every Tuesday for PAT Cycle - I.
g. Trading was held on only one Power Exchange i.e. IEX as the trading platform of PXIL was not ready.

The flow of activities for transaction of ESCerts and the defined timelines have been represented in Fig. 3.

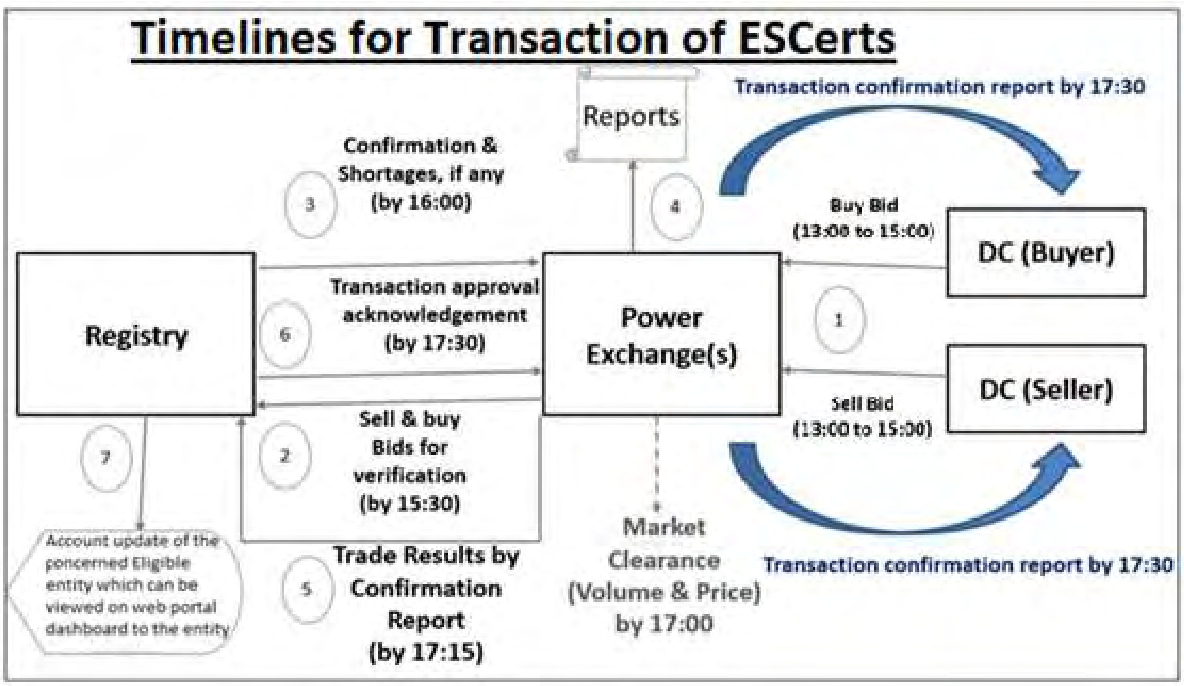

Fig. 3: Timelines for Transaction process of ESCerts

The Market Clearing Price(MCP) and the Market Clearing Volume(MCV) is discovered through a closed bid double-sided auction mechanism at the PX(s). On successful transaction on PX(s), the Registry accounts of the Eligible Entities shall be updated, whereby the sellers' accounts are debited and the buyers' account are credited.

The Sellers who have been issued ESCerts can trade their ESCerts during the current cycle or may use them for the purpose of banking. *Banking* is the process of retaining the ESCerts in their respective accounts of the Eligible entities till the next compliance cycle after which the validity of the ESCert stands expired.

On the other hand, the Buyers as eligible entities who have been advised to buy ESCerts can buy equal or more than the mandated number of ESCerts during the current cycle. The mandated number of ESCerts gets extinguished after compliance.

Extinguishment is the process of nullification of the ESCerts against the mandated target number of ESCerts to be bought for compliance. The balance (if any) may be used for the purpose of banking until the next compliance cycle after which the validity of the ESCert stands expired.

3. ANALYSIS OF ESCert MARKET IN PAT CYCLE-I:

Registry had successfully registered a total of 374 Eligible entities - 273 Sellers and 101 Buyers till the last session for trading for compliance as notified by BEE. The numbers of entities and ESCerts notified versus registered with Registry has been summarised in following Table No. 1.

Table 1: Summary of Number of entities and ESCerts notified versus registered with Registry

Description	Buyers	Sellers
Number of DCs notified by MoP	110	306
Number of DCs registered with Registry to become Eligible Entities(EE)	101	273
Number of ESCerts notified by MoP	1,423,007	3,824,999
Number of ESCerts registered with Registry	1,333,808	3,755,699

Registration of DCs as Eligible Entities versus notified Designated Consumers across the Indian states, arranged in increasing order of percentage of registration with Registry:

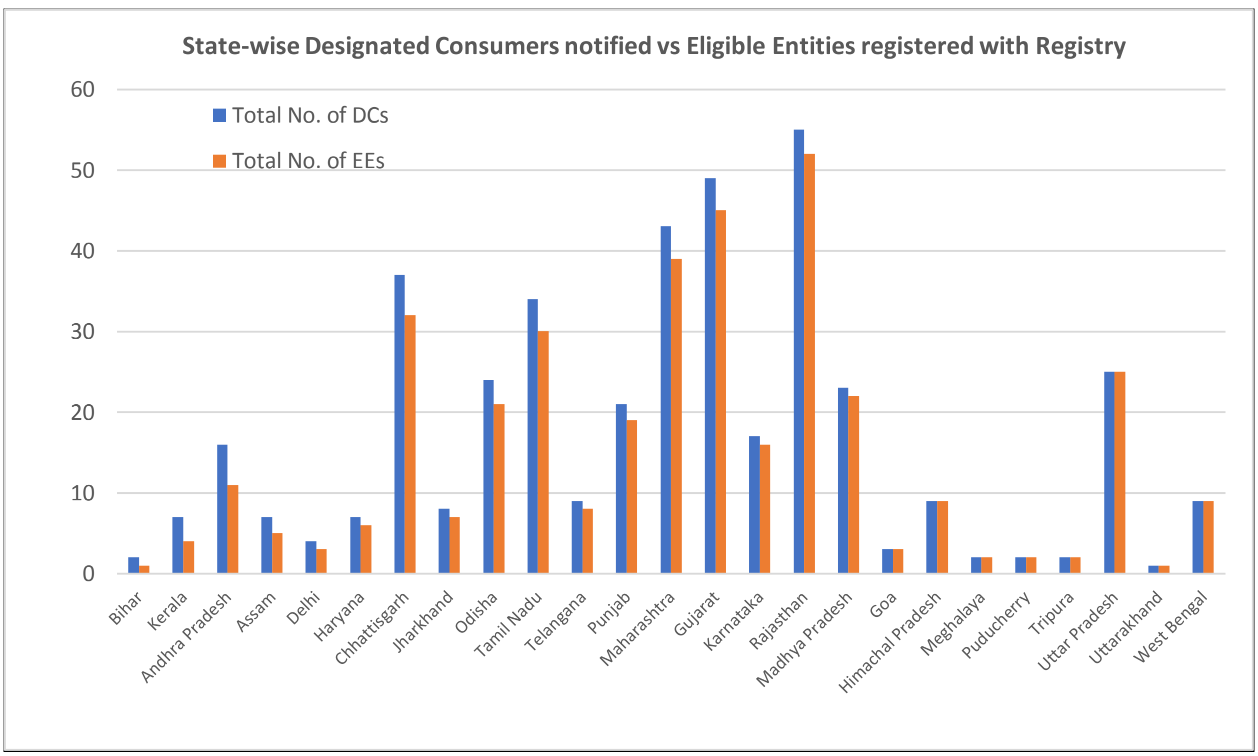

Fig. 4: State wise representation of notified DCs versus registered EEs

As per PAT Rules, Registration is not mandatory, therefore, there was a difference between the number of DCs notified by MoP and the number of EEs registered with Registry for attaining eligibility for transaction of ESCerts on PX.

Likewise, there was a difference between the number of ESCerts notified by MoP and the number of ESCerts registered with Registry for transaction on PX(s).

Following Fig. 5 demonstrates the number of ESCerts registered for transaction versus the number of ESCerts transacted on IEX, across the Indian states:

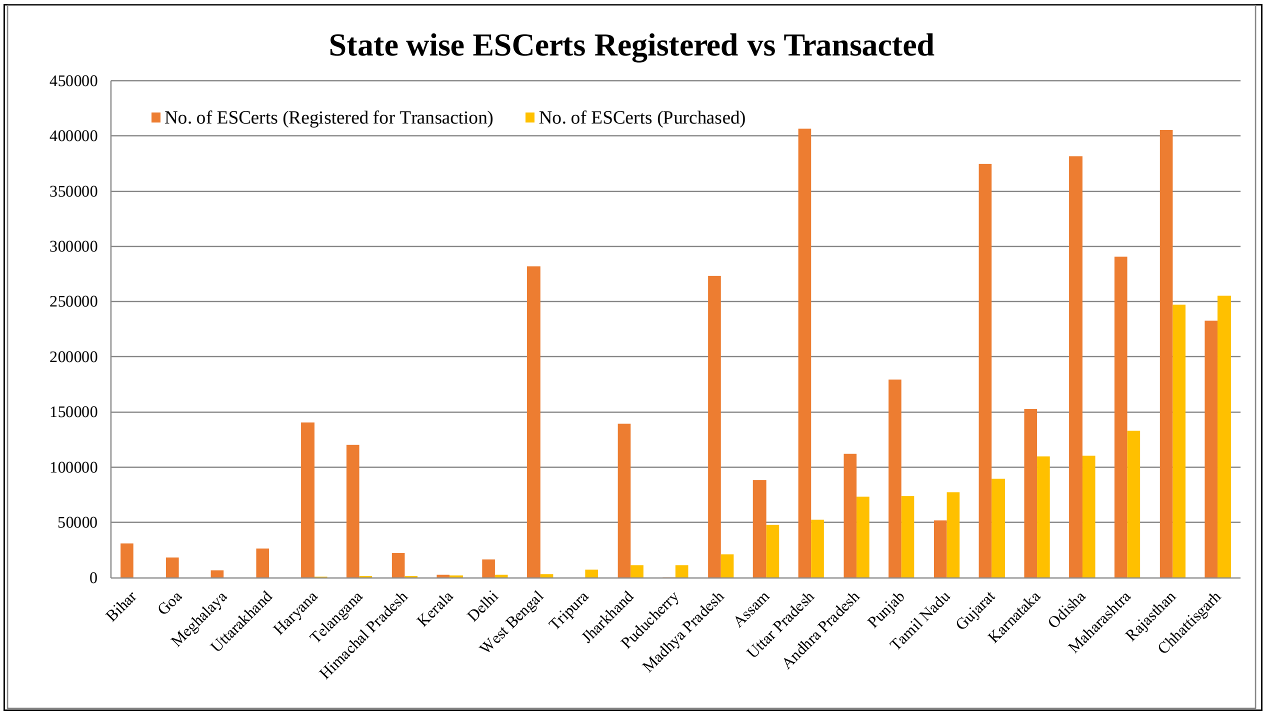

Fig. 5: State wise representation of status of number of ESCerts Registered versus transacted

MCP and MCV over the17 trading sessions at IEX

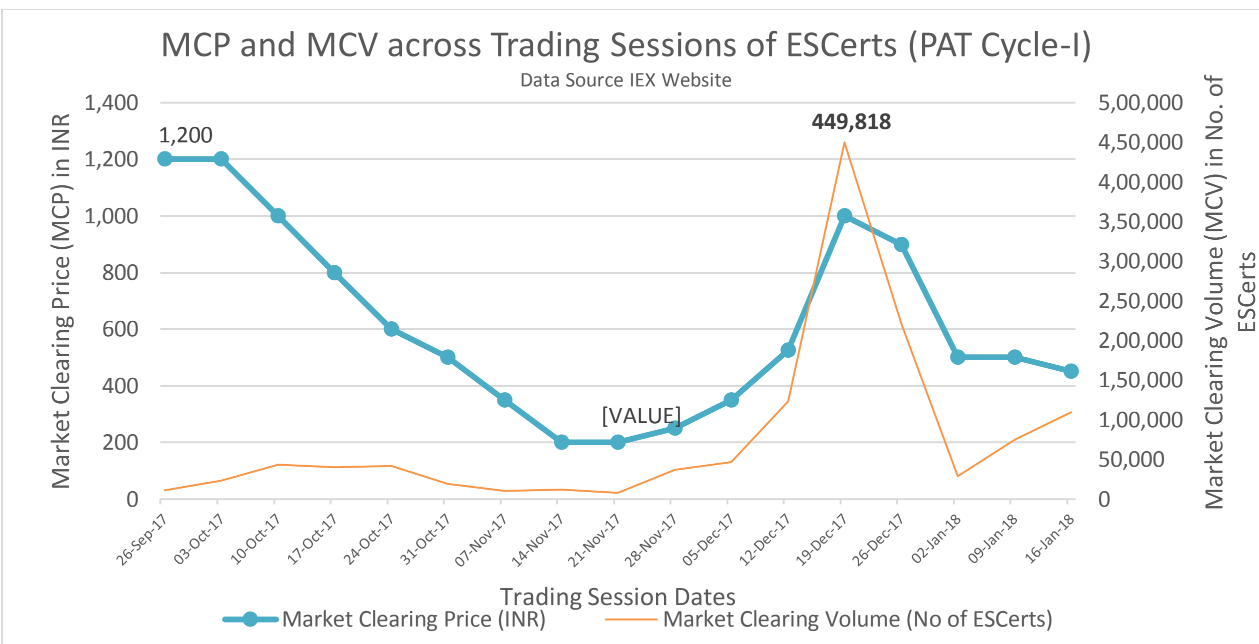

Fig. 6: Price Discovered and Volume of ESCerts transacted over the trading sessions

- The Fig 6 above illustrates the variation of MCP and MCV over the 17 Trading sessions were successfully held in PAT Cycle-I.
- As there was surplus in the availability of the ESCerts i.e. 3,824 Thousand (approx.) ESCerts available for transaction against a demand of 1,423 Thousand (approx.) ESCerts, the price in the initial trading sessions commenced from the value of INR 1,200 (~17.81 USD), which was recorded as the maximum price discovered for PAT Cycle – I.

- Over the series of trading sessions, the price discovery was governed by the Buyer's bid price, as was most likely, due to the three-fold abundance of ESCerts against the purchase mandate and even recorded a low of INR 200 (~2.97 USD).
- Volume of transacted ESCerts gained momentum, as the deadline for compliance was drawing to a close. Maximum volume of ESCerts recorded was 449,818 ESCerts, transacted on the thirteenth trading session.
- A cumulative of 1,298,904 ESCerts were transacted during the trading sessions, accounting for transactions to the tune of INR 998.2 Million (~15 Million USD) and a balance inventory of 2,456,795 ESCerts out of the registered numbers.

Sector wise break-up of transaction of ESCerts:

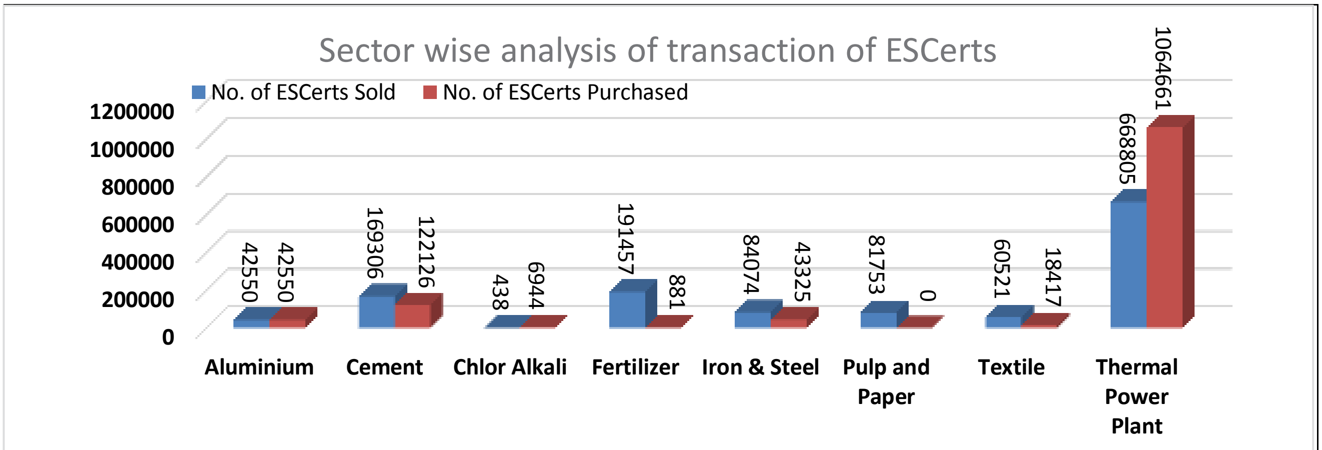

Fig. 7: Sector wise analysis of transaction of ESCerts

- 91.28% Compliance achieved in PAT Cycle – I.

Graphical representation of the state wise compliance

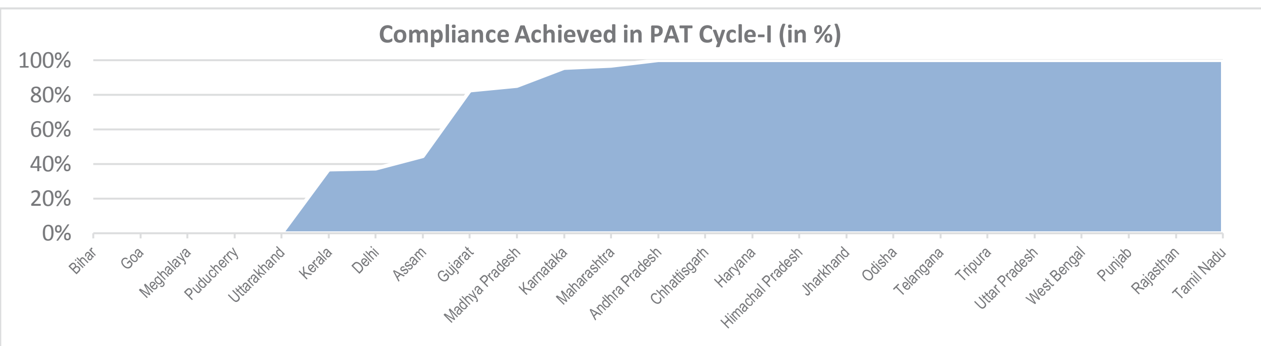

Fig. 8: Compliance scenario across Indian States

Sector wise representation of compliance

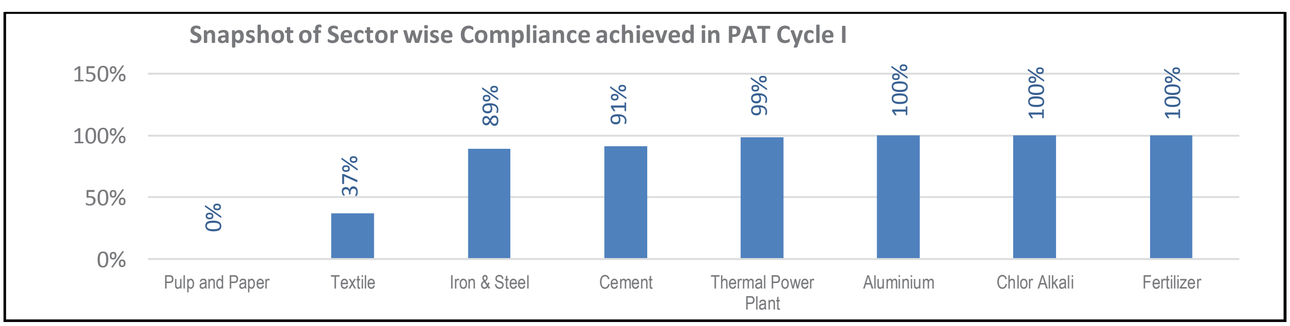

Fig. 9: Sector wise Compliance by the Registered entities

As per provisions of Energy Conservation Act, the compliance mechanism for energy efficiency is in place, and following penalty may be imposed on DCs for non-compliance of the mandated targets:

a) Maximum penalty of INR 1 million [~ 14,839.72 USD]
b) Additionally, value of shortfall in achieving target SEC in terms of Price of per metric ton of oil equivalent of energy consumed in a particular assessment year i.e. (Shortfall in Number of ESCerts obligated to purchase to comply with the target) x 10,968 INR.

Sector wise Achievements against notified targets for PAT Cycle –I, have been tabulated below in Table 2:

Table 2: Sector wise Energy Reduction Target vs Achievements for PAT Cycle – I

Sl. No.	Sector	No. of DCs	Annual Energy Consumption for the DC (million ton of oil equivalent)	Energy Reduction Target for PAT Cycle - 1 (million ton of oil equivalent)	Achievements / Savings (million ton of oil equivalent)
1	Aluminium	10	7.71	0.456	0.73
2	Cement	85	15.01	0.815	1.48
3	Chlor-Alkali	22	0.88	0.054	0.09
4	Fertilizer	29	8.2	0.478	0.78
5	Iron & Steel	67	25.32	1.486	2.1
6	Pulp and Paper	31	2.09	0.119	0.29
7	Textile	90	1.2	0.066	0.13
8	Thermal Power Plant	144	104.56	3.211	3.06
Total		**478**	**165**	**6.7**	**8.7**

4. CHALLENGES AND WAY FORWARD

4.1 *Infrastructure (Software / Hardware/ Human Resource):*

Registry experienced few challenges during the development of the software to facilitate the trading of ESCerts and to execute the functions as per CERC Regulations. However, the experienced gained during the design and development of the software will be utilised in the upcoming PAT Cycles with regard to trading of ESCerts over multiple Power Exchanges, accounting of ESCerts e.g. fresh issuance, banking, extinguishment, tracking of validity of ESCerts etc.

4.2 *Capacity Building:*

It has been observed that capacity building workshops should be organised more frequently to increase the awareness about various rules, regulations and procedures among stakeholders.

4.3 *Gap in Demand and Supply of ESCerts:*

ESCerts available for sale is more than the demand. It has biased the discovery of price in favour of buyers. Moreover, voluntary buyers are not allowed to purchase at this stage in the scheme. Therefore, development of voluntary market in future will improve the price discovery as well as cleared volume of ESCerts.

4.2 *Deepening and Widening of PAT Scheme:*

The Parliamentary Standing Committee on Energy, Executive Committee on Climate Change under Prime Minister’s Office (PMO) and Group of Secretaries have recommended accelerated coverage of DCs under PAT, in a progressive manner, on a rolling cycle basis. Deepening i.e. inclusion of more entities from existing notified sectors and widening of the Scheme i.e. inclusion of new sectors and entities, have been undertaken by the BEE. Relevant snapshot is reproduced in following Table 3.

Table 3: Snapshot of Rolling Cycles Notified in PAT:

Sl No	PAT Cycle Details	Period (Year)	No. of DCs	No. of Sectors	Energy Reduction Target (million ton of oil equivalent)	Remarks
1	PAT Cycle – II	2016-19	621	11	8.9	03 new sectors viz. Railways, Refineries and DISCOMs notified, avoidance of about 5,764 MW of demand
2	PAT Cycle – III	2017-20	116	6	1.1	06 existing sectors viz. Thermal Power Plant, Cement, Aluminium, Pulp & Paper, Iron & Steel and Textile
3	PAT Cycle – IV	2018-21	109	10	0.69	8 sectors of PAT Cycle – I & 02 new sectors i.e. Petrochemicals and Commercial buildings (Hotels) notified

In the forthcoming days, sustainable energy policies world-over are discussing ideas for reshaping energy systems amalgamated with concerns for climate change, fungibility of RECs and ESCerts in terms of Certified Emission Reductions (CERs)/ Carbon credits with perspectives of international market.

ACKNOWLEDGEMENT

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REFERENCES

[1] Energy Conservation Act, 2001- https://powermin.nic.in/sites/default/files/uploads/ecact2001.pdf
[2] Bureau of Energy Efficiency- https://beeindia.gov.in/
[3] National Mission for Enhanced Energy Efficiency - https://beeindia.gov.in/content/nmeee-1
[4] Perform, Achieve and Trade (PAT)- https://beeindia.gov.in/content/pat-3
[5] PAT Rules, 2012- https://beenet.gov.in/UI_Forms/Registry/Registry_Doc/PAT_Rules_English.pdf
[6] Ministry of Power- https://powermin.nic.in
[7] Central Electricity Regulatory Commission- http://cercind.gov.in
[8] Registry for ESCerts - https://beenet.gov.in/UI_Forms/Registry/default.aspx
[9] Indian Energy Exchange- https://www.iexindia.com
[10] Power Exchange of India Ltd.- http://www.powerexindia.com
[11] International Energy Agency – equation of mtoe, MWh- http://www.iea.org/statistics/resources/unitconverter/
[12] Central Electricity Regulatory Commission, (Terms and Conditions for Dealing in Energy Saving Certificates) Regulations, 2016 -http://cercind.gov.in/2016/regulation/G_124.pdf
[13] Determination of Fee and Charges payable under Regulation 12 of the Central Electricity Regulatory Commission (Terms and Conditions for Dealing in Energy Savings Certificates) Regulations, 2016 - https://beeindia.gov.in/sites/default/files/CERC%20Fee%20order_24th%20March%202017.pdf
[14] Amendment to Determination of Fee and Charges payable under Regulation 12 of the Central Electricity Regulatory Commission (Terms and Conditions for Dealing in Energy Savings Certificates) Regulations, 2016 - https://beeindia.gov.in/sites/default/files/CERC%20fee%20order%2019%20May%202017.pdf
[15] Central Electricity Regulatory Commission, Approved Procedures for transaction of ESCerts - http://cercind.gov.in/2016/regulation/Final%20Procedures_ESCerts.pdf
[16] Web portal for Registration of DCs (PATNet) - https://beenet.gov.in/UI_Forms/General/Login.aspx

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CIGRE- AORC Technical Meeting 2018 – International Conference on Global Energy Transition – Issues and Challenges, 24-25 May 2018, Gangtok, Sikkim, India

New Maintenance Technology for Defective Gusset-Plate of Steel Tower

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SUMMARY

Lamination has been confirmed in the gusset-plate of transmission towers manufactured in Japan from 1950 to 1960. Lamination is a phenomenon in which water and salt penetrate into the interior of the gusset-plate due to inclusions and bubbles contained in the steel material manufactured by the ingot making method and rust develops, resulting in peeling into two sheets. Laminations were found on 275 kV, double circuits and 154 kV, single circuit overhead transmission lines. The defective gusset-plate that connected the cross arm for the ground wire and the steel tower body was removed without disassembling the cross arm due to small load from the ground wire. The residual tensile strength of the removed defective gusset-plate was evaluated. The defective gusset-plate that caused the lamination was slightly deteriorated and sufficient gusset-plate thickness and tensile strength remained, but there was concern that required tensile strength would be insufficient due to progress of deterioration. Lamination also occurred in the gusset-plate connecting the cross arm for conductor and the steel tower body. In order to replace this defective gusset-plate, it was necessary to remove the conductor and dismantle the cross arm. However, due to heavy load, it is impossible to stop the two circuits of transmission lines simultaneously for a long time, it was necessary to establish a construction method to replace the defective gusset-plate without removing the conductor and disassembling the cross arm.

First of all, since the defective gusset-plate is replaced without disassembling the cross arm under one circuit energized condition of the transmission line, the load applied to the defective gusset-plate was calculated by three-dimensional structure analysis.

Next, a jig for reducing the load applied to the defective gusset-plate was developed. The conductor load was simulated on a newly constructed real scale model tower, and the working procedure and safety of a defective gusset-plate replacement method using a jig was verified. In addition, a repairing method was studied to prolong the defective gusset-plate that can not be replaced. These specimens simulated lamination were repaired to fill the gaps with the three selected materials and they were subjected to a cold cycle / wet test to verify the tightness of the gap in the specimen. As a result, metal patty which had the best tightness was selected as a repair material. The defective gusset-plate which was removed by lamination was repaired by this selected material and subjected to an accelerated deterioration test. Based on the test results, it was confirmed that the metal putty satisfies the required performance as a repair material. As a result of these series of R & D, the construction method which can replace the defective gusset-plate plate without disassembling the cross arm under one circuit of the transmission line energized condition and repair method to suppress progression of lamination and prolong the life of gusset-plate were established. These technological developments contribute to shortening the outage of transmission lines and reduce maintenance cost of steel towers.

KEYWORDS
Lamination, Defective gusset-plate replacement, Real scale model tower, Jig, Accelerated deterioration test, Metal patty, Reduce maintenance cost

1. INTRODUCTION

Lamination was found on the gusset-plate connecting the cross arm and tower body in the transmission tower built in the 1950s and 1960s. In replacing the defective gusset-plate, it was necessary to remove the conductor from the cross arm and to dismantle the cross arm. However, because it was impossible to stop two circuits of the transmission line simultaneously for a long time, we had to establish a defective gusset-plate replacement method which does not remove the conductor and replaces the defective gusset-plate without dismantling the cross arm. First of all, a jig for replacing a defective gusset-plate under one circuit energized condition without disassembling the cross arm. Then, a full scale model steel tower was built in the factory, and the existing steel tower was imitated by applying the load from the conductors, and the work procedure and safety of the defective gusset plate replacement method using the developed jig were verified.

Next, a repairing method was studied to prolong the life of defective gusset plates that cannot be replaced. Metal putty, which had the best tightness to lamination among three different materials, was selected as repair material. As a result of repairing the defective gusset plate removed by lamination with metal putty and carrying out the accelerated deterioration test, it was confirmed that the metal putty satisfied the required performance as repair material. In this paper, we will introduce the results of these research and development and the results applied to existing steel towers.

2. Lamination phenomenon of gusset-plate

Lamination of the gusset-plate refers to a phenomenon in which a part of the steel plate is peeled off thinly. At present, in the production of general steel materials, contamination of oxide-based or sulphide-based impurities and bubbles is suppressed by the continuous casting method, and the defect occurrence rate by them is controlled.
It was thought that the ingot production method was used for the production of the steel of the overhead transmission line (completed in 1960 and 1963) where the lamination was found. The term "ingot making method" refers to steel manufacturing method in which molten steel cast in a predetermined mould is poured and solidified as it is to form a steel ingot. According to the manufacturing method of the ingot making method, defects due to impurities and bubbles in the steel material may occur. Representative defects occurring in the ingot making method include contamination of impurities and bubbles, segregation (uneven distribution of impurities).
Figure 3 shows mechanism of lamination corrosion.

Figure 1 Lamination example (Gusset-plate connecting the cross arm and steel tower body for 275 kV transmission line)

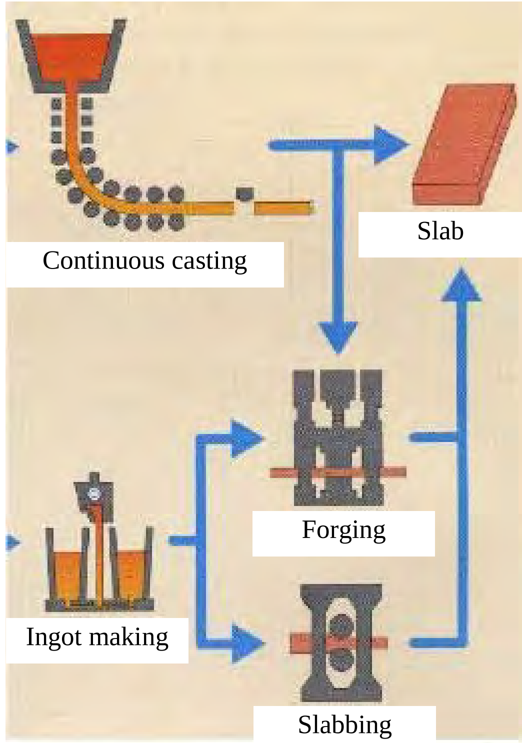

Figure 2 Ingot making method and Continuous casting method

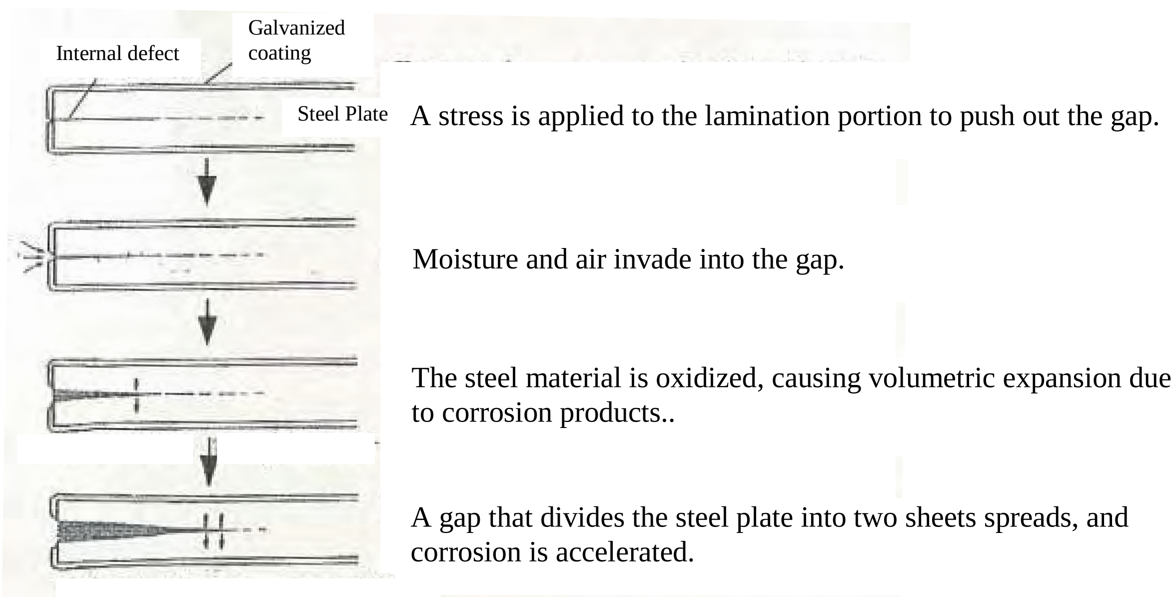

Figure 3 Mechanism of lamination corrosion

3. Mechanical performance of gusset plate with lamination

Detailed plate thickness measurement of the entire gusset plate with lamination is difficult because there are obstacles such as bolts. However, in order to calculate the bearing pressure strength of the gusset-plate with lamination, it is essential to estimate the thickness of the gusset-plate.

Therefore, thickness measurement of gusset-plate with lamination which was removed in the past by ultrasonic inspection was carried out. As a result, the gusset-plate thickness of the lamination part was as low as 7.8% at the maximum, and it was evaluated that there was no remarkable decrease in the mechanical strength of the gusset-plate with lamination. Figure 4 and 5 show the example of ultrasonic diagnosis results. According to Figure 5, it can be seen that lamination occurs in the entire-gusset plate.

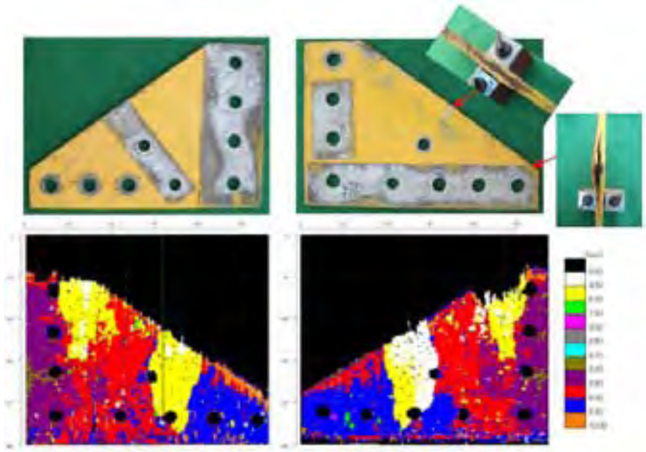

Figure 4 Example of ultrasonic diagnosis result of gusset-plate with lamination

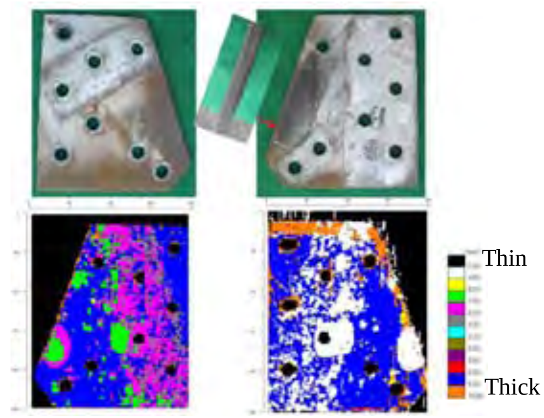

Figure 5 Example of ultrasonic diagnosis result of gusset-plate with lamination

4. Verification of lamination gusset plate replacement method

The defective gusset-plate that caused the lamination was slightly deteriorated and sufficient gusset-plate thickness and tensile strength remained, but there was concern that required tensile strength would be insufficient due to progress of deterioration. Lamination also occurred in the gusset-plate connecting the cross arm for conductor and the steel tower body.

In order to replace this defective gusset-plate, it was necessary to remove the conductor and dismantle the cross arm. However, due to heavy load, it is impossible to stop the two circuits of transmission lines simultaneously for a long time, it was necessary to establish a construction method to replace the defective gusset-plate without removing the conductor and disassembling the cross arm.

First of all, the load applied to each tower member including the defective gusset plate was calculated by three-dimensional structure analysis.

Next, a real scale steel tower simulating four panels including the bottom cross arm was built, and the targeted stress (axial force) was applied to the wire rope attached as shown in Figure 6 so as to act on each member.

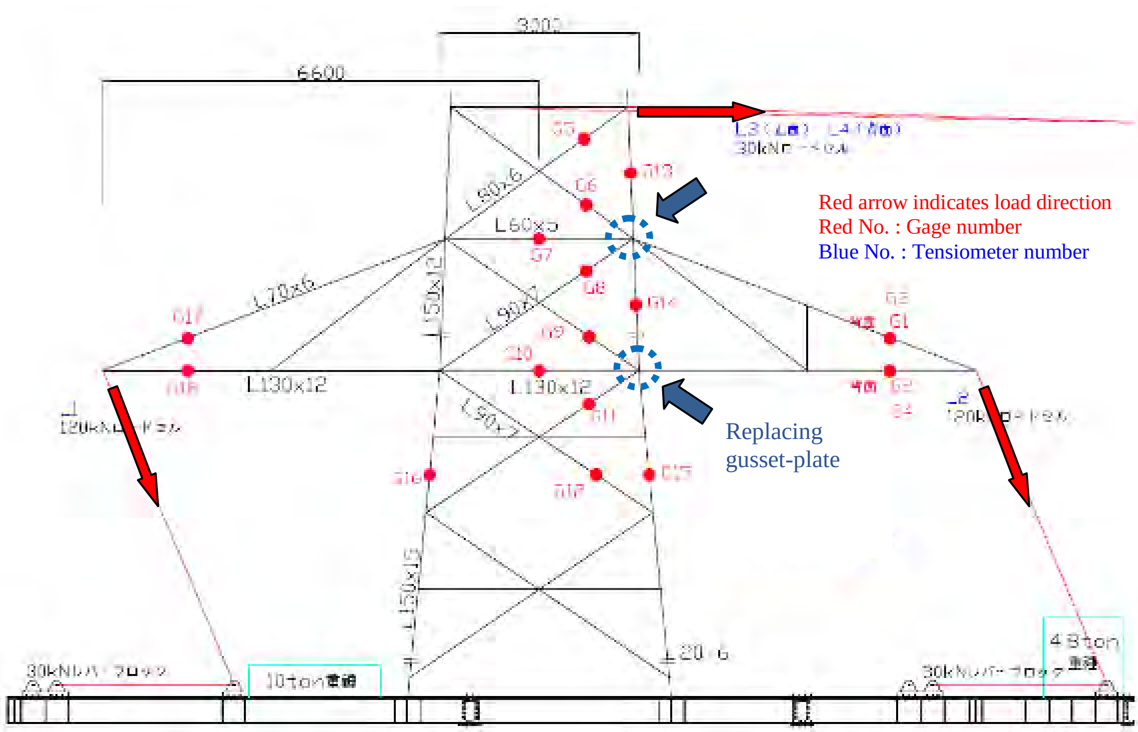

Figure 6 Load direction and measurement points

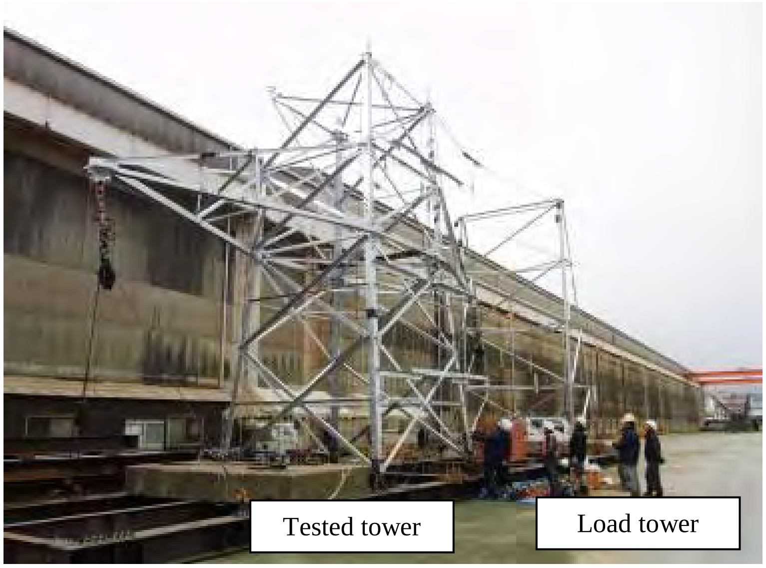

Figure 7 The configuration of the full-scale test tower

Figure 8 Remove gusset plate

Figure 9 Remove gusset plate

Figure 10 shows installation position of the developed jigs on the steel tower. The horizontal jig adjusts the width of the steel tower body on horizontal plane and the reinforcement jig adjusts the width of the steel tower body on vertical plane.

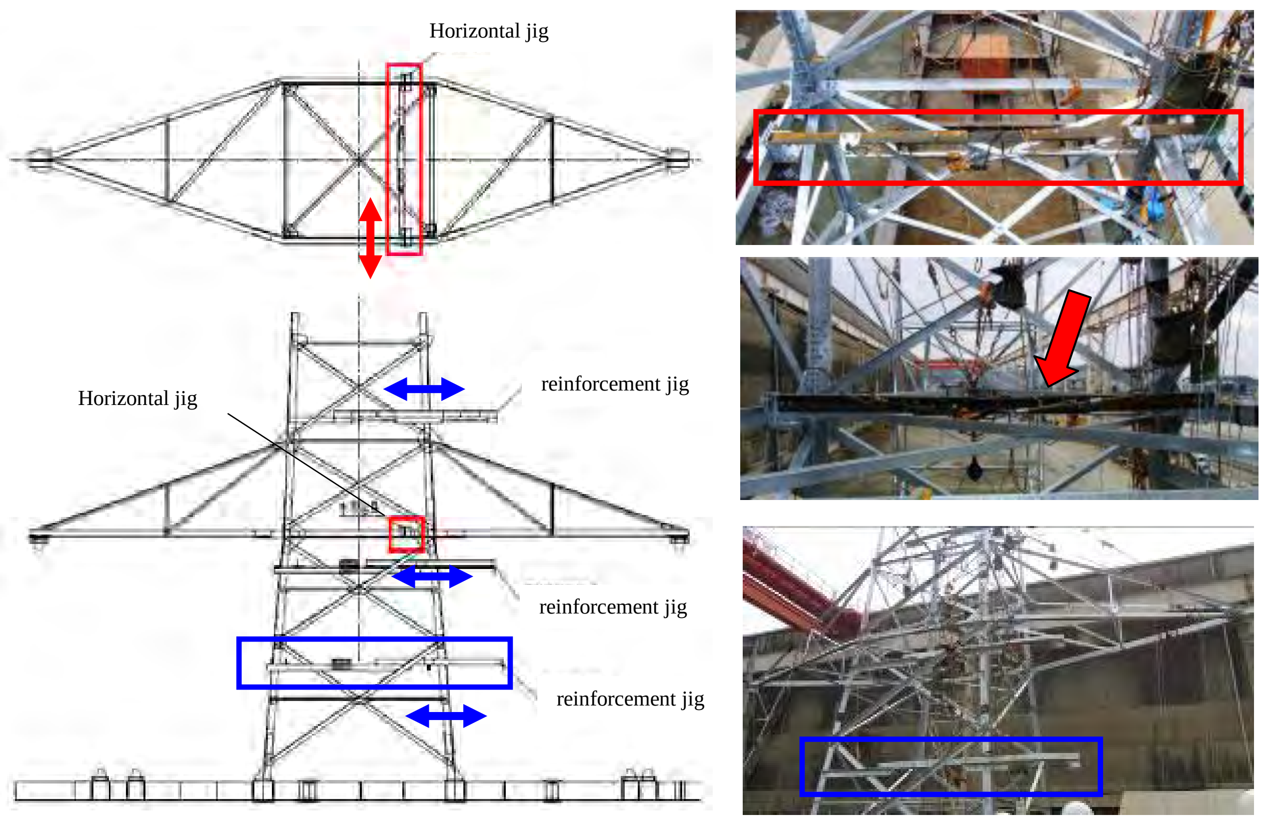

Figure 10 Installation position of the developed jigs on the steel tower

In the full scale model steel tower to which the load simulating the conductor was added, replacement work of the gusset-plate connecting the cross arm and tower body was carried out, and work procedures and safety were confirmed.

5. Replacement of defective (lamination) gusset plate in existing tower

Using the developed jig, in 2013 the replacement of defective (lamination) gusset-plate under 1circuit energizing condition was carried out for 7 of 275 kV transmission towers. It took two days to replace one defective gusset-plate by 10 workers per group. This is a very short time compared with the conventional construction method which disassembles the cross arm by removing the conductor. Figure 11 to 16 show the actual work of replacing the defective (lamination) gusset-plate at site.

Figure 11 Defective gusset-plate

Figure 12 Defective plate replacement with jig

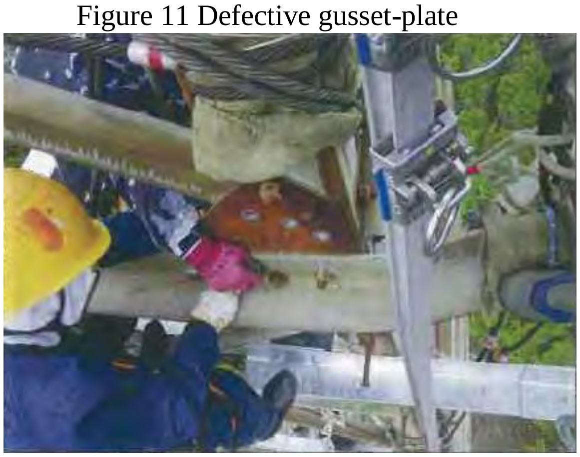

Figure 13 Removing the defective gusset-plate

Figure 14 After removing the defective gusset-plate

Figure 15 Inserting a new gusset-plate

Figure 16 Completed the replacement work

6. Development of repair method of gusset plate with lamination

Regarding minor lamination, examination of repair method to prevent the progress of lamination was conducted. Test pieces simulating lamination were repaired with three types of materials (silicone, epoxy putty, metallic putty), cold heat repetition and moisture test were carried out, and the adhesion to the test piece and the sealability of the slit were verified.

Three test pieces were prepared by welding two steel plates so that the length was 100 mm, the width was 50 mm, and the slit T was 2, 4 and 6 mm, and the gusset-plate on which lamination occurred was simulated.

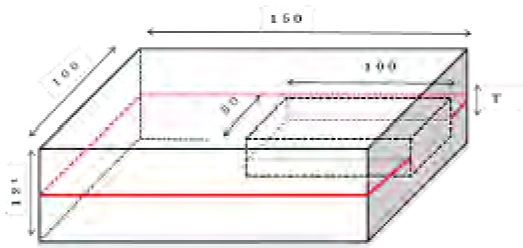

Figure 17 Lamination simulated specimen

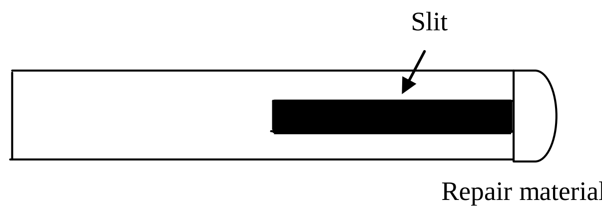

Figure 18 Sealing treatment with repair material

7. Cold heat repetition and moisture test

i) Sealing treatment with repair material

The slit of the test piece is sealed with repair material.

ii) Masking

Masking was carried out to prevent corrosion of the surface of the specimen, as the surface of the specimen corroded and its thickness changed by cold heat repetition and moisture test.

iii) Drying and curing

Conditions for the cold heat repetition and moisture test are shown in Table 1. Conditions 1 to 4 are one cycle, and it takes for 2 hours and 30 minutes. A test of 150 cycles (375 hours) was conducted and it was confirmed whether the repairing material was able to seal the lamination part over a long term.

Table 1 Cold heat repetition and moisture test (1 cycle)

Condition	Temperature (°C)	Relavive hymidity(%)	Time (min)
1	-10		30
2	-10 → 60	90	30
3	60	90	30
4	60 → -10		30

■ Visual inspection after the cold heat repetition and moisture test

After the cold heat repetition and moisture test, these specimen were dipped in penetrant and divided by two pieces. The inspection result of the cold heat repetition and moisture test is shown in Figure 19.

(1) Silicon
Rusting : Yes
Penetration : Yes

(2) Epoxi putty
Rusting : None
Penetration : None

(3) Metallic puty
Rusting : None
Penetration : None

Figure 19 Rusting and penetration inside the slit of the specimen

■ Evaluation of repair materials

Table 2 shows the workability, adhesiveness, and sealability of each repair material. It was revealed that the metallic putty has superior performance in any item among tested repair materials.

Table 2 Evaluation result of repair materials

Repair material	Workability	Adhesiveness	Sealability	Overall evaluation
Silicon	Fair	No good	No good	No good
Epoxi putty	Fair	Fair	Excelent	Fair
Metallic putty	Good	Fair	Excelent	Excelent

8. Verification of repair method using removed gusset-plate with lamination

In order to investigate the corrosion resistance of the repair material and the corrosion behavior of the lamination due to the presence or absence of the repair material, A specimen was prepared using the defective gusseted-plate which was removed by lamination and subjected to a cycle corrosion accelerating test (JIS G 0594).

Method C of JIS G 0594 was applied to the cycle corrosion accelerating test. Method C is a cyclic corrosion accelerating test in neutral salt solution spraying, drying and humid environment, and was developed at Japan Building Material Industry Association based on Method B of ISO / DIN 1651.

The test condition of Method C is shown in Table 3.

Table 3 Test condition of Method C

	Item	Condition
1	Neutral salt solution spraying	
	i) Temperature	35 °C ± 1 ºC
	ii) Neutral salt solution	Salt concentration 1 g / ℓ ± 0.1 g / ℓ, Neutral salt solution of pH 6.0 to 7.0
2	Dry	
	i) Temperature	50 °C ± 1 ºC
	ii) Relative humidity	Less then 30 % RH
3	Humid	
	i) Temperature	40 °C ± 1 ºC
	ii) Relative humidity	90 % RH ± 5% RH
4	Time and content of one cycle	Total duration; 8 hours Neutral salt solution spraying; 1 hour Drying; 4 hours Wetting ; 3 hours (Transition time is included respectively)
5	Transition time (Time to reach specified temperature and relative humidity)	Drying from spray; within 30 min Wetting from drying; within 15 min Spraying from wetting; within 30 min (Spraying starts instantaneously)
6	Test specimen holding angle	With respect to the vertical direction, 20 ° ± 5 °

■ Duration of the cycle corrosion accelerating test

According to the Sub-Clause 10; Duration of time in JIS G 0594, the following two recommended test cycles were applied.

- 96 cycles (768 hours)
- 192 cycles (1,536 hours)

■Visual inspection after the cycle corrosion accelerated test

Examples of specimens before and after the cycle corrosion accelerated test are shown in Figure 20 and 21.

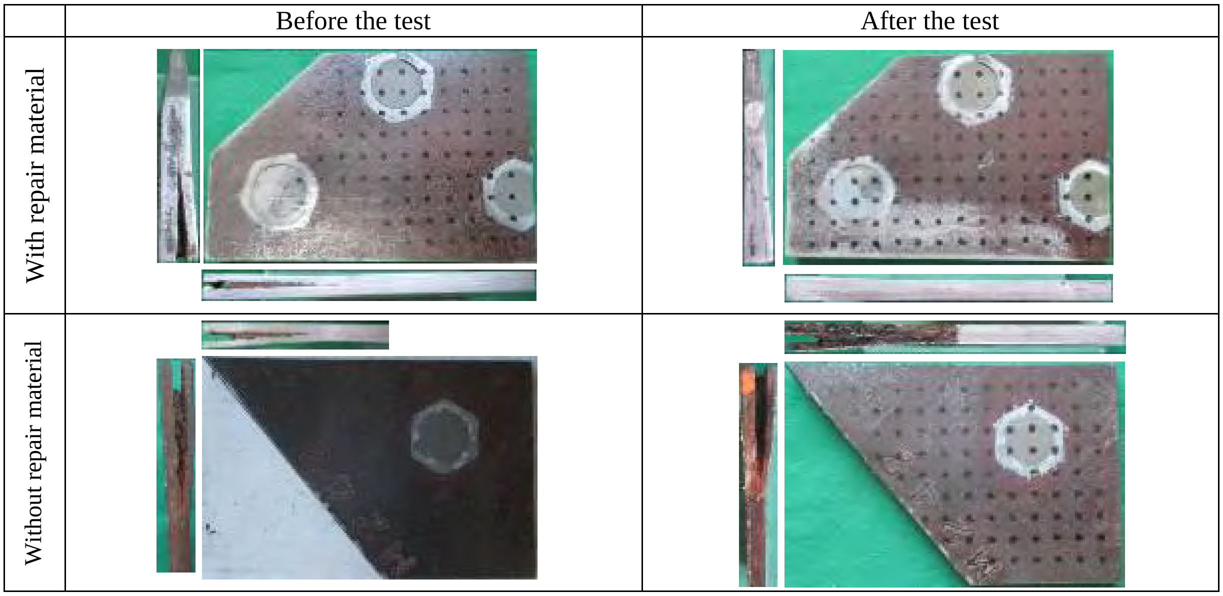

Figure 20 Examples of specimens before and after the cycle corrosion accelerated test (96 cycles)

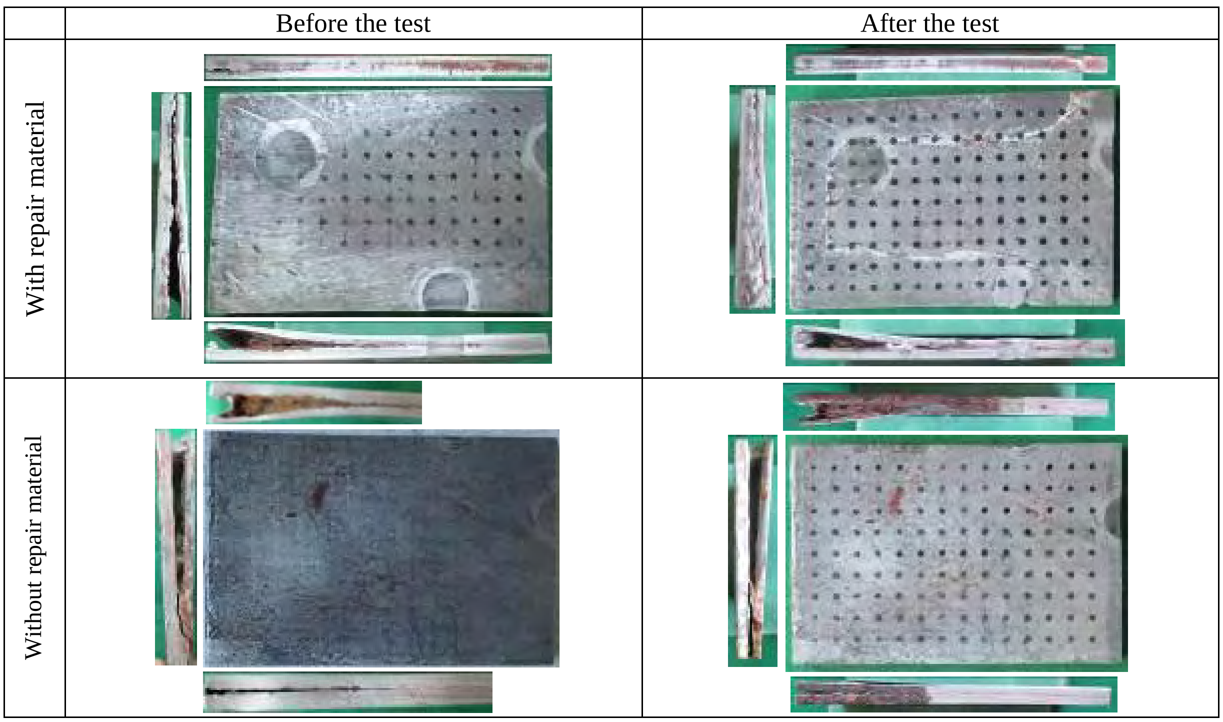

Figure 21 Examples of specimens before and after the cycle corrosion accelerated test (192 cycles)

Metaliic putty was contained in the opening of the lamination repaired with metallic putty. In the openings of the lamination which were not repaired, white rust occurred when zinc plating remained at the ends, and red rust occurred when they did not remain.

■ Evaluation of repair method by metallic putty

The examination revealed the following two points.

- Metal putty selected as a repairing material has sufficient long-term durability.
- By covering the opening of the lamination with a metallic putty, it is possible to delay lamination progress, that is, corrosion and deterioration of the defective gusset-plate.

9. Repair of defective (lamination) gusset-plate in the existing steel towers

In February 2018 repair work was carried out with two steel towers with defective (lamination) gusset plates. The work was done with 2 people per group, and the repair work was completed on 0.5 days per tower. The repair work of the defective (lamination) gusset-plate by the metal putty is shown in Figure 22 to 25.


Figure 22 Before repair work


Figure 23 Preparation of metallic putty


Figure 24 Applying metallic putty


Figure 25 Completion of repair work

10. Conclusion

With respect to the defect (lamination) gusset-plate found in the transmission tower constructed in the 1950's and 1960's, a construction method was established to replace the defective gusset plate without disassembling the conductor and disassembling the cross arm under one circuit energized condition. Next, a repair method was established to delay the progression of corrosion and deterioration of the non-replaceable defect (lamination) gusset-plate and prolong its life.
Both methods were applied to the existing towers and the effectiveness was confirmed.

These research and development and experience of actual work on the existing steel towers greatly contribute to reduction of the tower maintenance work and shortening of power outage of the transmission line.

BIBLIOGRAPHY

[1] Corrosion and abrasion phenomena of steel material of overhead power transmission facility, Technical Report of the Institute of Electrical Engineers of Japan (IEEJ) No. 1163, July 2009 (in Japanese)

CIGRE- AORC Technical Meeting 2018 – International Conference on Global Energy Transition – Issues and Challenges, 24-25 May 2018, Gangtok, Sikkim, India

RE and Grid Balancing in Southern regional grid in India

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Summary

Power grid operators around the world have been experiencing challenges in operating the grid with increasing penetration of Variable Generation (VG) sources like Solar PV and Wind. Variability in one form of generation must always be compensated with other forms of generation at all times to ensure grid stability [6]. Experience of power grids around the world that have been aggressively expanding the renewable energy has shown that operating the grids beyond 20% of penetration of variable sources of electricity becomes a significant challenge. This paper focuses on the variability introduced into the Indian power grid due to addition of RE. In the first part, the paper analyses the frequency and temporal distribution, duration curves of hourly ramps of Wind, Solar, Net load and demand. It also discusses about the technically available operational flexibility of individual power system units.

Introduction

Government of India in 2015-16 launched an ambitious initiative of installing 175 GW of renewable energy on the Indian power grid by the year 2022.This target includes 100 GW of Solar energy along with 60 GW of wind energy and 15GW of Biomass power and other forms of renewable energy like small hydro etc. Integration of renewable generation represents a key pillar of the Indian govt's broader energy and climate objectives in reducing greenhouse gas emissions, improving security diversity of energy supply. India has a total installed generation capacity of 344 GW as of March 2018 out of which renewable energy sources (excluding large hydro) contribute about 69 GW.

Operational flexibility is an important property of electric power systems and plays a crucial role for the transition of today's power systems, many of them based on fossil fuels, towards power systems that can efficiently accommodate high shares of variable Renewable Energy Sources (RES). The availability of sufficient operational flexibility in a given power system is a necessary prerequisite for the effective grid integration of large shares of fluctuating power in-feed from variable RES, especially wind and solar power [5].

Renewable Energy in Southern region

Installed RE capacity in states in Southern region ranges between 639 – 12438 MW including wind energy, PV, biomass and mini-hydro. Except for biomass power plants, all of these RES are intermittent power sources.

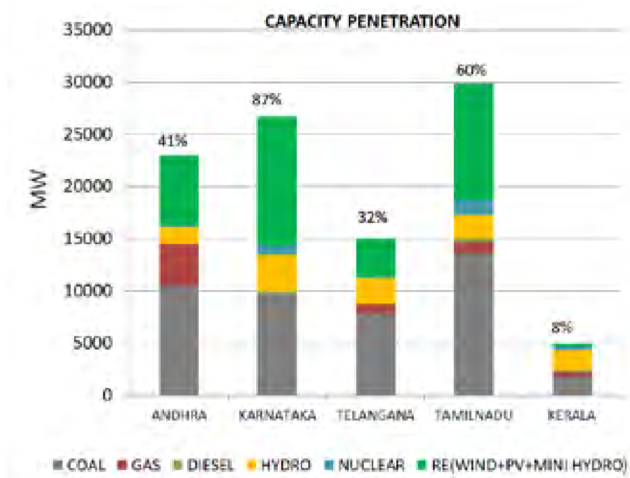

Figure 1 : Capacity penetration of renewables

Today capacity penetration of the Renewable Energy with respect to total installed capacity in States in Southern region (Tamil Nadu, Andhra Pradesh, Karnataka and Telangana) as on April 2018 ranges between 32% to 87%.

Table 1 : Highest RE penetration in SR (2017-18)

State	RE Generation / Demand (MW)	Instantaneous RE Penetration (MW)	RE Generation / Consumption (MU's)	Over the day RE penetration (MU's)
Andhrapradesh	3,809 / 5,509	69 %	64.46 / 133.30	48 %
Telangana	2995 / 7448	35 %	18.04 / 102.00	17 %
Karnataka	2,627 / 5,558	47 %	46.53 / 158.63	29 %
Tamil Nadu	4,931 / 10,242	48 %	103.30 / 290.60	36 %
Southern Region	12,995 / 33,387	39 %	216.20 / 807. 50	27 %

Table-i shows the highest instantaneous and entire day RE penetration in terms of total demand met for RE rich states of SR. It can be observed that the instantaneous penetration ranges from 48 to 69% and over the day penetration ranges from 36% to 48%. For Southern regional grid the instantaneous RE penetration is 39% and over the day penetration is 27% in term of total demand met.

Analysis of hourly ramp rates of RE, NET load and demand

The frequency and temporal distributions of hourly ramp rates are an important measure for short-term flexibility requirements of the power system. The impact of those ramps on system operation depends on whether they were forecasted or not. If they are predictable, even slower power plants can be started up early enough to be available exactly when the ramp occurs. However, accuracy of prediction is lower the day ahead and increases when temporally closer to the event. Thus, the power system should be designed in a way to meet those 1-hour gradients by power plants that are already online or have a fast starting capability (hydro, gas turbine) [4].

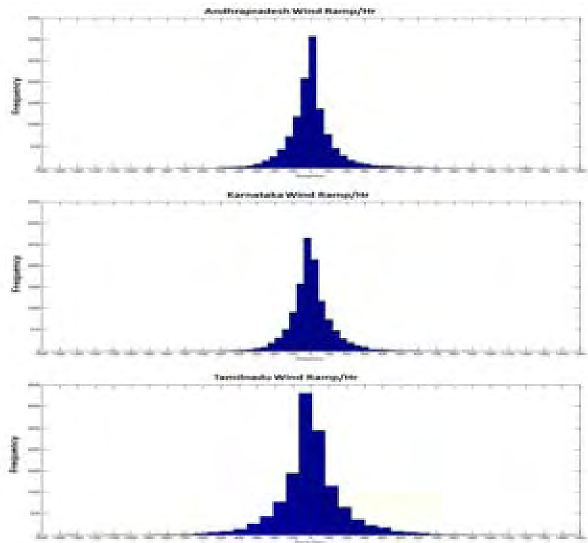

Figure 2 : Frequency distributions of hourly ramps of wind power production (Jan to Dec 2017) : (a) Andhrapradesh (b) Karnataka (c) Tamilnadu

Fig.2 illustrates the basic shape of the frequency distributions of wind power variations. Wind power is characterized by high frequency, low magnitude ramps concentrated around the center of the distribution. It can be observed that the largest positive & negative hourly ramp is 300MW for Andhrapradesh & Karnataka, 400MW for Tamilnadu. It is also observed that the frequency of occurrence of negative hourly ramps is more when compared to the positive hourly ramps in Tamilnadu and Karnataka.

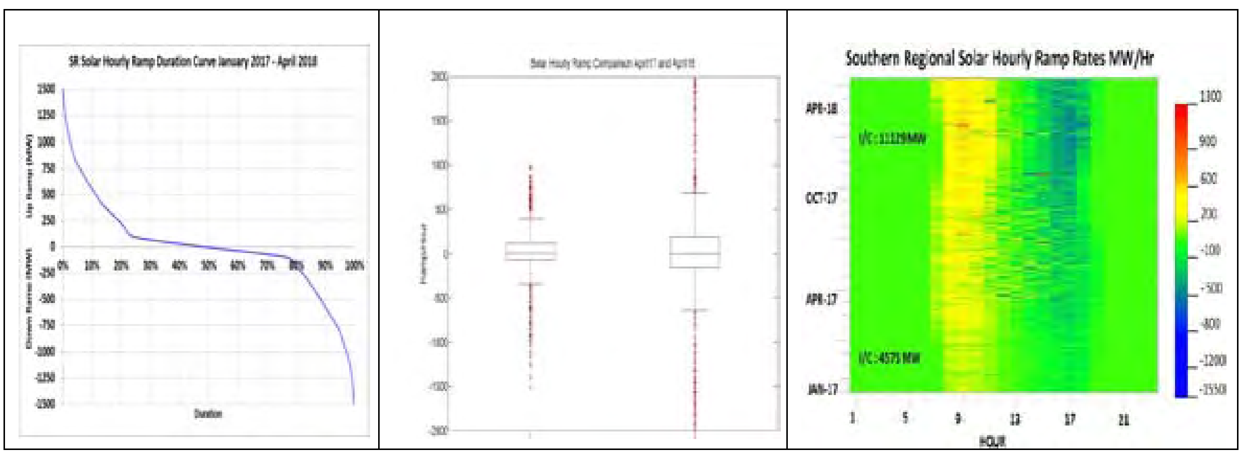

Figure 3 : (a) Duration curve (b) Box plot of distribution of ramps (c) Temporal distribution of hourly solar ramps

Fig.3 organizes the hourly Solar ramps into (a) a duration curve (a) distribution of ramps in box plot (b) Temporal distribution of ramps (c) aggregated to the regional level. The peak 1-hour upward ramp in and downward ramp in April 2017 is observed to be 450MW and in April 2018 to be 600MW. The distribution of data between 1st & 3rd quartile is far wider in April 2018 when compared to April 2017. From fig.2.c it can be observed that about half of all hourly solar power ramps are equal or close to zero because of zero production at night. It can be observed that adding more PV capacity to the system results in an increase in the frequency of high ramps.

Net load and demand hourly ramp rates

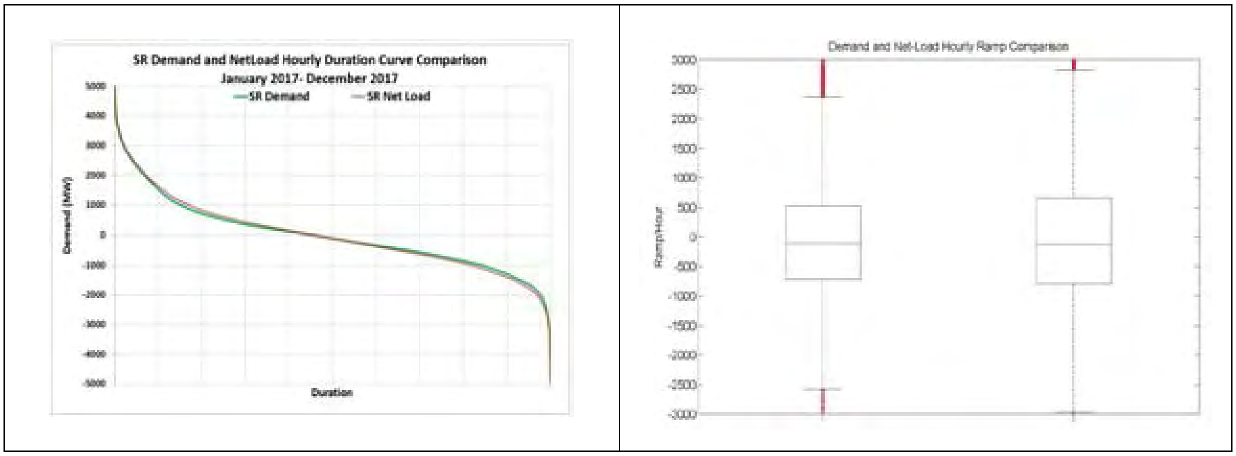

Figure 4 : (a) Duration curve (b) Box plot of distribution of hourly demand & netload ramps

Analysing net load helps to identify periods that may be operationally challenging and hence the generation that serves net load, in aggregate, must be more flexible. In Southern region, each control area meets the net load with its own thermal and hydro sources, along with imports and exports to smooth the net load variability. Figure-4(a), (b) shows the hourly ramp rates load and the net load for the Southern region from January to December 2017. The upward and downward hourly ramp rates of net load are 17% & 13% higher when compared with the one hour ramp rates of Southern region demand. The maximum net load one hour up ward ramp rate is 3000MW and downward ramp rate is 2900 MW. For demand the maximum one hour upward ramp rate is 2400MW and downward ramp rate is -2600 MW.

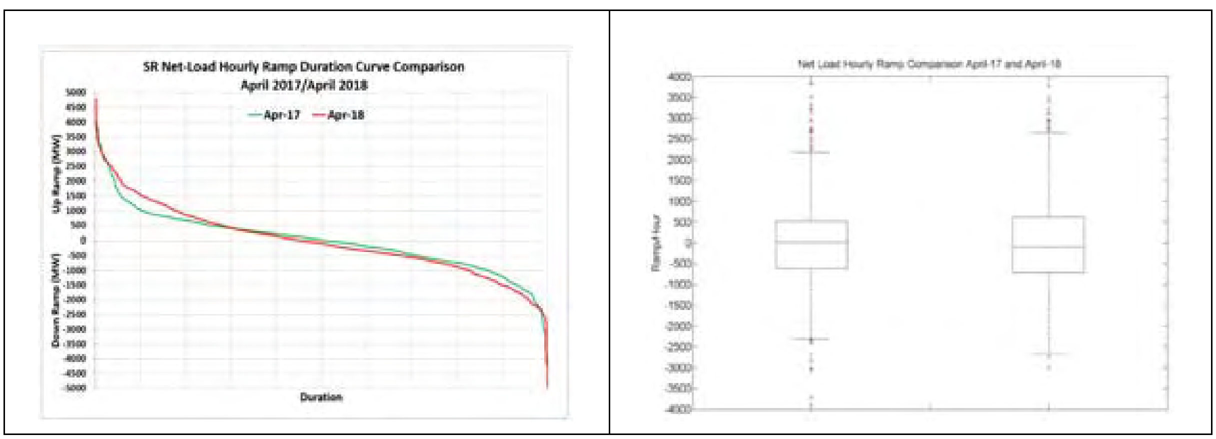

Figure 5 : (a) Duration curve (b) Box plot of distribution of hourly netload ramps in April-17 & 18

Figure-5 shows the comparison of hourly ramp rates of net load for April-2017 and April-2018, duration curve (a), and also shows a distribution of ramps (b), aggregated to the regional level. The peak 1-hour upward and downward ramp increased by 19% & 11% in April 2018 when compared to hourly ramps in April 2017. Load and R.E ramping up or down at the same time counterbalance one another, whereas wind and Solar power ramps in the same direction add up to increase the system balancing requirements.

Balancing potential available in SR grid

The state grid operators in the Southern regional grid in India meet the ramping needs through conventional generation i.e. from Coal, Hydro, Gas plants etc. 60% of the installed generation capacity on the Indian power grid is thermal generation using coal as fuel.

Flexibility of thermal and hydro power

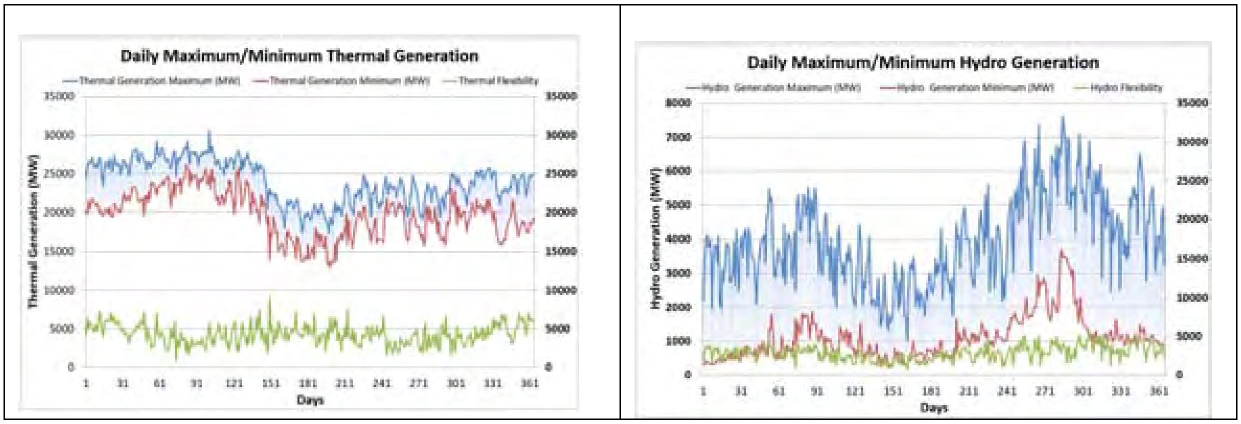

Figure 6 : (a) Thermal generation S.R (b) Hydro generation in S.R

Fig. 6(a), (b) illustrates the flexibility of thermal and hydro power plants in Southern region (January to December 2017). It can be observed that the thermal generation is minimum during high RE season i.e. from May to September in-order to absorb maximum RE generation. It can also be observed that the flexing per day is in the range of 5000 to 7000 MW per day (variation between maximum and minimum generation in a day). On the other hand the hydro generation is mainly used take care the morning and evening peak demand and also for managing the imbalances arising from RE. It can be observed that the maximum hydro generation is varying from 4000MW to 7500 MW round the year.

Ramping capability of Thermal and Hydro Stations in S.R

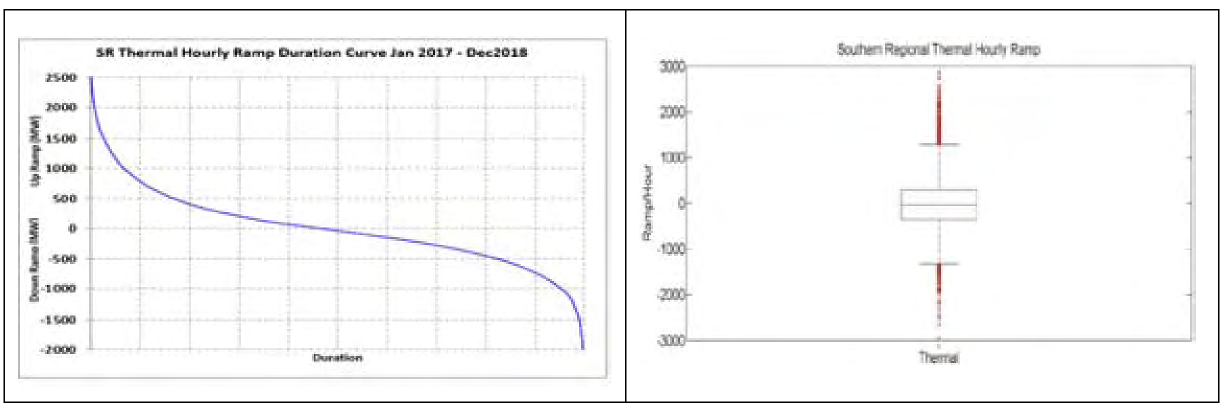

Figure 7 : (a) Duration curve (b) Box plot of distribution of ramps of hourly Thermal generation

The maximum upward and downward one hour ramp rate for Thermal generation in Southern region is observed to be in the range of 1100 to -1100 MW. However there are instances where upward hourly ramps went upto 2800 MW and downward ramp upto 2900MW

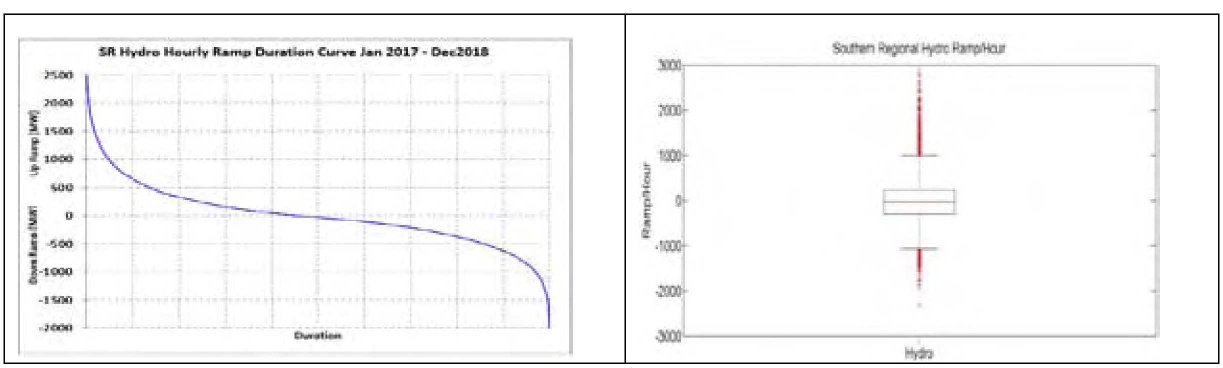

Figure 8 : (a) Duration curve (b) Box plot of distribution of ramps of hourly Hydro generation

The maximum upward and downward one hour ramp rate for Hydro generation in Southern region is observed to be in the range of 1000MW & -1000MW. However there are instances where upward hourly ramps went upto 2800 MW and downward ramp upto 1900MW

Use of pumped hydro storage plants

Pumped storage hydro power plants have been used as a source of flexibility i.e. as a peak generation to meet highest demand in short period of time, load and net load balancing. At present out of the 11800 MW of hydro generation capacity, 2000MW is designed & capable of operation as pumped storage units. However due to various reason only 1300MW of PSP capacity is presently in operation in Southern region.

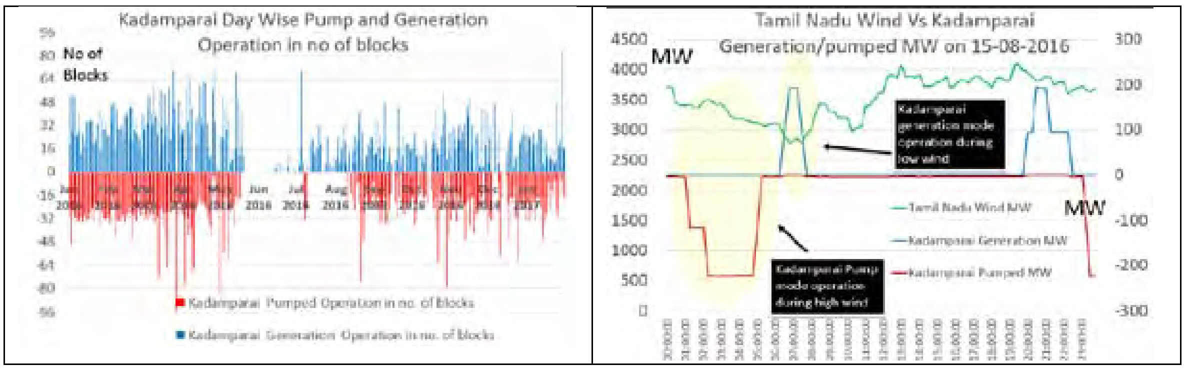

Figure 9 : (a) Kadamparai Pump and Generation mode of operation (b) Balancing during High/ low RE

Figure-9(a), (b) shows the operation of Kadamparai pump storage power plant operation round the year and during high wind season. It can be observed that the unit is being run in pump mode during under drawl from grid caused by high RE/ low load and in generation mode during low RE/ high load.

Power markets for RE balancing

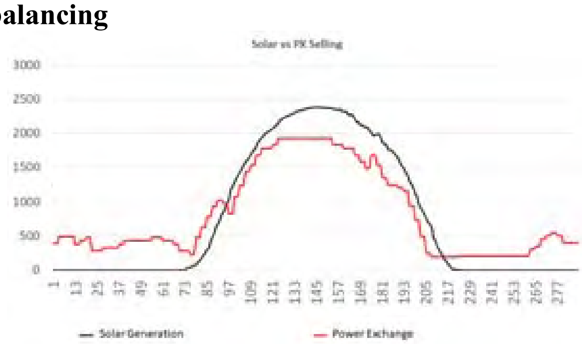

Figure 10 : Solar generation Vs Px selling

It can be observed from figure that the Power markets are being used as a source for balancing of RE i.e. Solar power being sold in the Day ahead market.

Need for regional balancing & faster dispatch

In present scenario, the balancing of RE is mainly done within states and balancing potential i.e. increase or decrease of conventional generation available in other states is often not taken into account for re-scheduling or improved dispatch. In states with high penetration of RE, the other generation sources need to be backed down during the period of peak RE generation in order to maintain load-generation balance. Eventually there is curtailment of RE if the unbalance persists even after flexing all the conventional resources within the state control area. The thermal balancing capability on the regional level is higher compared to the states capabilities due to lower installed RE capacity in relation to the existing thermal capacity. Hence the complete available balancing capacity of a region can be used as and when required. Regional balancing needs to be incentivized given efficient market mechanisms to export power. A regulation which covers cost differences between market prices of green energy and thermal power may be required additionally, in order to ensure that RE generation is profitable [1].

Fast dispatch helps manage the variability of renewable generation because it reduces the need for regulating resources, improves efficiency, and provides access to a broader set of resources to balance the system. When generators have fixed schedules for longer periods, generators are committed to their set schedules and not available to help balance the system in the case of schedule deviations. With faster dispatch, load and generation levels can be more closely matched, reducing the need for more expensive regulating reserves. This enables more efficient balancing and utilization of the most economical resources within the system. Five-minute dispatch is currently the norm in many ISOs throughout the world. Five minute scheduling has helped reduce regulation requirements to below 1% of peak daily load in many ISO/RTOs. Studies have shown that integration costs are lower in areas with faster dispatch [7].

Conclusion

In this paper, the hourly ramp rate of RE, load, net load and of thermal/ hydro generation in Southern region along with present balancing potential available in S.R grid were analysed. Also the ratio in which the solar and wind is being added needs to be analysed during R.E integration as this will impact the hourly ramping requirements from conventional generators. Apart from other measures to improve balancing, it is important to move towards regional balancing faster dispatch as it will lead to a higher efficiency in power plant dispatch and an economical way of better balancing.

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Disclaimer

The views expressed in the paper are that of the authors and may or may not represent the views of the organizations to which they belong.

References

[1] Report on forecasting, concept of REMC & Grid balancing, GIZ-India green energy corridor report
[2] Report on Grid integration of renewables in India – Analysis of forecast, Scheduling & DSM, Prayas Group
[3] Report on Market design for an electricity system with higher share of RE energy sources, GIZ-India green energy corridor report
[4] Integration of wind and solar power in Europe: Assessment of flexibility requirements, https://www.sciencedirect.com/science/article/pii/S0360544214002680
[5] Analyzing Operational Flexibility, Power Systems Laboratory, ETH Zurich, Switzerland, https://arxiv.org/pdf/1312.7618.pdf
[6] Managing the Power Grid Ramping challenges critical to success of India's Renewable Energy Targets, https://web.iima.ac.in/assets/snippets/workingpaperpdf/14473831782017-08-01.pdf
[7] Integrating Variable Renewable Energy: Challenges and Solutions, NREL Report, https://www.nrel.gov/docs/fy13osti/60451.pdf

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Grid Integration of Large Scale Renewables in Indian Context

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SUMMARY

Energy needs of the country is growing at a very fast pace to meet high GDP growth rate. Present peak electricity demand of the country is 164GW which is expected to grow to about 226 GW & 299 GW by the end of 2021-22 & 2026-27 respectively as envisaged in the 19th EPS report of CEA. To meet growing demand and to reduce supply- demand gap, there is a need of large capacity addition through conventional as well as from renewable sources. However, to achieve sustainable growth, energy security is of paramount importance.

Considering the depleting domestic fossil fuel reserves in the country as well as increasing demand for energy consumption along with environmental concern, there is a need to harness alternate sources of energy. Abundant Renewable Potential in the country, presents excellent solution to meet above challenges i.e. attaining energy security – Access & Delivery at affordable price along with addressing climate change concerns.

Present installed capacity for power generation in the country is about 344 GW (Mar'18) which constitutes capacity from conventional sources (80%) viz. Coal (198 GW), Gas(24.9GW), Nuclear (6.8 GW) and large hydro (45.3 GW). Balance 69GW (20%) contribution is from renewable generation which has 50% share from Wind generation alone. Coal dominates as fuel resource (58%) in overall energy (electricity) resource portfolio

To promote increased RE capacity penetration in total generation capacity portfolio, Interstate transmission charges & losses have been waived off on transmission of electricity through Interstate transmission system for sale of power by wind & solar projects commissioned till 31.03.2022. Further, Ministry of New & Renewable Energy notified "Guidelines for Implementation of Scheme for Setting Up of 1000 MW Interstate transmission system Wind Power Projects". The scheme was aimed at facilitating transfer of wind power to fulfill non-solar renewable purchase obligations (RPO) of various states as well as to boost investment in the sector so as to achieve the goal of reaching 60 GW of wind power capacity by 2022. As a result of above endeavors, wind generation tariff has become competitive. In this direction, already four stages of bids with cumulative wind capacity addition of 6000MW is already completed and More such bids (wind & solar) for ISTS connected wind bids are envisaged in next 1-2 years.

Initiatives were taken to facilitate integration of large scale renewables mainly through wind & solar. In this direction, a comprehensive plan comprising transmission strengthening at Intra state and Inter state level as well as control infrastructure was identified as a part of “Green Energy Corridors”. In addition, the works evolves requirement of other control infrastructure like establishment of Renewable Energy management centres (REMC) equipped with advanced forecasting tools.

Government of India also has plans to establish total 1,00,000 MW Solar and 60,000 MW Wind generation capacity by 2022. Solar capacity targets of 1,00,000 MW includes setting up of at least 50 nos. solar parks in various states thereby targeting around 40,000 MW solar generation installed capacity. Balance Solar capacity comprises through Roof top Solar PV and distributed solar generation. In first phase a comprehensive transmission plan for power evacuation arrangement for the identified Thirty Four (34) Solar Power Parks of about 20,000 MW capacities in Twenty one (21) States envisaged through Intra state & Interstate evacuation was evolved as Green Energy Corridors-II.

As part of targeted wind capacity of 60GW by 2022, wind capacity of about 34GW is already achieved in Mar’18. Large no. of connectivity applications have been received in ISTS for wind capacity, it is expected that wind capacity may cross the milestone of 60 GW in next 3-4 years/ To evolve the transmission plan for potential wind energy zones, an exercise was carried out by all stakeholders viz. MNRE, POWERGRID, NIWE, STUs and SNAs of wind potential rich states as well as wind developers/IPPs. Based on the inputs and information provided by all stake holders, wind energy zones were prioritized along with the capacity for which assessment of Interstate transmission infrastructure requirements.

KEYWORDS

Renewable, Integration, Wind, Solar, Transmission, Renewable Energy Management Centre, Wind Energy Zones, renewable purchase obligation

1. Present Power Scenario

The Indian power sector is one of the most diversified in the world. The Sector has been continuously progressing in generation capacity addition through conventional viz. coal, lignite, gas, hydro and nuclear power as well as non-conventional/renewable sources viz. wind, solar, small hydro, Biomass etc. Present generation installed capacity in the country is about 344 GW (Mar’18) which constitutes capacity from conventional sources (80%) viz. Coal (198 GW), Gas(24.9GW), Nuclear (6.8 GW) and large hydro (45.3 GW). Balance 69GW (20%) contribution is from renewable generation capacity which has 50% share from Wind generation alone. Coal dominates as fuel resource (58%) in overall energy (electricity) resource portfolio. Present generation portfolio along with their resource composition is shown at Fig 1

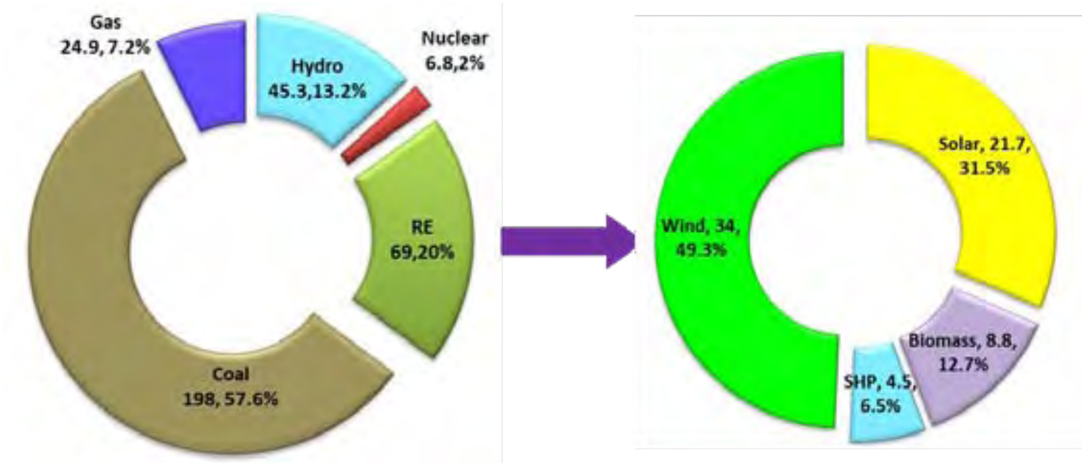

Figure 1: Installed Generation Capacity (Conventional & Non conventional)

Overall peak demand of the country is encountered as 164 GW in year 2017-18 with only about 1-2% power and energy deficit. In view of the growing challenges on coal supply, as well as environmental concern, impetus is given to harness abundant renewable potential in the country. In these scenarios, harnessing of renewable potential in effective manner is becoming need of the hour, which can provide sustainable power supply as well as mitigate the negative environmental impact due to increase use of fossil fuel.

India has been continuously progressing in conventional as well as renewable capacity addition. Since 9th Plan, share of renewable capacity has increased from 2% to 20% as on today (about 10 fold increase). Electricity generation due to renewable has also increased to about 7-8% in overall electricity generation mix. Growth of Generation capacity from different resources including RE is shown below (Fig 2)

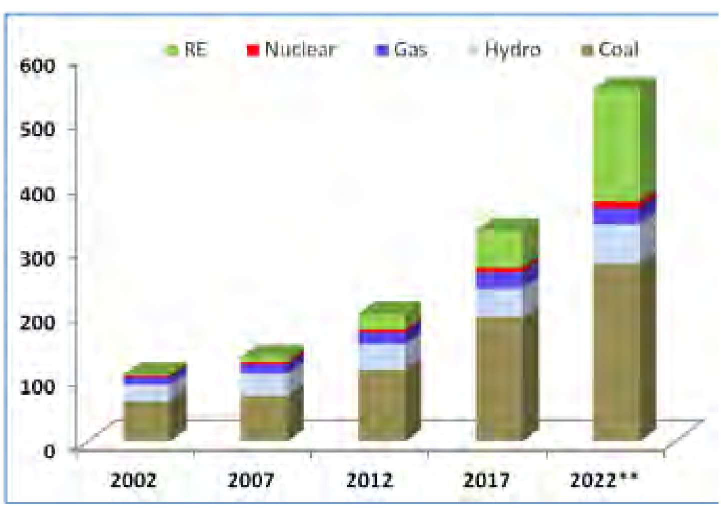

Fig 2: Growth In Installed Capacity

** projected

According to the report on 19th Electric Power Survey by Central Electricity Authority, electricity demand in the country is expected to grow to 226 GW by the end of 2021-22. In order to meet increasing requirement of electricity, generation capacity addition in the country is required, with considerations of energy security and sustainability aspects. It is envisaged that about 74 GW conventional and 118GW renewable capacity (including grid connected roof top and distributed solar) shall be added in13th plan (2017-22) period to meet the expected demand

Unlike solar, wind generation is confined in few states i.e Tamil Nadu, Karnataka and Andhra Pradesh in Southern region, Gujarat, Maharashtra and Madhya Pradesh in Western region and Rajasthan in Northern region due to good wind potential (Higher Wind power density/CUF) as well as land availability. Tamil Nadu is having highest wind capacity penetration (34%) followed by Rajasthan (24%) and Gujarat (21%). Wind penetration is continuously increasing in wind rich states. Wind penetration in various states is shown below in Table

S.No	State	RE Penetration (%)*	Wind Penetration (%)**
1	Tamil Nadu	45.5%	33.9%
2	Rajasthan	36.5%	23.6%
3	Gujarat	26.1%	21.1%
4	Karnataka	42.0%	20.5%
5	Andhra Pradesh	32.0%	18.7%
6	Madhya Pradesh	24.9%	16.4%
7	Maharashtra	22.1%	13.7%

**RE Capacity/total installed capacity* ***Wind capacity /total installed capacity*

During monsoon months or peak wind season, in some of the highly RE penetrated states i.e. Tamil Nadu, instantaneous wind capacity penetration increases more than 40-45%.

2. Wind & Solar potential in India

One of India's major advantages today and going forward is that its renewable energy (RE) potential is huge and largely untapped. India Energy Security Scenarios 2047 show a possibility of achieving a high of 410 GW of wind. NIWE Wind potential map at 100 meter hub height is as under (Fig 3) NIWE estimated wind potential of 302GW at 103 meter hub height.

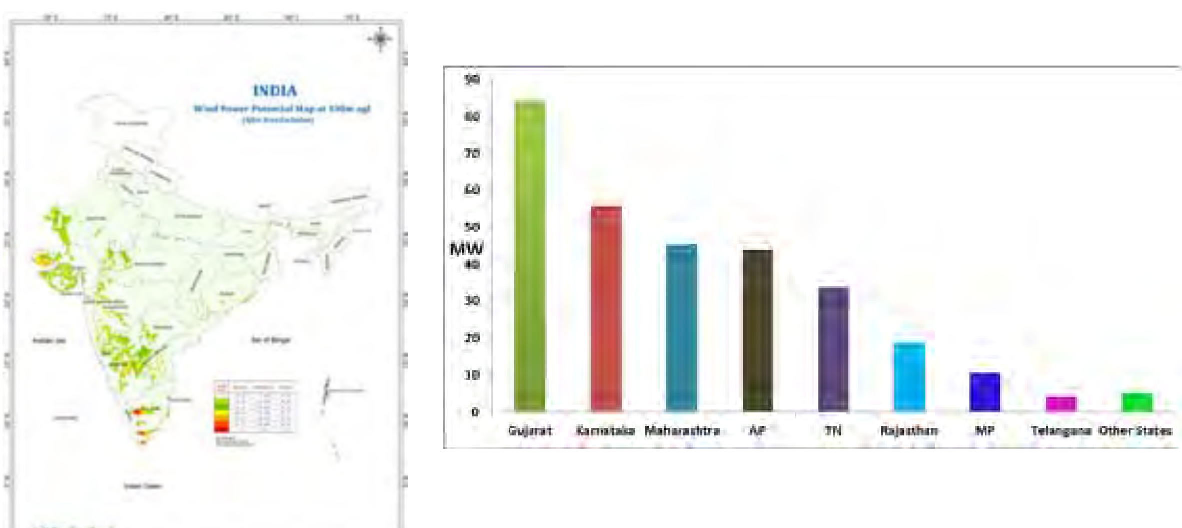

Fig 3 : Wind potential at 100m hub height

Out of total potential of 302GW, 97% wind potential comprises in six wind resources rich states viz. Gujarat, AP, Tamil Nadu, Maharashtra, Karnataka & Rajasthan.

Unlike wind, solar potential is distributed in most of the Indian states. As per assessment done by National solar institute of solar energy, India has 749GW solar potential. Figure 5 depicted solar potential in the states (>20GW) is as under

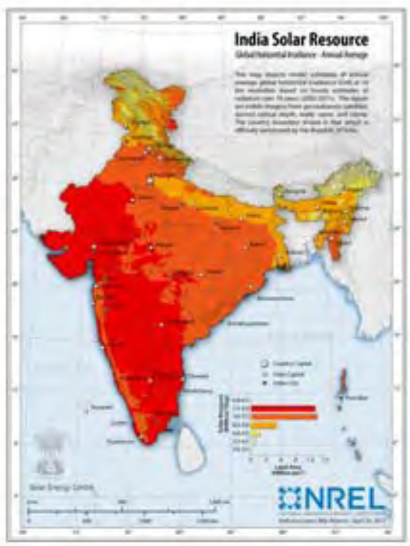

Fig 4 : India solar irradiance map

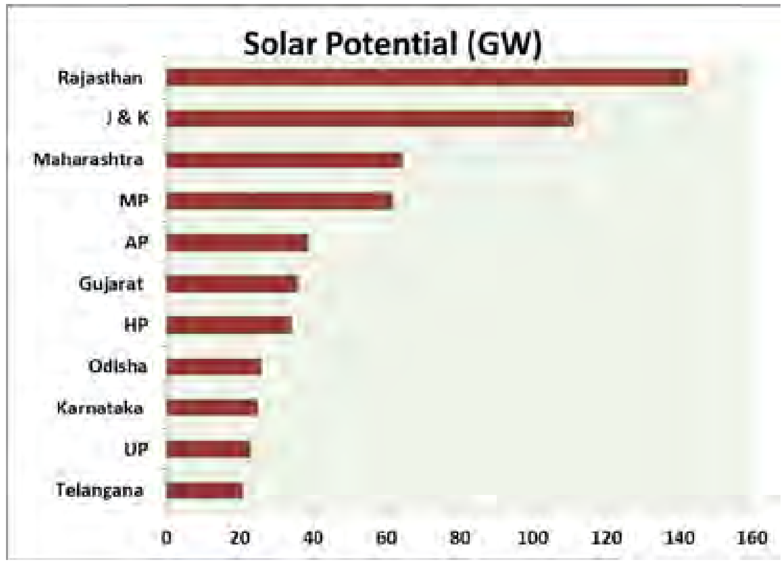

Fig 5 : Sate wise Solar Potential in India

3. Promotion of Renewable Energy

At present, most of RE generation is connected at Intra state level and consumed by the host states only. However, most of the RE potential states have fulfilled their renewable purchase obligation (RPO) and facing various challenges to accommodate more RE capacity within their state. Further to promote increased RE capacity penetration in total generation capacity portfolio, Interstate transmission charges & losses have been waived off on transmission of electricity through Interstate transmission system for sale of power by such wind & solar projects. This waiver shall be available for the period of 25 years from date of commissioning of project and available only for projects entering into power purchase agreements (PPAs) with all entities including distribution companies for sale of power for compliance of RPO. However wind & solar project needs to be awarded through competitive bidding process in accordance with the guidelines issued by Central Government.

Ministry of New and Renewable Energy (MNRE) notified "Guidelines for Implementation of Scheme for Setting Up of 1000 MW ISTS Wind Power Projects". The scheme was aimed at facilitating transfer of wind power to fulfill non-solar renewable purchase obligations (RPO) of various states as well as to boost investment in the sector so as to achieve the goal of reaching 60 GW of wind power capacity by 2022. The implementation of the scheme was assigned to Solar Energy Corporation of India (SECI) to carry out bidding/ auction for award to the wind projects. The generation projects under the Scheme are envisaged for commissioning within 18 months from the issuance of the Letter of Award by SECI. At present total 6000MW capacity bidding (SECI stage 1 & 2 of each 1000MW capacity & SECI stage 3 & 4 of each 2000MW capacity) is already completed.

As a result of above endeavors, wind generation tariff has become competitive and State DISCOMs are encouraged to buy more Renewable Energy. More such biddings for ISTS connected wind bids are envisaged in FY18-19.

4. Integration of large scale Renewable Generation

To integrate large scale renewables, a comprehensive plan comprising transmission strengthening at Intra state and Interstate level as well as control infrastructure was identified as a part of “Green Energy Corridors”. Intra state transmission system is being implemented by respective state transmission utilities.. The Interstate transmission scheme of Green energy corridor is being implemented by POWERGRID comprises about 3200ckm transmission lines and 6 substations having 17000MVA transformation capacity. The inter transmission scheme is under various stage of implementation, out of which some of transmission elements are already commissioned.

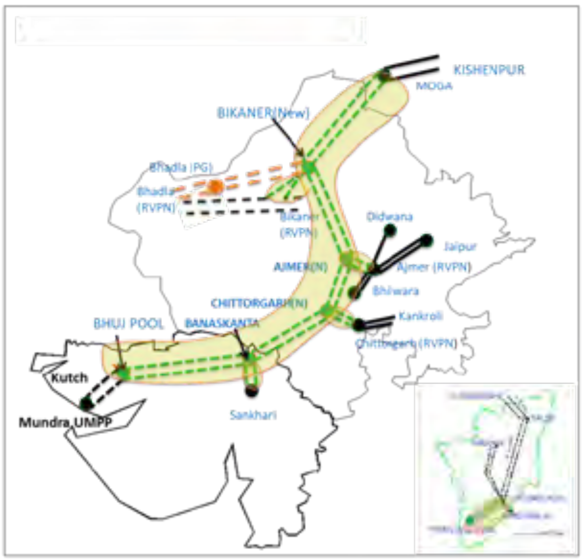

Fig 6 : Transmission schème in Green Ennery Corridor

POWERGRID is also establishing Renewable Energy Management Centres (REMCs) comprising RE forecasting & RE scheduling systems, integrated with existing SCADA co-located with SLDC/RLDC/NLDC at 11 locations [Tamil Nadu, Andhra Pradesh, Karnataka, Gujarat, Maharashtra, Madhya Pradesh & Rajasthan, SRLDC, WRLDC, NRLDC & NLDC]

Government of India also has plan to establish total 1,00,000 MW Solar and 60,000 MW Wind generation capacity by 2022. Solar capacity targets of 1,00,000 MW includes setting up of at least 50 nos. solar parks in various states thereby targeting around 40,000 MW solar generation installed capacity. Balance Solar capacity comprises through Roof top Solar PV and distributed solar generation. In first phase a comprehensive transmission plan for power evacuation arrangement for the identified Solar Power Parks of about 20,000 MW capacities in Twenty one (21) states envisaged through Intra state & Interstate evacuation was evolved as Green Energy Corridors-II .

POWERGRID evolved comprehensive transmission plan for evacuation of about 20,000 MW capacity envisaged through Intra & Interstate system and prepared report titled “Green Energy Corridors-II. Implementation of transmission scheme for eight (8) solar parks viz. Ananthapur (1500 MW), Pavagada (2000 MW), Rewa (750 MW), Bhadla-III (500 MW), Bhadla-IV (250

MW), Essel (750 MW), Banaskantha (700MW) & other solar parks in MP (750MW) have been entrusted to POWERGRID.

As part of targeted wind capacity of 60GW by 2022, wind capacity of about 34GW is already achieved in Mar’18. In view of the wind capacity expansion plan as well as connectivity applications received in ISTS for wind capacity, it is expected that wind capacity may cross the milestone of 60 GW in next 3-4 years/ To evolve the transmission plan for potential wind energy zones, an exercise was carried out by all stakeholders viz. MNRE, POWERGRID, NIWE, STUs and SNAs of wind potential rich states as well as wind developers/IPPs. For assessment of wind potential, following inputs/data was provided by stakeholders :

- NIWE provided the district wise potential of various pockets/REZ (Out of total potential of 302GW at 100m above ground level based on Rank-I/II/III grading land) in wind rich states
- SNA inputs for district wise technical potential and balance developable potential by 2022
- STU informed about pooling station wise sanctioned capacity which is likely to come up by 2022
- CTU has provided the data for wind applications received in ISTS in last 1-1.5 years

Based on the inputs and information provided by all stake holders, following wind energy zones was prioritized along with capacity for which assessment of Interstate transmission infrastructure requirement including ISTS pooling stations & line bays needs to be carried out.

S.No	District/Complex	Capacity (MW)
1	Koppal in Karnataka	2500
2	Kurnool in Andhra Pradesh	3000
3	Gujarat	
3a	Dwarka	2000
3b	Kutch (Bhuj)**	3000
3c	Kutch (Bhuj-II)	3000
3d	Lakadia (Bachau)	2000
4	Tamil Nadu	
4a	Karur	2500
4b	Tirunelveli/Tuticorin**	2000
5	Osmanabad in Maharashtra	2000
	Total (MW)	**22000**

*** high transmission capacity corridor already exist /being implemented viz. Bhuj in Kutch distt (Gujarat) & Tirunelveli/Tuticorin distt (Tamil Nadu)*

Accordingly, comprehensive transmission scheme was identified for evacuation/transfer of power from proposed WEZs . The transmission scheme is under various stages of finalization.

. **Conclusion**

India is bestowed with abundant Renewable potential, which offers an excellent solution to attain energy security, environmental sustainability & provide energy access. Transmission planning for integration of large scale renewable generation is a major challenge vis-à-vis planning of transmission system for conventional generation. The gestation period for development of renewable generation is much lesser than time required for development of transmission system. Considering above, a proactive initiative viz. evolution of Green Energy Corridor was taken up, where transmission for high potential renewable zones was planned in anticipation of subsequent Renewable development.

Future large sized wind generation projects & ultra mega solar power plants are more often located at distant location to load centers such as at Deserts, wastelands etc. would necessitate development of long distance transmission infrastructure in phased and modular way. Due to volatility of renewable generation and resulting variation in power flows over high capacity corridors, establishment of hybrid EHV AC & HVDC transmission system were planned. This shall not only help in transfer of power from renewable resource rich states to other deficit States but also complement parallel transmission corridors of conventional generation projects/grid strengthening scheme for transfer of power as well as to maintain grid parameters.

Flexibility can be provided by four types of assets; Interconnections, storage, Demand side management and flexible generation. Therefore apart from strong interconnections, target for flexible generation addition through hydro (including Pumped storage hydro as well as reservoir type), gas and super critical thermal generation are to be followed in line with Renewable capacity addition targets.

6. ACKNOWLEDGMENT

Authors are thankful to the management of POWERGRID for granting permission to present the paper. Views expressed in the paper are of authors only and need not necessarily be that of management.

7. BIBLIOGRAPHY

[1] Central Electricity Authority, Government of India, “Monthly report of Power sector – Mar’18”

[2] Central Electricity Authority, Government of India, “Draft National electricity plan Vol II- Transmission” December 2016

[3] Ministry of New & Renewable Energy, Annual report 2017-18

[4] National Institute of Wind technology “Estimation of Installable Wind Power Potential at 100 m level in India”

[5] CEA 19th Electric power supply report

[6] Solar potentail in India , NISE data “https://mnre.gov.in/file-manager/UserFiles/Statewise-Solar-Potential-NISE.pdf”

[7] National Renewable energy laboratory “India Solar Resource Maps and Data”

[8] Report on Green Energy Corridor

[9] Report of the Expert Group on 175 GW RE by 2022 - NITI Aayog

CIGRE- AORC Technical Meeting 2018 – International Conference on Global Energy Transition – Issues and Challenges, 24-25 May 2018, Gangtok, Sikkim, India

Experience on Energy Time Shift Application of Grid Connected Battery Energy Storage System

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ABSTRACT

Battery Energy Storage Systems are being established as possible solution to problems arising from Renewable Energy intermittency and variability. Renewable Power Output Smoothing, Renewable Energy Firming and Energy Time Shift are some of the areas which are being focused on in this regard. Power Grid Corporation of India Limited has implemented grid connected Battery Energy Storage System with Frequency Regulation and Energy Time Shift application. For the project two technologies are being explored: Lithium Ion and Advanced Lead Acid.

This paper summarizes the aspects associated with Energy Time Shift Application with Lithium Ion and Advanced Lead Acid BESS.

KEYWORDS

Battery Energy Storage System; State of Charge (SoC); Frequency Regulation; Energy Time Shift; Demand Side Management(DSM); Peak Load.

I. INTRODUCTION

Battery Energy Storage System (BESS) are being implemented at source side for renewable output smoothing, renewable firming applications. On the other hand, large scale battery energy storage system at grid level can achieve frequency regulation and energy time shift applications.

One of the key verticals of smart grid is Demand Side Management (DSM). DSM is alteration of electricity consumer behavior in such a way that energy consumption is lesser during peak hours. Energy time shift application of Battery Energy Storage System is aimed at altering the load curve by charging during off peak hours and discharging the stored energy during peak hours.

Power Grid Corporation of India Limited, the Central Transmission Utility of India, has carried out a pilot project in Puducherry with Frequency Regulation and Energy Time Shift Applications.

Two different technologies: Advanced Lead Acid and Lithium Ion have already been commissioned in Puducherry substation of POWERGRID.Frequency Regulation and Energy Time Shift functionalities are implemented through this BESS pilot project. Different aspects of Energy Time Shift Application through Lithium Ion and Advanced Lead Acid Battery are discussed in this paper.

II. STORAGE TECHNOLOGIES

Energy Storage Systems can come in different forms such as mechanical (flywheel, pumped hydro), thermal (Compressed Air), electro-chemical (BESS) etc. Battery Energy Storage Systems are increasingly becoming popular for grid connected applications due to their advantages of modularity, scalability, fast response etc.

The two technologies as mentioned below were chosen for the following advantages.

A. Advanced Lead Acid

Lead-based batteries have been well established in industrial applications for over 100 years, and are well-fitted in several on-grid applications for grid operators and end-users.

Lead acid cells are robust and less sensitive to application conditions. They can be connected in large battery arrangements without sophisticated management systems. As commercial viability of Lead Acid Battery is already established, it is the most economical grid-connected energy storage option.

B. Lithium Ion

Lithium Ion Batteries have the advantages of high energy density, higher efficiency and a maintenance free design. Another major advantage of Lithium Ion is versatility in design and scalability. Lithium Ion batteries can be adapted to any voltage level and any power-energy requirement, ranging from high power intensive to high energy intensive applications.

Lithium ion is also a fast maturing technology with a number of pilot and large scale projects being implemented world-wide.

III. ARCHITECTURE OF BESS

Different Battery Energy Storage System technologies are designed independently and hence the DC bus voltage (an integral multiple of cell voltage) is different for each technology. Each BESS technology comprises of its own Power Management System (PMS) and Power Conditioning System (PCS). PMS and PCS is collectively known as the Battery Energy Management System (BMS). Functionalities of PMS and PCS is described briefly as follows

A. Power Management System (PMS)

Power Management System (PMS) comprises of necessary software and hardware to perform pre-programmed applications such as Energy Time Shift and Frequency Regulation.

B. Power Conditioning System (PCS)

The primary function of PCS is to invert DC bus voltage to a previously fixed AC voltage and synchronization with the Grid. Apart from grid synchronization PCS also houses the control and protection system of the BESS. PCS is equipped with suitable filter harmonic banks to ensure power quality.The system sizing is such that 1.25 MW of BESS will be installed when the complete project is commissioned. Keeping the overall size of the project and tolerance margin in consideration a 2 MVA transformer is considered for stepping up the 433 V of point of common coupling to local grid voltage of 22 kV.

C. Technical Paramaters of BESS

Advanced Lead Acid and Lithium Ion BESS pilot project was conceived with the following parameters:

Parameters	Advanced Lead Acid	Lithium Ion
Capacity	500 kW, 250 kWh	500 kW, 250 kWh
Charging Rate	3hrs from rated DoD to 100% SoC	3hrs from rated DoD to 100% SoC
DC-DC Round Trip Efficiency	>90%	>80%
Service Life	10 years	10 years
Life Cycle	4000 cycles (900 MWh)	3000 cycles (675 MWh)

IV. ENERGY TIME SHIFT APPLICATION

The design of energy time shift algorithm is done from this intuitive stage:

i. BESS should charge during off peak hours

ii. BESS should discharge during peak hours

iii. BESS shall remain idle during normal hours

However, another important consideration for energy time shift application is the State of Charge of the Battery. At the beginning of start of peak hours, the SOC of the BESS shall be sufficiently high so that it can discharge during peak hours. On the other hand, at the beginning of off-peak hours the SOC of the battery shall be sufficiently less.

The below setting were deployed for Energy Time Shift application for Advanced Lead Acid and Lithium Ion BESS system.

Lithium Ion		
Duration	**kW**	**Status**
01:00-05:00	50	Charging
07:00-07:30	100	Discharging
07:30-08:30	150	
08:30-09:00	100	
11:00-12:00	50	Charging
13:00-14:30	100	
15:00-17:00	50	
18:00-19:00	150	Discharging
19:00-20:00	100	
23:00-24:00	50	Charging

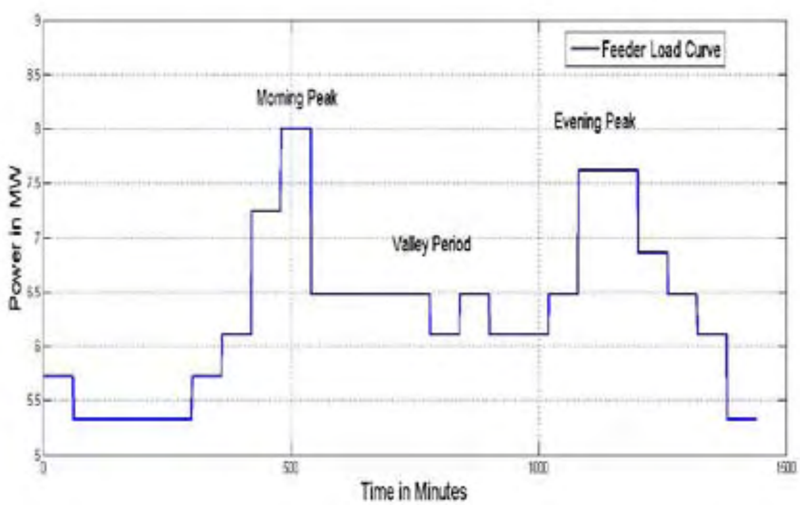
Advanced Lead Acid		
Duration	**kW**	**Status**
01:00-05:00	50	Charging
07:00-07:30	125	Discharging
07:30-08:30	150	
08:30-09:00	125	
11:00-12:00	50	Charging
13:00-14:30	50	
15:00-17:30	100	
18:00-19:00	175	Discharging
19:00-20:00	100	
23:00-24:00	50	Charging

The reason behind slightly different charging characteristics for Lithium Ion and Advanced Lead Acid is reduction of aggregated load on feeder while charging the BESS system.

V. FEEDER LOAD CURVE

The energy time shift application shall demonstrate its effect on 22 kV feeder load curve. However, the feeder has significant industrial load and power of the same is high when compared to the capacity of installed BESS. For analysis purpose, we shall retain the load curve pattern while scaling down the power values, so as to match with capacity of BESS.

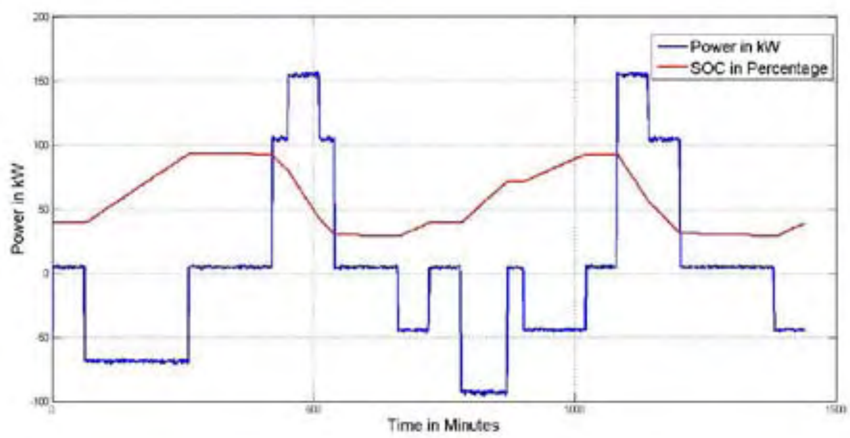
Time vs. Feeder Load Profile is plotted here.



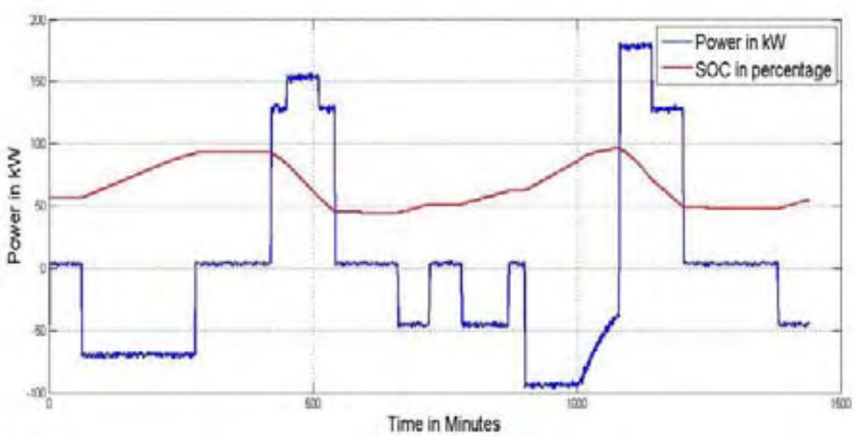
VI. ANALYSIS OF BESS OUTPUT

In this section actual output from the Lithium Ion BESS system, output of Advanced Lead Acid system and their combined effect on the feeder load profile is discussed.

A. Lithium Ion System Output

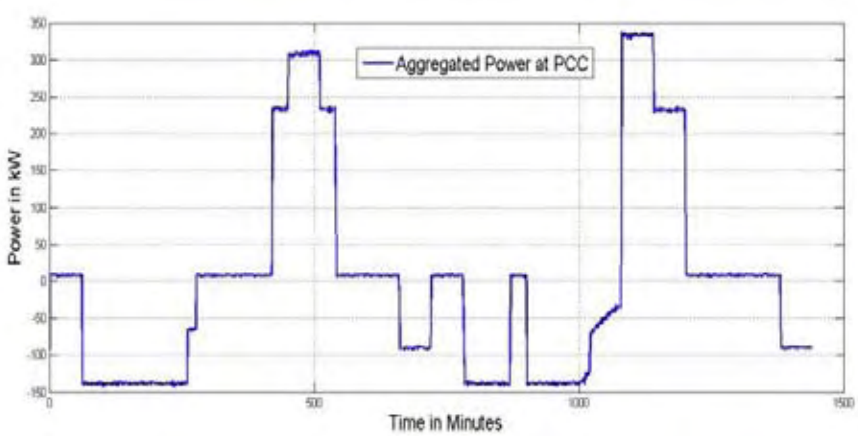


B. Advanced Lead Acid System Output



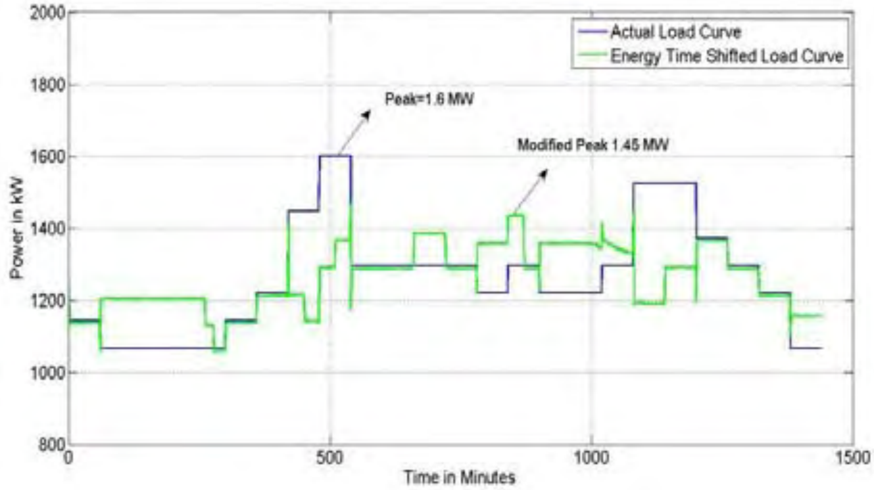
C. Combined System Output

The combined system output at the point of Connection can be depicted as follows:



VII. RESULTS AND DISCUSSION

For demonstrating the effect of Energy Time shift feeder load profile data is scaled t suitable extent without altering the pattern of the load curve. The feeder load curve in t analysis has been scaled by a factor of 0.2. The modified load curve is simulated a considering the effect of energy storage output power.



It is observed that through energy time shift application the peak load on the feeder is reduced from 1.6 MW to 1.45 MW. Reduction in peak load in 1.5 MW which means 9.4% of the peak load can be shaved through energy time-shift application of BESS. The maximum output of BESS system is 325 kW for flattening a peak of 1.6 MW. Hence, 20% BESS is resulting in 9.4% peak shaving in this installation. From the above figure, it can be seen the peak load point (1.6 MW) has been reduced to 1.275 MW. However, a new peak load point (1.45 MW) is created at midday. This is due to charging of the battery during off peak hours to maintain its SOC value, so that energy is available in the BESS for discharging during evening peak hours.

From the load curve of the feeder, following may be defined as peak, off peak and normal hours.

Morning Peak Period	7AM to 9AM
Normal Period	9AM to 6PM
Evening Peak Period	6PM to 10PM
Off Peak Period	10PM to 7 AM

Following are the energy consumption at different periods of the day:

Time of Day	kWh in Normal Load Curve	kWh in Energy Time Shifted Curve
Morning Peak Period	3048	2513
Normal Period	11436	12026
Evening Peak Period	5716	5134
Off Peak Period	10039	10571

From the above analysis it can be seen 1117 kWh energy is shifted from peak hours to normal/off-peak hours using energy time shift application of BESS.Earlier 8716 kWh energy was consumed during peak hours, which is reduced to 7614 kWh after flattening of load curve.

VIII.CONCLUSION

BESS have already been established as an effective solution towards problems arising from grid integration of renewable energy. POWERGRID has demonstrated frequency regulation and energy time shift application through BESS commissioned in Puducherry. This paper discusses the benefits achieved through Energy Time Shift application of BESS. It was found that significant reduction of peak load can be achieved through installation of grid connected BESS support. Further, flattening of load curve is results into shifting of energy consumption from peak hours to off-peak hours.

ACKNOWLEDGEMENT

Authors are thankful to the management of POWERGRID for granting permission to present the paper. Views expressed in this paper are of the authors only and need not necessarily be that of the management of POWERGRID.

REFERENCES

[1] R. P. Sasmal, S. Sen and A. Chakraborty, "Solar photovoltaic output smoothing: Using battery energy storage system," *2016 National Power Systems Conference (NPSC)*, Bhubaneswar, 2016, pp. 1-5.

[2] S. A. Abdelrazek and S. Kamalasadan, "Integrated PV Capacity Firming and Energy Time Shift Battery Energy Storage Management Using Energy-Oriented Optimization," in IEEE Transactions on Industry Applications, vol. 52, no. 3, pp. 2607-2617, May-June 2016.

[3]M. Ahmed and S. Kamalasadan, "Energy storage PV capacity firming with forecasted power reference and optimal error minimization," 2015 North American Power Symposium (NAPS), Charlotte, NC, 2015, pp. 1-6.

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Operation Models of Electric Vehicle Charging Stations in Indian Context

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SUMMARY

Large-scale deployment of electric vehicles (EVs) is anticipated in the foreseeable future in India. The envisaged mass adoption shall require efficient operation of the public charging stations because of the comparative higher charging time requirement with respect to conventional fossil fuel filling station. Further, the additional charging load of EVsmay create bottlenecks in distribution supplying capacity and expose power system to severe security risks. In addition as India is aiming at high renewable energy (RE) penetration, to effectively utilize the same inside the city proper design of and siting RE source and integration is vital for overall cost reduction and making the entire EV charging process free of pollution. In order to reduce the cost of ownership of EV and to get rid of range anxiety issue battery swapping model is an attractive solution. The battery swapping model needs to be designed efficiently such that it shall cater the needs of the user effectively with least waiting time. The positioning of large amount of batteries connected to the grid can facilitate provisions like Battery to Grid (B-G), Grid to Battery (G-B) and also Battery to battery (B-B) these features shall ensure a reliable and secure grid.

In this paper, above said features and issues are addressed while referring to the existing literatures. In order to ensure seamless charging process at the charging stationan efficient operation model is discussed, where facilities like Time of Use (ToU) is adopted for peak demand issue. Further, towards integration of Renewable Energy and Energy Storage System (ESS) and their sizing and siting corresponding to the requirement of EV charging station is discussed. In case of, EV charging through battery swapping a queuing network is discussed, which shall ensure smooth operation at the charging station. Similarly towards G-B, B-G and B-B an optimization model is discussed. Present paper has tried to address the issues in Indian context.

KEYWORDS

Electric Vehicle, Plug in Charging, Battery Swapping, Charging Station, Peak Load Demand, Renewable Energy, Energy Storage System, Optimization

1. INTRODUCTION

The development of Electric Vehicleis a major direction of modernautomobile vehicles. EVs have zero emissions and lownoise level; therefore, they have become an essential approachto solve environmental problems.

The National Electric Mobility Mission Plan 2020 (NEMMP 2020) of Govt. of India is an ambitious initiative that envisages a combination of policies aimed at gradually ensuring a vehicle population of about 6-7 million electric/hybrid vehicles in India by the year 2020. This plan intends to support EV market development and its manufacturing system. NEMMP envisaged a total fuel saving of about 9500 million litres by 2020 that will be around Rs. 62,000 crore of fuel cost. NEMMP is supporting following schemes; (i) Demand side incentives to facilitate acquisition of hybrid/electric vehicles, (ii) Promoting R&D related to EV sector, (iii) Promoting charging infrastructure development, (iv) Supply side incentives, (v) Encouraging retro-fitment of on-road vehicles with hybrid kit. The 2020 roadmap estimates a cumulative outlay of about Rs.14000 Cr by 2020. As part of NEMMP, Department of Heavy Industries (DHI) has launched a scheme namely FAME (Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles) in India. As on 31st March'17 total 1,36,862 EV have been purchased under this scheme. Recently, Ministry of Heavy Industries and Public Enterprises has announced Rs 437 crore subsidies to 11 cities under FAME scheme, for launching electric buses, taxis and three-wheelers. The cities include Delhi, Ahmedabad, Bangalore, Jaipur, Mumbai, Lucknow, Hyderabad, Indore, Kolkata, Jammu and Guwahati. These cities shall have total of 390 buses, 370 taxis and 720 three wheelers. For the next five years i.e. till end of FY 2022-23 FAME has raised a total funding of total Rs. 9381 Crore, where Rs. 629 Cr, Rs. 1215 Cr, Rs. 2304Cr, Rs. 2604Cr, Rs. 2629Cr shall be disbursed year by year.

In last decades, the investments on renewable energy resources havesignificantly increased, promoted by the incentives offered bythe governments.Although relying on such resources presents environmentaladvantages and increases self-sufficiency, there are alsosevere drawbacks that can challenge the traditionaloperational and planning procedures of electric powersystems. The most significant disadvantage is that themajority of renewable energy resources, including wind andsolar power production, are highly volatile and non-dispatchablebecause of their dependence on meteorologicalconditions. Thus, the system operators shouldcarefully take into account this high variability especially inthe case of power systems with significant penetration of renewable energy systems.In particular, the distribution system has a more vulnerablestructure compared to transmission system, and the increase inthe integration of renewable energy sources in the form of distributed generation units needs proper planningactions from the system operator (SO) side. In the same time, the demand sidehas recently shown a considerable change due to the uptake ofa new generation of electric loads. For instance, electricvehicles (EVs) have significant levels of power requirementsas a load and avital potential as a mobile storage unit via the Vehicle-to-Grid(V2G) operation mode with considerable battery capacities[1]. Moreover, the introduction of distributed energystorage systems (ESSs) within the distribution system hasbeen also recognized by SOs as a means of enhancing theoperational flexibility [2].Considering all the aforementioned elements the planningof investments in renewable based Distributed Generation (DG) units and theintegration of new technologies, such as EVs and ESSs, at thedemand side is a prevalent issue.

For countries like India where electricitymarket is regulated, the electricity pricesare decided by the government and, once enacted, remain unchangedfor a relatively long time. At present, the electricitypricing mechanism in India mainly includes the catalog price,the stepwise power tariff and in some places the time-of-use (TOU) price. Unlikecatalog price and the stepwise power tariff, TOU price isnot the same in the different periods of one day, which makesit an important method for demand side management. It isestimated that by 2030 the number of EVs in India will reach 30% of total vehicle, and the total charging load will be up to multiple GWs.With such a considerable capability, the EVsin India will play a significant role in balancing power supplyand demand. Thereby, research on intelligent response to TOUprice is of significance importance [3] [4].

Acceptance of electric vehicles (EVs) isstarting to be evident. However, there are still concernshindering the wide spread adoption of these devices, chieflyrelated to limited mileage range, long charging times, and largebattery replacement costs. Although the number of batterycharging locations are increasing, the charging time at thesestations is either too long or reduce battery life by forcingthem to undergo fast charging processes. An alternative tothese charging stations is the deployment of Battery SwappingStations (BSS), which swap a customer's discharged batterywith a fully charged one of the same type [5]. These stations couldreduce the customers' concerns about long charging times orhaving enough stored energy to finish a trip.

The literature on battery swapping is comparatively smaller. Available literature explains, a mixed queuing networkthat consists of a closed queue of batteries and an open queueof EVs to model the battery swapping processes, and analysesits steady-state distribution [6]. Optimal charging schedule of a battery swapping station with an efficient distributedsolution that scales with the number of charging boxes inthe station is of prime importance [7] [8]. Forecasting a day-ahead modelfor the operation of battery swapping stations and use of robustoptimization technique to deal with future uncertainty of batterydemand and electricity prices helps in reducing overall price [9] [10].

In present paper various mode of operation of EV Charging Station, both Plug in Charging and Charging with Swapping is discussed. Different efficient way of operating the charging stations in Indian context is also presented.

2.ELECTRIC VEHICLE CHARGING STATION

Electric VehicleCharging stations fall into three basic contexts:

i. Residential charging stations; where an EV ispluggedat home, and the car recharges overnight. A home charging station usually has no user authentication, no metering, and may require wiring a dedicated circuit.

ii. Charging while parked (including public charging stations) – a commercial venture for a fee or free, offered in partnership with the owners of the parking lot. This charging may be slow or high speed and encourages EV owners to recharge their cars while they take advantage of nearby facilities. It can include parking stations, parking at malls, small centres, and train stations (or for a business's own employees).

iii. Fast charging at public charging stations the chargers allow for quick charging. They may also be used regularly by commuters in metropolitan areas, and for charging while parked for shorter or longer periods.

iv. Battery swaps technology aims towards least waiting time at charging station and sharing of capital investment towards EV with charging infrastructure developer.

3.PLUG IN ELECTRIC VEHICLE CHARGING STATION

3.1Operation and Control

Remote operation of EV Charging station ensures maximum competitiveness in the business and also helps consumer towards adopting Electric Vehicles. Figure 1 shows operation and control of an E-Car Charging Station, where through a Mobile App/Web based system backend with Charging point management system and customer management system efficient operation is ensured.

The Open Charge Point Protocol (OCPP) [11] is an application protocol for communication between EV charging stations and a central management system, also known as a charging station network. Through this protocol based chargers Charging station owners, or hosts, are less vulnerable to individual system suppliers – if a charging station manufacturer ceased to exist, the host could switch to another OCPP-based network. Giving charging station customers choice and flexibility& interoperability to use any network on any charge station would, through market forces, encourage charging station manufacturers and network providers to compete on price, service, product features, and innovation – all of which encourages demand by charge station owners. The end result is a significant benefit to EV drivers as the charging station infrastructure expands.

OCPP also makes it easier to create a large-scale, visible network that uses a range of different charging stations since there is a requirement for only one operating system. Proponents of OCPP also cite a reduction in development costs since software designed to provide additional functionality would only need to be developed once and not several times to fit with each individual operating system.

3.2 EV Charging Station with Renewable Energy and Battery Energy Storage

In order to reduce the total operating cost ofa charging station integration with PV and fixed battery storage is best suited [2]. Day-ahead and hour-ahead predictive data can be used and model predictive control-based method can be utilized for the predicted data. Operating cost optimization model is established considering the potential uncertainties and customer satisfaction indices, where load can be classified by the significance and flexibility. EV discharging can be encouraged,which can attract more EV customers to participate to provide more resilience in face of unpredictable circumstances, and more reliably serve the customers by coordinating both supply and demand.

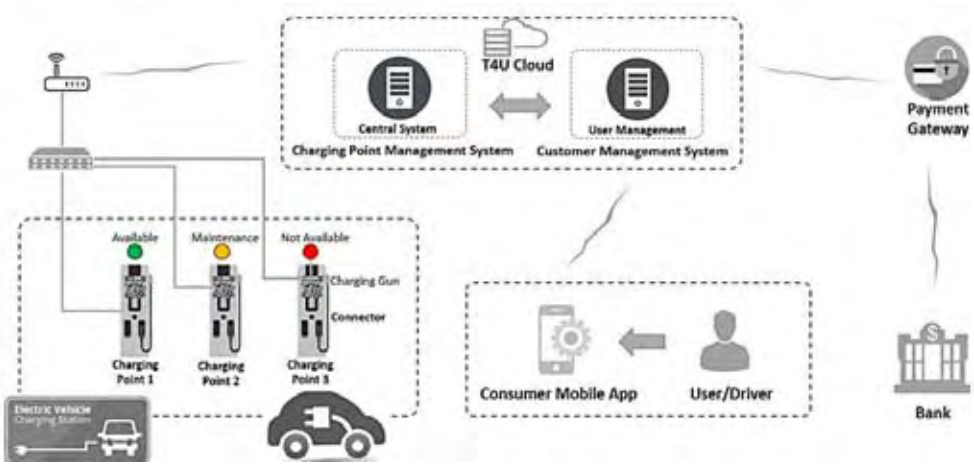


Fig. 1 Remote monitoring and operation of EV Charging Station

For simulation purpose an integrated smart charging station is considered [2], shown in Fig. 2. Building is connected to the same bus as the integrated charging station components, namely PV panels, and fixed battery storage. The PEVs are assumed to support both the charging and discharging mode. Fixed battery storage also operates in the two modes as needed. The output power of PV generation is strongly affected by ambient weather conditions. The integrated charging station considered in this paper is assumed to be located in the parking lots inside or close to the commercial building. It is rational and beneficial to supply the load demand of the building when the integrated charging station has more power supply available, instead of directly injecting power back to the grid. It will be better if the imbalance between the supply and demand can be self-digested. Thus, in this paper, the building is integrated with the charging station, and the load of the building is considered as a “responsibility” for the integrated charging station. Therefore, the load of the building is directly supplied by the integrated charging station. The profit or the load loss cost will also be attributed to the charging station owner.

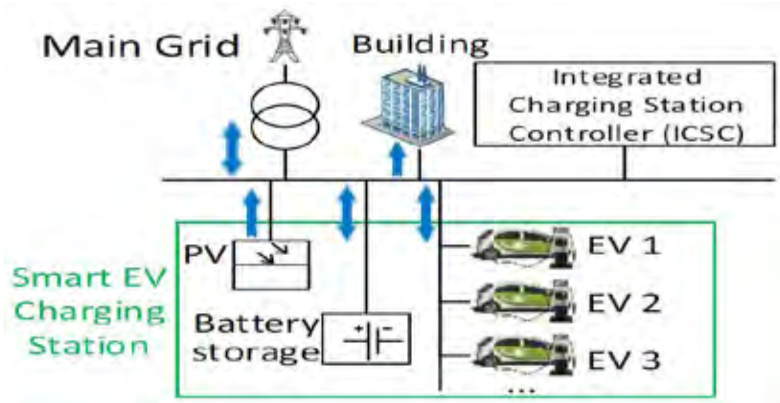


Fig. 2 Network of integrated smart charging stations [2]

In order to coordinate the operation of the integrated charging station, an optimization and control algorithm is used and discussed in Fig. 3. Chance-constrained optimization is utilized in Stage I and Stage III, aiming at supplying the building energy need by the integrated charging station in a more reliable way considering various uncertainties. According to the load demand on-peak and off-peak hours, the result from Stage I is used in Stage II to obtain new charging price based on and maximum participation bonus to attract PEV customers to be involved in charging/discharging program for the next day, as well as to guarantee a specific maximum cost boundary. To make it a better reference for the real-time operation, Stage III optimization considering hour-ahead forecast data with prices obtained in Stage II, is implemented every hour, i.e. 15 minutes before each hour. Each simulation covers the hours from the start of next hour to the last departure time of the predicted PEV participant. To manage the difference between predicted and real data, real-time control aimed at adjusting the hour-ahead schedules is implemented in Stage IV. The highlight of the four-stage algorithm lies in the design of the timeline spanning three time scales, an additional stage to maximize the participation bonus for PEV discharging, and the use of proposed control scheme.

The four-stage optimization and control algorithm reduces the operational cost of the integrated smart charging station. The proposed algorithm spans three time scales, has an additional Stage II to deal with PEV charging/discharging prices to attract customers to participate, and offers a novel control scheme design to improve the operational performance. The following are some major findings from the study: (i) By using the extended coverage hours, no temporary parameter needs to be assigned, and also the integrated station is more prepared for unpredictable condition, (ii) It is beneficial for both PEV customers and charging station owners to use updated PEV charging price and discharging program participation bonus in Stage II, (iii) Using the hour-ahead forecast data to optimize the schedules will not only provide more accurate data, but also dramatically decrease the overall cost, (iv) The proposed control scheme provides higher tolerability for unpredictable circumstances. This algorithm can easily be applied to integrated charging stations connected to any other types of building by replacing the predicted load profile, consumption percentage of each load type and predicted PEV consumption (probability distribution of arriving time) as needed.

3.3 EV Charging Station load and Dynamic Pricing

In order to the cater to the issues pertaining to peak demand government should allow dynamic pricing like TOU in advance, and the prices remain unchangedfor a long time. The user can set the expected ending time ofcharging when EV is connected to the grid through the charger.To protect the battery from being damaged in charging process,the maximum charging power can be also set artificially. Thecharger with embedded TOU price module can intelligently formulateoptimized charging scheme in consideration of the SOCcurve and the maximum charging power set by user (Fig. 4), the aimof which is to minimize the cost and realize peak clipping andvalley filling [4].

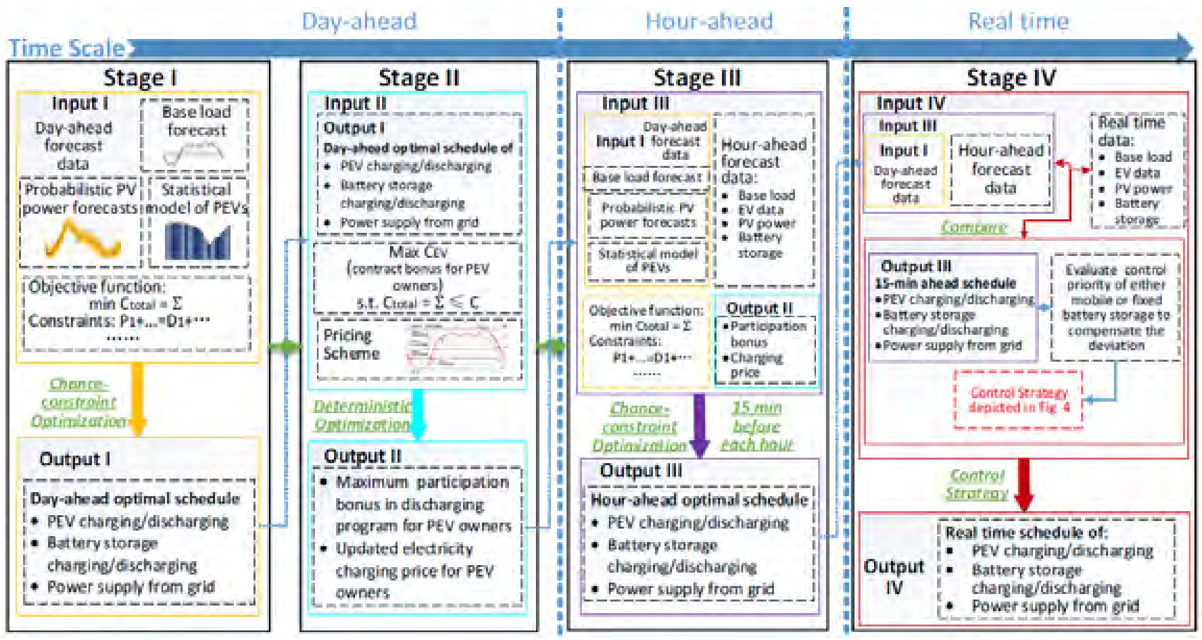
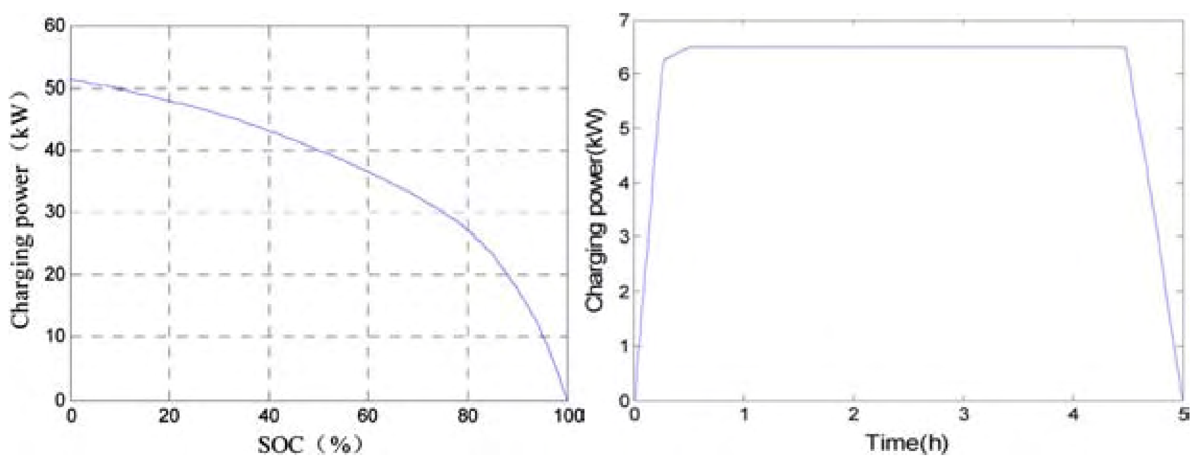


Fig. 3 Optimization and Control algorithm [2]



(a) (b)

Fig.4 (a) The SOC curve, and (b) The charging curve of the lithium-ion battery [4]

4.BATTERY CHARGING AND SWAPPING STATION

Owning an EV will allow the customer to use electricityfor motion rather than fossil fuels. However, potential EVowners are concerned about the long charging times, inabilityto install chargers, limited range, and limited number of publiccharging stations. These concerns can be alleviated but requireinfrastructure investments. The BSS can eliminate these concerns, because the customers do notneed to make an upfront investment in a high-power chargerand will get the expected service in a short-time. Further, the BSS could operateas a storage facility and help avoid or defer investments in thedistribution network. With more customers utilize battery swapping as an alternative to residential charging, less investment inthe distribution network will be required.

4.1 Operation and Control

The Charging and Swapping station operation process are explained in Figure-5. All the batteries to be used in the EV shall be charged at the centralized charging station. Proposed location for centralized charging station should be adjacent to the electrical sub-station. Batteries are to be charged in controlled environment for ensuring maximum battery life cycle. Charged batteries shall be transported to the battery swapping outlets. It is expected that the EV shall swap the batteries from the respective swapping outlet once their batteries gets discharged. The swapping operation has to be done fast to avoid waiting time for the vehicles. The discharged battery from Swapping Outlet shall be shifted to the centralized charging station through logistic vehicle for re-charging.The swapping outlet would be equipped with battery storage racks to store both charged and discharged batteries.

The operation, control and monitoring of the entire process shall be done through a Mobile App. This shall ensure smooth operation at the swapping and charging station. Availability of battery at the swapping station and movement of battery between charging station & swapping station shall be monitored through this App. The BMS (Battery Management System) shall also have communication feature, which communicate the SOC of the battery against which accurate billing can also be done.

4.2 Grid-Battery, Battery-Grid, Battery-Battery

A BSS emulates an energy storage stationthat has the ability to reshape its demand so that peaks are saved rather than increased if the BSS injects electricity backto the power system. This storage capability enables the BSS toperform arbitrage in the electricity market and hence increaseits profit.However, upgradesto the system may be required at the location of the BSSwhich should be reflected in the business model. Lastly, theenergy storage capabilities of the BSS can provide services toa micro grid by supporting the transmission system in cases ofa contingency. The BSS communicates bi-directionalwith the power system to participate in market activities.The BSS optimally schedules batteries to discharge energyto the grid (B2G), charge energy from the grid (G2B), ordischarge/charge energy to and from other batteries (B2B).These features will pose the BSS as an ideal candidate toparticipate in electricity markets andthus exploiting the time-dependency of wholesale electricityprices, while satisfying the energy needs of its battery stock, refer Fig. 6.

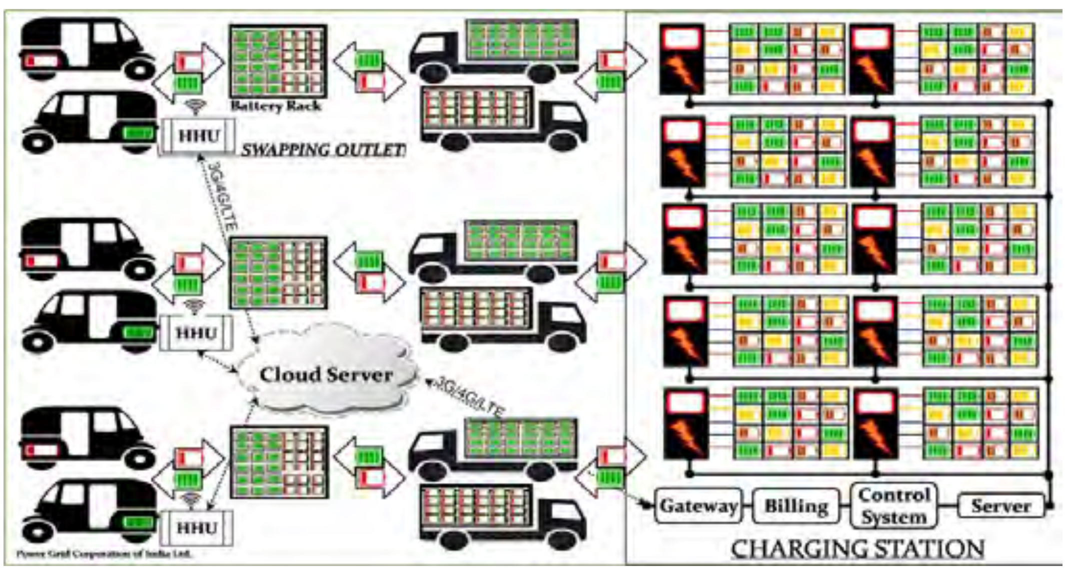


Fig. 5 Operation model of Battery Charging and Swapping process

A business case and an optimizationmodel for a battery swapping station are discussed [10]. The BSS can alleviatecustomer concerns related to long charging times and rangeanxiety. Not only does the BSS benefit customers financiallybut also benefits the power system by participating inelectricity markets and by avoiding or deferring expensiveinfrastructure upgrades. To be profitable, the BSS needsto ensure that the fees it charges, the risk it takes of notsatisfying its customers, and the discounts it offers areproperly designed. Results show that the utilization of marketprices allows batteries to pre-charge during low price periods(G2B), partially discharge during high price periods (B2G),and transfer electricity between batteries when purchasingenergy from the electricity market should be avoided (B2B).

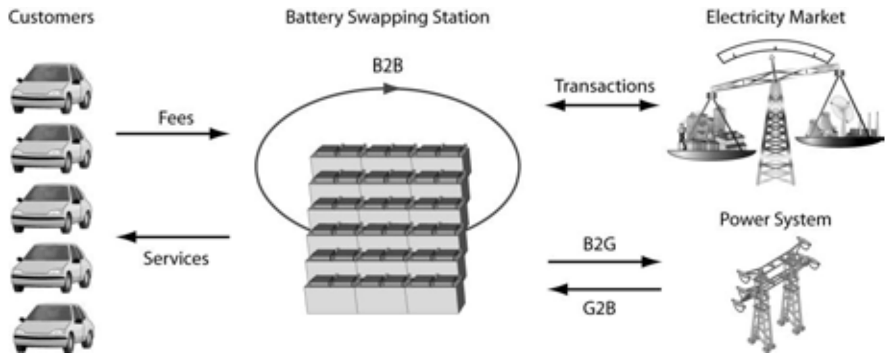


Fig. 6 BSS interactions with customers, market, and power system [10]

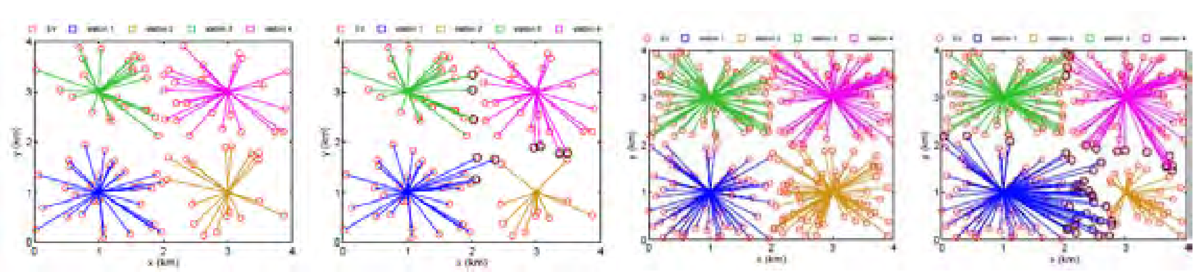
4.3 Swapping Station Allocation

Centralized battery charging and swapping station requires certain additional effort towards effective operation for allocation of swapping station to user. This shall ensure maximize life cycle of the battery and circulation in battery usage, and shall reduce waiting time and manpower. A fleet of EVs and a set of stations operate in a region that is supplied by an active distribution network [6]. It is assumed thatperiodically, the system determines a set of EVs that shouldbe scheduled for battery swapping, e.g., based on their currentstate of charge or EVs' requests for battery swapping. At thebeginning of the control interval the system assigns to eachEV in the set a station for battery swapping. The EVs travel totheir assigned station to swap their batteries before the end ofthe current interval, and batteries returned by the EVs start tobe charged at the stations from the next interval. The goal isto design an assignment algorithm that optimizes a weightedsum of electricity generation cost and the distance travelled forbattery swapping, while respecting the operational constraintsof the distribution network.

Figure7 (a) and (b) shows twospecific cases with 100 and 300 EVs, respectively. In order to decide upon the swapping station allocation, two approaches are proposed Nearest-station policy and Optimal assignment.

In the "Nearest-station policy", without optimization, the default policy is that all EVs head for their nearest stations to swapbatteries refer Fig 7 (a-i) and (b-i). In practicethis myopic policy can lead to battery shortage at a stationif many EVs cluster around that station due to correlation intraffic patterns. Moreover it can cause voltage instability.

In the "Optimal assignment", refer Fig 7 (a-ii) and (b-ii) show the optimalassignments computed using the proposed algorithm for theabove two cases, respectively. The nearest stations are notassigned to some of the EVs (marked black in the figures)when grid operational constraints such as voltage stability aretaken into account. The numbers of such EVs is higher inthe 300-EV case than that in the 100-EV case. The trade-offbetween EVs' total travel distance and the total generation costis optimized. Under the optimal assignment, thedeviations of voltages from their nominal value found to be lessthan the 5%



(i) (ii) (i) (ii)

(a) (b)

Fig. 7 EVs=100(a) and 300 (b) Nearest-station policy (i) Optimal assignment (ii) [6]

With model specifications like EV Arrival, Swapping Servers, SoC Distribution and Charging Servers [7] the queuing network modelto serve as a performance analysis framework for BSSs is explained in Fig. 8. Theproblem was formulated as a mixed queuing network withan open queue of EVs and a closed queue of batteries. It is showed that the equilibrium equations forthe queuing system and that the steady-state distribution is the solution.Authors have used embedded Markov chain to present an alternative yet mucheasier way to obtain the steady-state distribution. Validity of the queuing model and practical insightsfor the design and control of future battery swapping stations is demonstrated.

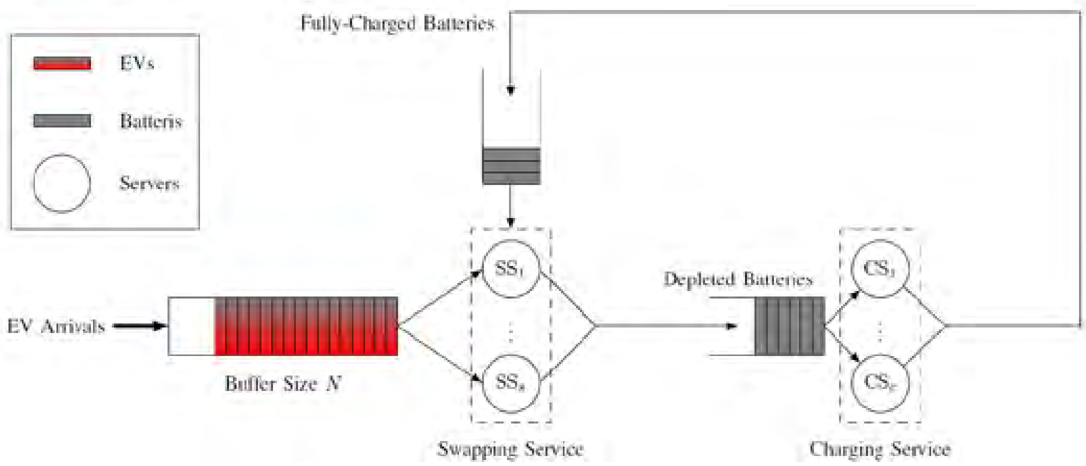


Fig. 8 The queuing network model for the EV charging station with battery swapping

5.CONCLUSION

This paper discusses various processes like remote operation of EV Charging Station, towards RE integration it discusses about sizing and siting of Renewable source, Energy Storage system, and to cater the peak loading situation the use of dynamic pricing or ToU is proposed. These features at EV Charging Stations ensure smooth operation both at Charging Station and Grid level in Indian context.

In case of Battery Charging and Swapping Station, this paper discusses about Grid-to-Battery, Battery-to-Grid, and Battery-to-Grid for improvement of reliability of the Grid and also the charging station. Towards, seamless operation at the swapping station remote operation & control, allocation of EV corresponding to availability, queuing network type of efficient methods are discussed in Indian context.

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BIBLIOGRAPHY

[1] OzanErdinç, Akın Taşcıkaraoğlu, Nikolaos G. Paterakis, “Comprehensive Optimization Model for Sizingand Siting of DG Units, EV Charging Stationsand Energy Storage Systems”, 2017, 1949-3053, IEEETransactions on Smart Grid,DOI 10.1109/TSG.2017.2777738.

[2] Qin Yan, Bei Zhang, and MladenKezunovic, “Optimized Operational Cost Reduction foranEVCharging Station Integrated with Battery Energy Storage and PV generation”, 2017, 1949-3053, IEEE Transactions on Smart Grid, DOI 10.1109/TSG.2017.2788440

[3] Qifang Chen, Fei Wang, Bri-Mathias Hodge, “Dynamic Price Vector Formation Model BasedAutomatic Demand Response Strategy for PV-assisted EV Charging Stations”, 2016, 1949-3053, IEEETransactions on Smart Grid, DOI 10.1109/TSG.2017.2693121

[4] Yijia Cao, Shengwei Tang, Canbing Li, Peng Zhang, Yi Tan, Zhikun Zhang, and Junxiong Li, “An Optimized EV Charging Model Considering TOUPrice and SOC Curve”, IEEE Transactions On Smart Grid, Vol. 3, No. 1, March 2012

[5] Xiaoqi Tan, Bo Sun and Danny H.K. Tsang, “Queueing Network Models for Electric Vehicle Charging Station with Battery Swapping”, 2014, ConferenceSmartGridComm2014, DOI: 10.13140/2.1.5034.2085

[6] Pengcheng You, Steven H. Low, Wayes Tushar, GuangchaoGeng, Chau Yuen, Zaiyue Yang, and Youxian Sun, “Scheduling of EV Battery Swapping, I: CentralizedSolution”, 2017, IEEE Transactions on Control of Network Systems, DOI: 10.1109/TCNS.2017.2773025

[7] X. Tan, B. Sun, and D. H. Tsang, “Queuing network models for electricvehicle charging station with battery swapping,” in Proc. of IEEE InternationalConference on Smart Grid Communications (SmartGridComm),pp. 1–6, 2014.

[8] P. You, Z. Yang, Y. Zhang, S. H. Low, and Y. Sun, “Optimal chargingschedule for a battery switching station serving electric buses,” IEEETrans. on Power Systems, vol. 31, no. 5, pp. 3473–3483, 2016.

[9] M. R. Sarker, H. Pandˇzi´c, and M. A. Ortega-Vazquez, “Optimal operationand services scheduling for an electric vehicle battery swappingstation,” IEEE Trans. on Power Systems, vol. 30, no. 2, pp. 901–910,2015.

[10] Mushfiqur R. Sarker, HrvojePandzi, Miguel A. Ortega-Vazquez, “Electric VehicleBatterySwappingStation:Business Case and OptimizationModel”, ConnectedVehicles and Expo (ICCVE), 2013 International Conference 2013, DOI: 10.1109/ICCVE.2013.6799808

[11] http://www.openchargealliance.org/

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Synchrophasor Measurement based Analytics : Field Implementation Challenges & Experiences

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SUMMARY

Today transmission grid is an interconnected network for large power transfer across the geographically spread regions. This has introduced complexity in system operations.Smartgrid technologies utilizing PMUs are widely installed world-wide in transmission to provide self-healing capabilities.PMU provides reliable, fast and synchronised measurements which helps in advance power system protection and control schemes. Such advance technology will improve situational awareness by enhanced visualisation system to the operator and will facilitate in actuating control signals to improve reliability and efficiency thereby moving towards self-healing.

This paper presents development of PMUs based measurements along with analytical applications for Indian Grid. It presents a pilot deployment of wide area protection scheme in substation. The paper also highlights experiences, key learning from implementing these analytics in real grid environment.

KEYWORDS

Phasor Measurement Unit (PMU), Wide Area Measurement System (WAMS), Smart Grid, Phasor Data Concentrator (PDC)

1. INTRODUCTION

Synchronized measurements are the next generation of paradigm shift technology, enabling improvements in planning, operating and maintaining the vast Electric Grid. The real-time measurements have lot of potential applications and would help the system operator and planner in general. Some of the applications that are studied & discussed in literature are:

- Optimization towards transmission corridor capability.
- Identification of voltage instability
- Load shedding and other load control techniques such as demand response mechanisms to manage a power system stable operation & economics.
- Increase the reliability of the power grid by detecting faults early, preventing local events allowing for isolation of operative system, and the prevention of power outages.
- Monitoring of Inter-area oscillations
- Adaptive islanding
- Network model validation.

WAMS (Wide Area Measurement System) & its utilisation using big data analytics are important thrust area of research among utilities & academics across world. In line with the international findings & suggestions from experts, following analytical applications are taken up at first as a part of research & development with premier academic institute.

- Line Parameter Estimation
- Vulnerability analysis of distance relays
- Linear state estimator
- CT/CVT calibration
- Control Schemes for improving system security (based on angular, voltage and frequency instability)
- Supervised zone-3 distance protection

The work done so far on the analytics & experience gain in deploying the analytics at control centres is briefly discussed in this paper.

2. SYNCHROPHASOR MEASUREMENTS

Synchrophasor measurement is a time synchronized measurements across the widely spread power system network. Time synchronization allows phasors at different locations to be time-aligned and thus provide a comprehensive view of the entire grid. Phasor Measurement Unit (PMU) is the basic device used in Synchrophasor measurements that samples the voltage and current signal at field and converts them into phasors. These phasors are time tagged through a pulse from GPS and streamed at the frequency of 25 to 50 cycles per second. Phasor information is referenced with the GPS signal and transmitted in IEEE 37.118 format [1].Phasor Data Concentrator (PDC) collects the information from multiple PMU & PDCs, align the data by time tag and create a synchronized system wide snapshot.

Data from PMU are well suited for activating local and centralized control thereby making existing grid smarter. In India, PMU pilots in all 5 regions were done with few PMU at different locations & it was observed that visualisation & situational awareness has increased manifold with pilots commissioning. Further Synchrophasor data is being utilized in offline mode for forensic analysis of faults, post-dispatch analysis of grid performance and detection and analysis of oscillations in the power system. Gaining experience from the pilot & recognising the need of WAMS applications in Indian Power System, URTDSM (Unified Real Time Dynamic State Measurement) scheme has been taken up for wide area measurements across Indian Grid. The scheme includes installation of more than 1700 PMUs on substations at 400kV level and above in the State & Central grids, all generating stations at 220kV level and above HVDC terminals, inter-regional connection points, inter-national connection points etc., provision of PDC at all SLDCs, RLDCs and NLDC along with visualization aids. This shall facilitate an URTDSM towards improved system operation and planning. monitoring& visualization and analytics plays a key role in providing intelligent information to operator for secure & reliable grid operation. The paper discusses in brief the important analytics being developed & deployed under URTDSM project for Indian Power Grid.

3. PMU ANALYTICS

a) Line Parameter Estimation

In transmission system accurate line parameter information is required in line protection for relay settings, in network model, load flow analysis tool etc. Incorrect line parameter can lead to erroneous results in each of these applications. In the proposed analytics Line Parameters are estimated using Total Least Square Methods with measurements from PMU [2], [3]. The test setup to estimate the line parameters was carried out with following different field conditions:

- Open circuit test with Line opened from one end & charged from other end
- Short Circuit test (Line to Ground fault)-for zero sequence parameter

The analytics can be configured to run on-demand based on different loading conditions of the line, time of the day etc. It is also possible to process the transmission lines in batch or group and store the evaluated parameters for further analysis.

b) Vulnerability Analysis of Distance Relay (VADR)

Relays are configured with bias towards dependability, which means that they can issue false trip signal due to remote fault or under high stress. Also, with changing network conditions over the passage of time may render relay vulnerable. The mal-operation of such relays can pose threat for grid security. The aim of this module is to use PMU based measurements to identify such relays that are vulnerable to insecure tripping in the event of remote faults.

The relay characteristics from the actual relays are modeled in the analytics. This analytics module continuously checks the vulnerability of relays during stressed condition. Hence, it can expose hidden failures of relays before it can cause any bigger damage to system.

c) Linear State Estimation

Traditionally, a state estimator uses asynchronous measurements of real and reactive power flows and voltage magnitudes. This makes the state estimator non-linear and hence iterative techniques are required. It can suffer from convergence issues. With PMUs in place, it is possible to synchronously measure voltage and current phasors. As a result, state estimation becomes a linear problem and hence can be solved in a single step (non-iterative).

d) CT/CVT Calibration

Instrument transformers, especially CVTs, suffer from drift in characteristics under different operating conditions resulting in biased state estimation. This module will evaluate the accuracy of these instruments using highly accurate Synchrophasor measurement.

The errors will be logged and reported to a system operator. Internal corrections for state estimation will be done and facility to update measurements using correction factor will be provided.

e) Control Schemes for improving system security

Control schemes are fast and high impact schemes to ensure system integrity, or at least minimize the adverse effects of a disturbance. Global signals provided by synchrophasors will allow for more reliable decision making. Controls, involve automatic actions taken in relatively short time (2-3 Sec) where direct operator intervention may not be feasible.

The module will continuously monitor and analyse the stability (like voltage & angular) based on the trajectories of various parameters like voltage, current, breaker status etc. and detect events which may harm the system integrity [4]. Based on the analysis of the evolving trajectories, a decision on whether to take an automatic control action and its quantum & location has to be taken by such a scheme. Examples of controls are adaptive load tripping, generation tripping, and utilization of short term capabilities of HVDC/ FACTS, adaptive protection schemes/philosophies and controlled system separation.

f) Supervised Zone-3 distance protection

This analytic will implement an adaptive remote backup protection scheme to avoid unwanted zone-3 tripping due to quasi-stationary conditions like load encroachment or electromechanical oscillations like power swings. This analytics will work on real-time PMU data. Following are the features of this module.

- Identification of presence of persistent fault in the observable system.
- With PMUs placed at both ends of the transmission lines, differential currents can be computed to identify fault and decide whether the Zone-3 of the back-up relay should be blocked or not. Once, the Zone-3 is blocked, the relay won't operate even if it sees low impedance
- The software will generate control signal for blocking of Zone-3 protection based on system condition and adopted protection philosophy

The field implementation of this analytics is described in below sections

4. FIELD IMPLEMENTATION OF SUPERVISED ZONE-3 PROTECTION SCHEME

a) Preparations

A distance relay doesn’t depend on communication system failure as it operates with local signals. Sometimes, even local measurement’s lead to incorrect tripping. Therefore, there is a need of second level of dependency. Sub-sec synchronized PMU measurement with the help of differential current provides excellent discrimination between faulted and un-faulted transmission line[5]. This may be used as back-up protection for supervising Zone-3.

The backup protection provided by Zone-3 operates in around a second. There is ample time to determine whether there is really a fault using differential logic and communicate the same. This is the essence of a supervised scheme for Zone-3 protection facilitated by PMUs installed at both the ends.

b) The Scheme

With PMUs placed at both ends of the transmission lines, differential currents can be computed. Once differential currents for all backed up lines are available, it is easy to ascertain whether Zone-3 of the backup relay should be blocked or not. Once, the Zone-3 is blocked, the relay won't operate even if it sees low impedance. The critical aspect is that the whole procedure, i.e. obtaining synchrophasors from PMUs, differential currents computation and thereafter communicating appropriate decision to relay, should happen well within one second.

This scheme can even be used to signal accelerated trip in case a fault is actually observed. Consequently, we can send advance ASSERT BLOCK and ASSERT TRIP signals to the relay. Further, if enough information is not available to ascertain whether there is actually a fault in any of the backed up lines or not, then the scheme cannot issue either of the command with certainty. This can happen due to communication failure or unreliable data. In this case action is undecided, so an ENABLE TRIP signal can be communicated to relay. The system will remain in its original state.

Under normal conditions, when apparent impedance is far from Zone-3, relays are not required to be blocked. The requirement arises only if it enters Zone-3. Hence, rather than sending a decision for each PMU sample (every 20-40 msecs) we can start communicating as soon as apparent impedance is close enough to Zone-3. Also, as soon as the impedance is far enough, communication can be stopped. To define closeness, an envelope zone is constructed, which is magnified version of Zone-3 by 1.3 factor & it can be user configurable. If for a certain period (slightly longer than sampling period), no decision is received from the server, the state at the relay end will be set back to ENABLE TRIP. Presently this period is set to 50 msecs. To supervise zone-3 of all lines in the network, relay characteristics of each relay database has to be populated.

The ASSERT TRIP signal can be disabled as per the user requirement. In such case, only ASSERT BLOCK signal will be communicated by the relay. If no signal is received at the substation, the relay state will be defaulted to ENABLE TRIP.

c) The Scheme

In order to ascertain & verify the operating principles and communication requirement associated for the successful operations of the scheme, a small test setup was built around three substations, namely Gurgaon, Manesar and Neemrana. The test setup is as shown in fig 1. PMU data from all these locations are reporting at control center, where live streaming data from PDC is being fed to analytical server.

As there was no real time fault observed on the selected line during testing, fault scenarios were simulated offline which can cause power swing passing in the vicinity of Zone-3 of one of the relays.

Circuit-1 of Gurgaon-Manesar line was selected as the candidate line for this testing. Both live and simulated stream were fed to the supervised zone-3 analytic application. The two streams (both real time & simulated) were time aligned and fed to the analytics.

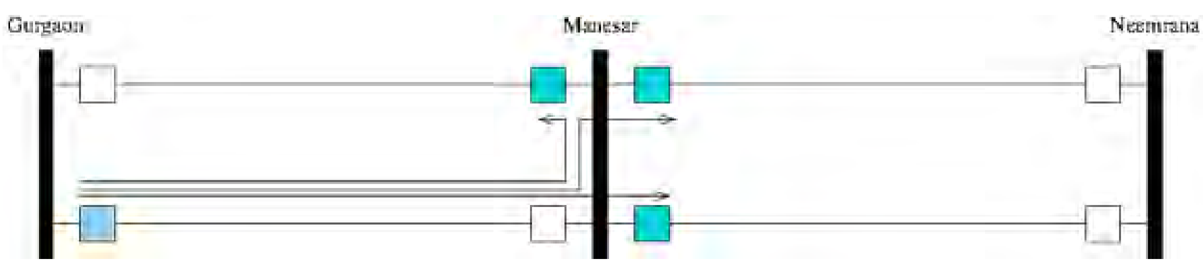


Fig. 1: Test network

A Functional Block diagram of this setup is shown in Fig. 2.

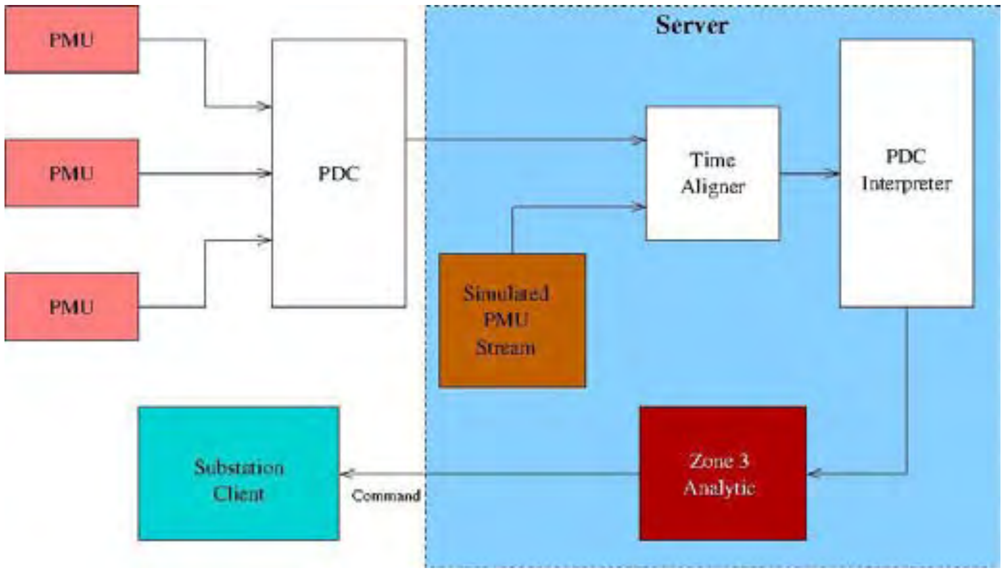


Fig. 2: Block diagram of test setup

During the testing period, it was observed by analytic through PMU data that none of the backed up lines were faulted at any point of time. Hence, whenever apparent impedance as seen by candidate relays was in the vicinity of Zone-3, block signal was issued to them.

d) Functional Description

As seen in fig. 2, the setup consists of various components. These are described as below.

PMUs and PDC

PMUs streams field measurements to the PDC, while PDC time aligns them to create a composite stream.

Simulated PMU Stream

Part of the network measurement has been generated from offline fault simulations. The same is then streamed through PMU simulator.

Time Aligner

The simulated streams are generated locally on server machine with local time stamp and the same are time aligned with the PDC stream through time aligner. This time aligned stream is fed to the analytics for the testing purpose.

PDC Interpreter

The binary streams are interpreted as per the format defined by configuration frame. Further, these measurements are associated with corresponding network element for being useful to the analytic.

Zone-3 Analytic

This block performs computation for Zone-3 supervision. As seen in fig. 3, it mainly contains two components. The first component is 'Zone-3 vicinity detector', which for every relay identifies if the apparent impedance is in vicinity of Zone-3. If it is so, it enables the switch which then relays output of `differential logic', the second component, to the command to be streamed.

Differential logic computes difference between currents at two ends of each line. If any of the line has difference more than threshold, i.e., it actually contains a fault, ASSERT TRIP command will be generated for all the backing up relays. For remaining relays, ASSERT BLOCK will be set.

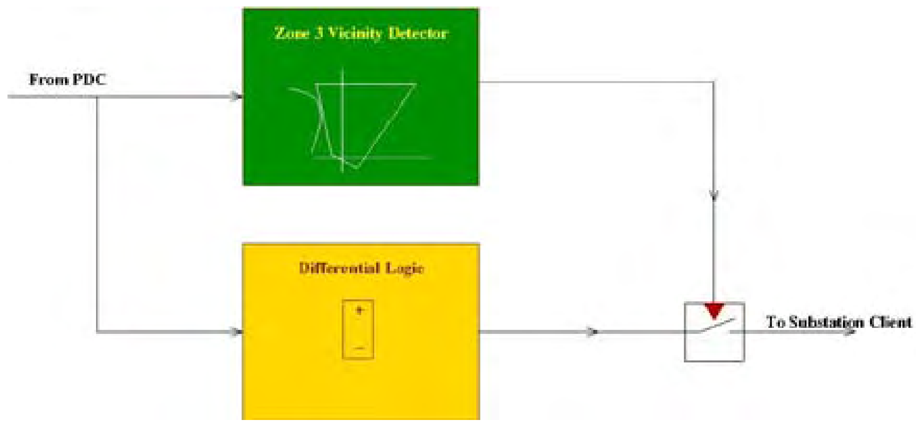


Fig. 3: Logical view of Zone-3 analytic

Substation Client

The above ASSERT TRIP & ASSERT BLOCK signals are extended to substation client through dedicated fibre optic communication channel. The ASSERT TRIP & ASSERT BLOCK signals shall be further extended to candidate relay for desired action. Once the command is received, client starts a timer for a period of 50 ms. If within this time span, next command is received, the same is reflected and time is restarted. If, however, the timer lapses, the state is set to ENABLE TRIP. This ensures that if communication fails, the performance level of unsupervised mechanism isachieved and security of the system is not compromised.

e) Observations

I. The PDC, analytic server machine and client machine need to besynchronized closely to obtain desired results of the scheme. The synchronization achieved between machines was within 3 msec.
II. Time stamp of live PDC stream when received by the analytic server was found to be 135 to 170 msec old due to delay in receiving in measurements from the field.
III. Impedance trajectory enters the vicinity of the relay for a short duration as seen in figure 4.
IV. Block signal associated with the same is received by the client. Corresponding delay from analytic server to client machine was within 10 msec. This is shown in fig 5.
V. The overall delay in complete operation of the scheme i.e. receiving PMU data from field at PDC, analysis by analytical application & further extension of output signal to substation client machine was achieved within 180 msec.

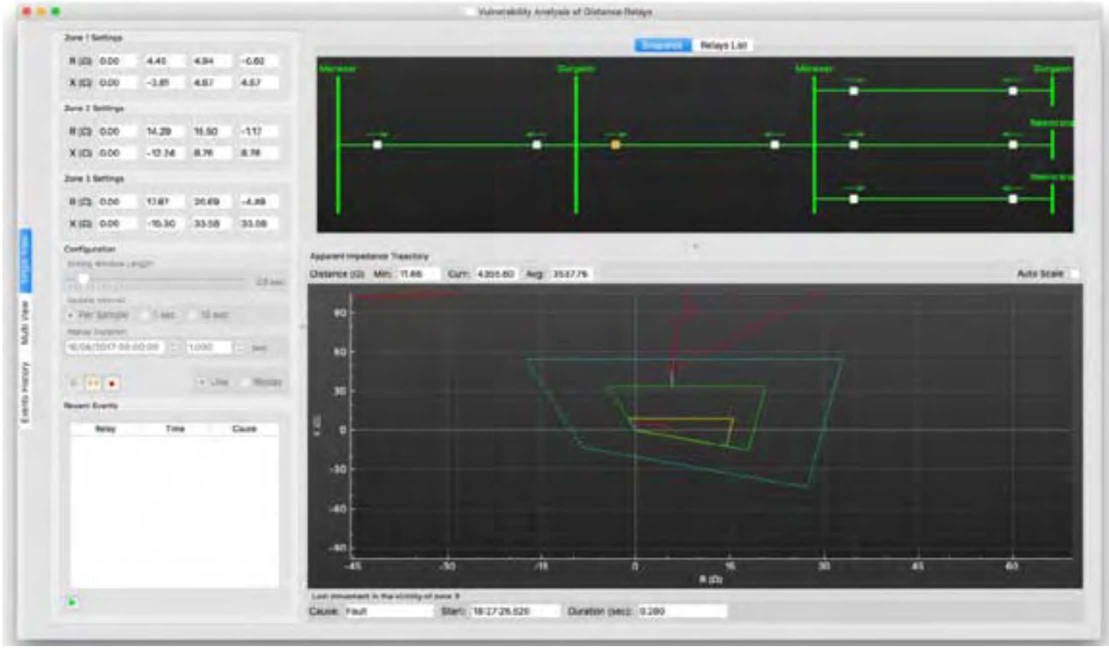


Fig. 4: Apparent impedance seen by analytics

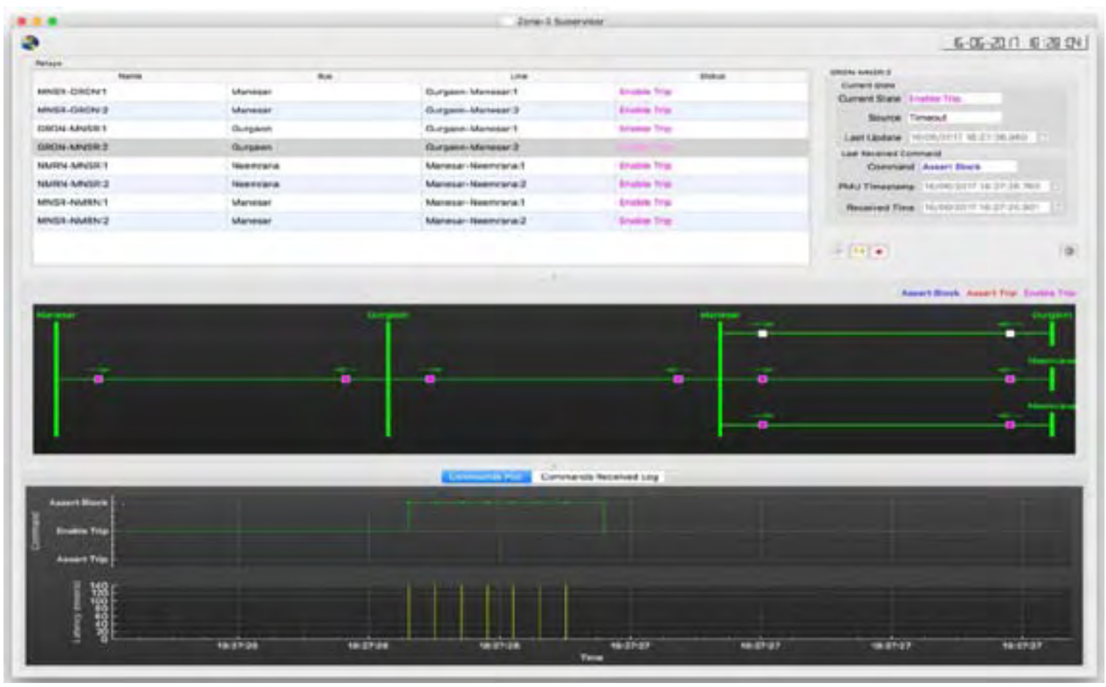


Fig. 5Command Plot

Observed delays are also marked in fig. 6

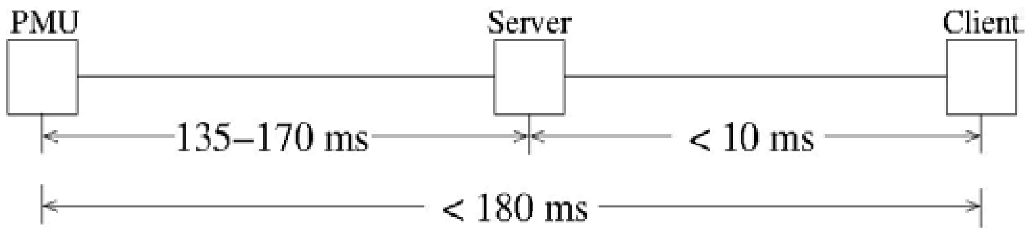


Fig. 6Delays

5. CONCLUSION

The deployment of PMUs under URTDSM scheme is under progress. Analytics such as Line Parameter Estimation, Vulnerability analysis of distance Relay, Linear State Estimation & Supervised Zone-3 distance protection have been developed in association with IIT Bombay & are being deployed on analytics server at control centers across India to analyze & observe the performance. The other applications CT/CVT calibration & control scheme are under development stage.

The Pilot testing of Zone-3 supervisory application was carried out to establish its feasibility in real time field environment. Further, it was observed that for test network, the overall delay in complete operation of the scheme i.e. receiving PMU data from field at PDC, analysis by analytical application & further extension of output signal to substation client machine was within 180 msec. The analytical application have successfully generated TRIP/BLOCK signal as per requirement of supervision of candidate line in zone-3.

Based on pilot deployment experiences & field inputs, these applications are being fine-tuned to address challenges posed by highly dynamic & fast growing Indian Power Grid.

ACKNOWLEDGEMENT

Authors are thankful to the management of POWERGRID for granting permission to present the paper. Views expressed in this paper are of the authors only and need not necessarily be that of the management of POWERGRID.

BIBLIOGRAPHY

[1] C37.118–2011: IEEE Standard for Synchrophasors for Power Systems, IEEE Std., 2011
[2] D. Lan, B. TianShu, and Z. DaoNong, “Transmission Line Parameters Identification Based on Moving-Window TLS and PMU Data,” in The International Conference on Advanced Power System Automation and Protection, vol. 3, Oct. 2011, pp. 2187–2191.
[3] G. H. Golub and C. F. V. Loan, “An analysis of the total least squares problem,” SIAM Jornal on Numerical Analysis, vol. 17, no. 1, pp. 883–893, Dec. 1980.
[4] S. A. Soman, T. B. Nguyen, M. A. Pai, and R. Vaidyanathan, “Analysis of angle stability problems: a transmission protection systems perspective,” IEEE Transactions on Power Delivery, vol. 19, no. 3, pp. 1024–1033, July 2004.
[5] P. V. Navalkar and S. A. Soman, “Secure Remote Backup Protection of Transmission Lines Using Synchrophasors,” IEEE Transactions on Power Delivery, vol. 26, no. 1, 2011

CIGRE technical trends, innovations for Transmission & Distribution of the future

Hiroki Ito
Chairman, CIGRE Study Committee A3

What is CIGRE?

Founded in 1921, CIGRE, the Council on Large Electric Systems, is an international Non-profit Association for promoting collaboration with experts from around the world by sharing knowledge and joining forces to improve electric power systems of today and tomorrow.

Perform studies on topical issues of the electric power system, such as Supergrid, Microgrid, HVDC and lifetime management of aged assets, and disseminate new technology and improve energy efficiency.

Review the state-of-the-art of technical specifications for power systems & equipment and provide technical background based on the collected information for IEC to assist international standardizations.

Maintain its values by delivering unbiased information based on field experience

2

Worldwide Association

3

CIGRE Technical Council: 16 Study Committees

A: Equipment	B: Sub-system	C: System
A1 Rotating electrical machines – N. Smith (S. Africa)	B1 Insulated cables – M. Marelli (IT)	C1 System development & economics – K. Staschus (Germany)
A2 Transformers – S. Ryder (UK)	B2 Overhead lines – H. Lugschitz (AT)	C2 System operation & control – S. Graaf (NL)
A3 High voltage equipment – H. Ito (Japan)	B3 Substations – T. Krieg (Australia)	C3 System environmental performance – H. Sanders (Netherland)
Disseminate new technology and Promote international standardization	B4 HVDC and Power electronics – M. Rashwan (Canada)	C4 System technical performance – Zia Emin (UK)
Technical committee Chairman: M. Waldron (UK) Secretary: Y. Maugain (France)	B5 Protection and Automation – I. Patriota de Siqueira (Brazil)	C5 Electricity markets & regulations – A. Ott (USA)
Secretary General: P. Adam (France)	Perform studies on topical issues of electric power system and Facilitate the exchange of information	C6 Distribution systems & dispersed generation – C. Schwaegerl (Germany)

D: Common technology

D1 Materials and emerging test technique	D2 Information systems and telecommunication
R. Pietsch (Germany)	P. Quenaudon (France)

4

Expansion for more Distribution

CIGRE has recognized that the organization needs to develop to meet the evolving needs of the electrical power system as a whole, including power distribution, distributed resources and a changing range of potential stakeholders.

Unfortunately CIGRE is still very much perceived as a transmission organization, focused primarily upon high voltage transmission systems. CIGRE should be recognized as the pre-eminent provider of "Enhanced knowledge on Energy Systems". A new slogan was created: "CIGRE, Sustainable Electricity for All".

In order to achieve this a transformation over time, it is evident that CIGRE must attract members and experts from a much wider group of stakeholders in the electricity supply industry than CIGRE is able to at present. One of the measures decided by the Steering Committee was to establish a task force "CIGRE SC-Structure" .

5

CIGRE reorganization

The last reorganization was implemented in 2002 (15 years ago)

Now CIGRE need to have an integrated view since SCs is now also dealing with distribution applications besides transmission. However the reorganization was postponed. Instead, keeping the existing organization, CIGRE decided to enforce the distribution activities by adding 6 regular members per each SC with MV backgrounds.

According to new process will select 30 regular members by adding 6 regular members with MV experts. After 8 years of the new operation, CIGRE will make a decision on our possible future organization for 2026-2028 period.

6

Technical challenges for the networks

- Long distance transport
- Better Interconnection between countries / continents
- Reversed load flow from low voltage to transmission level
- Transportations of intermittent distributed renewable sources
- Massive energy storages, penetration of new energy
- New equipment applied with new materials, power electronics
- Less clear boundary between transmission and distribution
- Increase of HVDCs, Hybrid AC & DC power networks

7

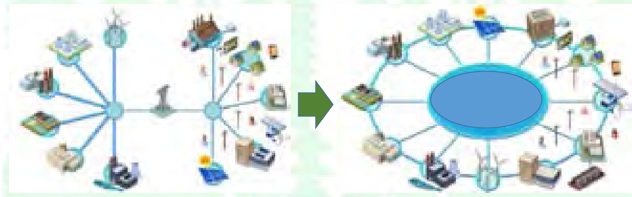
Challenges in power systems

Fast world economic growth requiring more and more power supply, and growing environmental awareness and requirements.

8

Challenges in power systems

The distribution of electricity has to consider the connection of dispersed intermittent generation (wind and solar energy). The distribution network operators have to reconsider the architecture of their networks for bilateral exchanges.



WG A3.40: MV DC switching equipment
WG C6.33: Multi-energy system interactions in distribution grids
WG C6.35: DER aggregation platforms for the provision of flexibility services
WG C6.37: Medium Voltage DC distribution systems

11

Challenges in power systems

First challenge for operators is to keep the existing power systems with old infrastructures / ageing assets operating properly even if they have to face new problems due to the fast development of intermittent power sources.

9

WORKING GROUPS

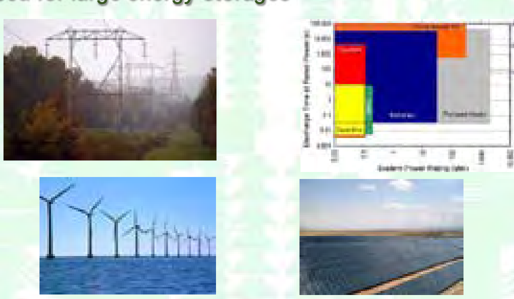
230 Working Groups produce between 40 and 50 Technical Brochures with field exprience and solutions per year.

CIGRE members can download the complimentary copy of the information.

12

Challenges in power systems

Rights of way to build new transmission infrastructures,
Incentives given to renewable energy sources,
Power balancing between countries,
Need for large energy storages



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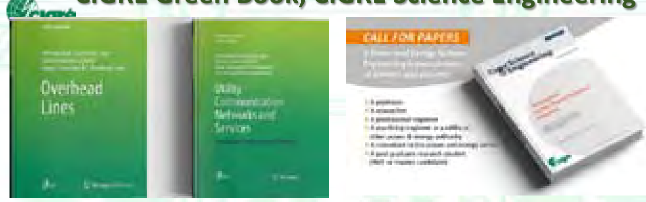
CIGRE Green Book, CIGRE Science Engineering



First Green Book on *Overhead Lines* prepared by Study Committee B2 was published in 2014.

Second Green Book on *Accessories for Extruded HV Cables and Utility Communication Network and Services* prepared by Study Committee B1 was published in 2014

Third Green Book on *Utility Communication Network and Services* prepared by Study Committee D2 was published in 2016.

The following Green Books are under preparation:
- SC A3: *High Voltage Equipment* will be published soon in 2018
- SC B1: *Insulated Cables*
- SC B3: *Substations. SF6*
- SC B4: *HVDC and Power Electronics*
- SC B5: *Protection and Automation*
- SC C6: *Distribution Systems and Dispersed Generation.*

CIGRE Green books are intended to use as a textbook for young engineers in electrical industries.

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Contents of A3 GB on Siwtching Equipment

Chapter 1: Activity of CIGRE Study Committee A3
Chapter 2: Switching Equipment in Power system
Chapter 3: Interrupting phenomena of circuit breaker
Chapter 4: Switching Phenomena in Power system
Chapter 5: History of Circuit Breakers
Chapter 6: SF6 Gas circuit breaker
Chapter 7: Vacuum circuit breaker
Chapter 8: Generator circuit breaker
Chapter 9: AC Disconnecting switch and Earthing switch
Chapter 10: Dielectric withstand voltage tests
Chapter 11: High power interrupting tests
Chapter 12: Modelling and simulation
Chapter 13: Fault Current Limiters
Chapter 14: Controlled switching
Chapter 15: Lifetime management and reliability surveys
Chapter 16: DC switching equipment
Chapter 17: Metal Oxide Surge Arresters
Chapter 18: Novel technologies

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Interruptions for the future

- Development for large capacity circuit breakers
- SF6 Alternatives Gases with C5-PKF and C4-PEN
- EHV Vacuum technology
- Power Electronic technology

Hiroki Ito
Chairman, CIGRE Study Committee A3

AORC TM, Gangtok, Sikkim, India, May 24-25, 2018

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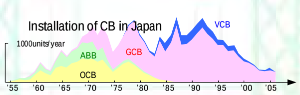
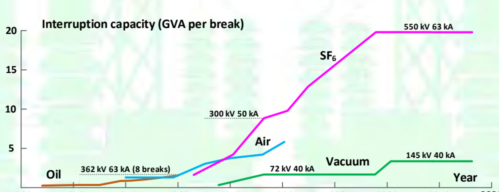
Development of Circuit Breakers





Transition from Air Blast Breakers to Gas Circuit Breakers occurred in late 1960s.
Higher voltage and larger capacity CB developments were accelerated in 80's & 90's.
Development slowed down in the middle of the 1990's.
Technical breakthroughs for HV-VCB and UHV single breaks is required.

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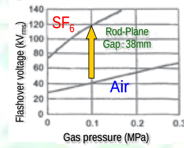
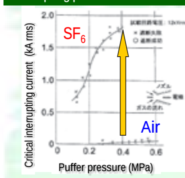
Superior SF6 dielectric, interrupting performance

Dielectric performance: 3 times better



Interrupting performance: 100 times better

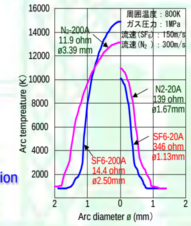


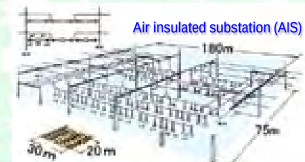
Environmental impact

Global Warming Potential value of 22800 (calculated in terms of the 100-year warming potential of one kilogram of SF_6 relative to one kilogram of CO_2)

SF_6
- Smaller diameter in arc (Less energy dispassion)
- Rapid switching: conductor to insulator (Faster resistance change)

Less breaks for interrupter
Compact equipment & substation





Gas insulated substation (GIS)
5% installation area, 1% volume as compared with AIS

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CIGRE Workshop on SF_6 alternatives

Manufacturer A proposes F-Ketones (C5-PFK) with CO_2 mixtures
Manufacturer G proposes F-Nitrides (C4-PFN) with CO_2 / O_2 mixtures

Table 1: Properties of pure gases compared to SF_6

	CAS number 3)	Boiling point/°C	GWP	ODP	Flammability	Toxicity LC50 (4h) ppmv	Toxicity TWA1) ppmv	Dielectric strength /pu at 0.1 MPa
SF_6	2551-62-4	-64 2)	23500	0	No	-	1000	1
CO_2	124-38-9	-78.5 2)	1	0	No	>300000	5000	**≈0.3**
C5-PFK	756-12-7	26.5	<1	0	No	>20000	225	**≈2**
C4-PFN	42532-60-5	-4.7	2100	0	No	12000	65	**≈2**

Table 2: Properties / performances of gases & mixtures in switchgear applications

	C_{ad} 1)	p_{min}/ MPa 2)	T_{min}/°C 3)	GWP	D.S. 4)	Toxicity LC50 ppmv
SF_6	-	0.43…0.6	-41…-31	23500	0.86…1	-
CO_2	-	0.6…1	≤ -48 6)	1	0.4…0.7	>3e5
CO_2/C5-PFK/O_2 (HV)	**≈6/12**	0.7	-5...+5	1	**≈0.86**	>2e5
CO_2/C4-PFN (HV)	**≈4…6**	0.67…0.82	-25…-10	327…690	0.87…0.96	>1e5
Air/C5-PFK (MV)	**≈7…13**	0.13	-25…-15	0.6	**≈0.85** 5)	1e5
N_2/C4-PFN (MV)	**≈20…40**	0.13	-25…-20	1300…1800	0.9…1.2	>2.5e4

Table 3: Switching performance of gases & mixtures compared to SF6 at increased operating pressures in HV applications

	Operating pressure [MPa]	Dielectric strength/ pu	SLF performance compared to SF_6 /pu 1)	Dielectric recovery speed/ pu
SF_6	0.6	1	1	1
CO_2	0.8…1	0.5…0.7	0.5…0.83	**≥ 0.5**
CO_2+C5-PFK/O2	0.7…0.8	close to SF_6	0.8…0.87	close to SF_6
CO_2/C4-PFN	0.67…0.82	close to SF_6	0.83…(1) 2)	close to SF_6

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CIGRE Workshop on SF_6 alternatives in 2016

Summary of interrupting performance

SLF interrupting performance with CO_2 was reported about 50-65 % and that with F-Ketone mixture is 80 % compared to SF_6.

SLF performance with a mixture of F-Ketones with CO_2 / O_2 (7-8 bar) is 80% compared to SF_6, 245kV GIS de-rated to 170 kV.

Interrupting performance with a mixture of F-Nitriles with CO_2 (7 bar) was cleared for 145 kV, unknown to compared with SF_6

Use of 245 kV (50kA for SF_6) GIS design using the drive with larger mechanical energy under higher gas pressures (7-10 bar for non-SF_6) can provide a 170kV GIS (31.5 to 40 kA for non-SF_6).

WG A3.41: Interrupting performance with SF_6 free switching equipment

Interrupting capability, EHV applicability, Compact designs
Long term stability and reliability
Maintenance works and toxicity of the decomposed gases

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WG A3.27: Application of vacuum switchgear at transmission voltage

2009-2014

245 kV load switch (USA) | 132 kV 16 kA VCB (UK) | 72.5 kV 31.5 kA VCB (France) | 72 kV VCB (China) | 72 kV 31.5 kA VCB (Japan) | 145 kV & 72 kV VI (Germany)

HV-VCB technical merits
Frequent switching capability, Less maintenance work, SF_6 free

HV-VCB challenges at transmission level despite of excellent experience at distribution
Limited experience on long term reliability
Scatter of dielectric performance especially for capacitive current switching
Limited current carrying capability, limited unit voltage
For more information: Refer to Technical Brochure 589

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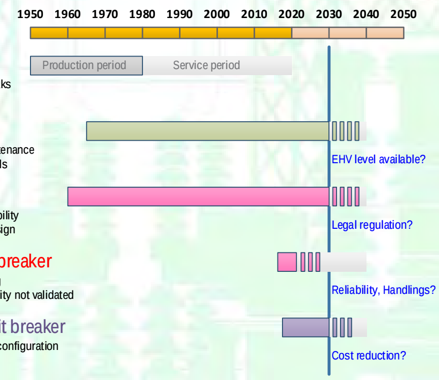
Next generation circuit breakers



Air blast circuit breaker
Less interruption capability _multi-breaks
Less dielectric capability _large size

Vacuum circuit breaker
High interruption capability _less maintenance
Less dielectric capability _No EHV levels

SF_6 gas circuit breaker
High interruption capability _high reliability
High dielectric capability _compact design

SF_6 alternatives gas circuit breaker
Less interruption capability _degrading
More decomposition _long term reliability not validated

Semiconductor HVDC circuit breaker
Rapid interruption capability but large configuration
Semiconductor base _Expensive

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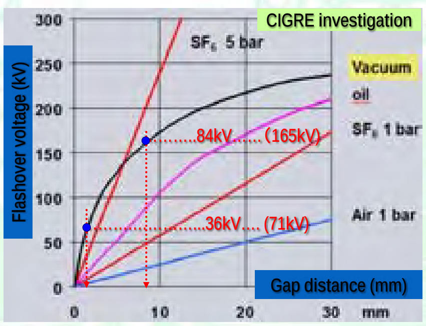
Challenge for EHV vacuum circuit breakers

Recovery voltage of small capacitive current interruption
Voltage factor = 1.7

Transmission levels (8 mm)
165 kV RV peak for 84 kV
141 kV RV peak for 72 kV

Distribution levels (2 mm)
71kV RV peak for 36 kV
47kV PV peak for 24 kV



Dielectric withstand voltage in SF_6 linearly increases with gap distance but that in Vacuum tends to saturate, which makes difficult to increase a unit voltage per break. Requirement for higher current carrying capability need a solution since a vacuum has good insulation properties resulting in less heat conductivity.

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CIGRE Reliability survey on equipment

Hiroki Ito
Chairman, CIGRE Study Committee A3

AORC TM, Gangtok, Sikkim, India, May 24-25, 2018

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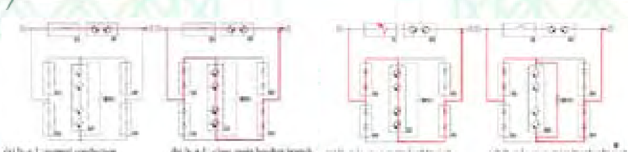
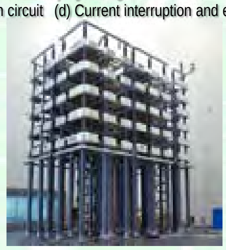
Hybrid mechanical-electronic DC circuit breaker



(a) Current carrying through a main circuit (b) Current commutation to interruption blanch (c) Open a main circuit (d) Current interruption and energy dissipation



China NR news: On December 15th 2016, ±500kV 25 kA DC circuit breaker demonstrated in Lab

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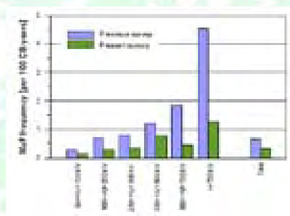
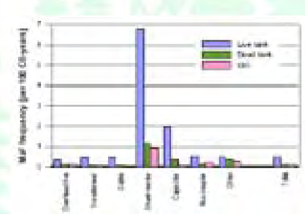
CIGRE WG A3.06: Reliability survey on Equipment

CIGRE Reports of the third international reliability survey on equipment
TB 319 Failure Survey on Circuit Breaker Controls Systems
TB 509 Reliability of High Voltage Equipment - Part 1: General Matters
TB 510 Reliability of High Voltage Equipment - Part 2: SF6 Circuit Breakers
TB 511 Reliability of High Voltage Equipment - Part 3: DS & Earthing Switches
TB 512 Reliability of High Voltage Equipment - Part 4: Instrument Transformers
TB 513 Reliability of High Voltage Equipment - Part 5: Gas Insulated Switchgear
TB 514 Reliability of High Voltage Equipment - Part 6: GIS Practices



Major failure frequency of CB increases with increasing rated voltages



Major failure frequency of CB for different switching applications

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CIGRE WG A3.06: Reliability survey on Equipment

Reliability surveys	1st survey	2nd survey	3rd survey
Period	1974 - 1977	1988 - 1991	2004 - 2007
Objective	All types of CB (In service after 1964)	Single pressure SF6 CB (In service after 1978)	Single pressure SF6 CB (No limitation)
Voltage class	63 kV and above	63 kV and above	60 kV and above
Participation (world)	120 utilities from 22 countries	132 utilities from 22 countries	83 utilities from 26 countries
Number of CB-year	77,892 CB-year	70,708 CB-year	281,090 CB-year

CIGRE reliability surveys can provide good feedback on validity of international standards. There is a well-known unwritten rule that the standards cover 90% of current network conditions in order to avoid too severe requirements, which means there are some special requirements are not covered by the existing standards. For examples,

- Some of CB requirements for transformer limited faults
- Some of CB requirements for reactor switching
- CB requirements for series-capacitor bank switching

For these requirements, special attentions are required for CB applications

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CIGRE Reliability survey in 2004-2007

SF6 circuit breakers (CBs):
281090 CB-years, 0.30 MaF / 100 CB-years

Disconnectors and earthing switches (DEs):
935204 DE-years, 0.21 MaF / 100 DE-years

Instrument transformers (ITs):
1290335 IT-years (1-phase units), 0.053 MaF / 100 IT-years

Gas insulated switchgear (GIS):
88 971 GIS CB-bay-years, 0.37 MaF / 100 GIS CB-bay-years

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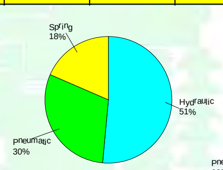
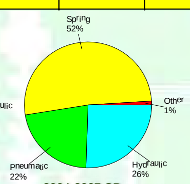
WG A3.06: CB Reliability surveys : rating voltages

Ratings	Major Failure, /100 unit・year			Minor Failure, /100 units・year		
	1st Survey	2nd Survey	3rd Survey	1st Survey	2nd Survey	3rd Survey
	1974 - 1977	1988 - 1991	2004 - 2007	1974 - 1977	1988 - 1991	2004 - 2007
60 - 99 kV	0.41	0.28	0.13	1.65	2.23	---
100 - 199 kV	1.63	0.68	0.28	4.18	4.75	---
200 - 299 kV	2.59	0.81	0.35	6.39	6.97	---
300 - 399 kV	4.55	1.21	0.78	16.35	7.76	---
500 kV & above	10.46	1.97	0.48	4.93	8.18	---
World data	1.58	0.67	0.30	3.55	4.66	2.37



1988-1991 CB survey



2004-2007 CB survey

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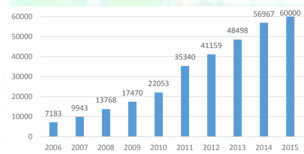
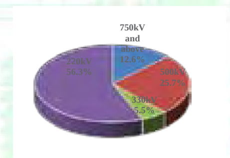
New data collection in 2015 (utility in China)

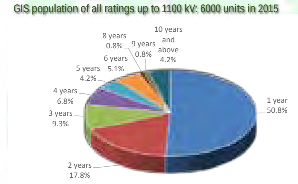
CB population of all ratings: 6000 units in 2015, 258381 units year in 2006-2015,
MaF: 183 units for 10 years, 0.0708/100-GIS/year, For 63 kV <U<1100 kV



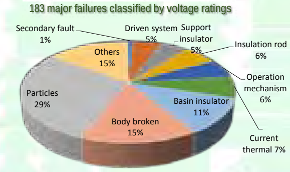
GIS population of all ratings up to 1100 kV: 6000 units in 2015



183 major failures classified by voltage ratings



183 major failures classified by service years



183 major failures classified by components/causes

29

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Exchange Based Trading of Power in South Asian Region

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SUMMARY

The South Asia Region (SAR) is confronting rapid growth in electricity demand, however, electricity supplies have not kept pace with demand and face frequent interruptions. There exists large but unevenly distributed electricity generation potential across countries which also varies across seasons. It is also important to provide incentives for use of efficient resources for power generation while minimizing the associated environmental impact.

Currently in the SA regional power market, there is long and medium term power trading through bilateral agreements. However to extract the full benefit of daily complementarities, a Day Ahead Market platform is essential. The sporadic demand-supply mismatch at the geographical level also calls for a market place where surpluses can be disposed of efficiently on a real time basis to optimise resource allocation. In the SA region, the complementarities among countries are substantial; the details of the same are discussed below.

To understand the actual realization of these complementarities in Day Ahead Market, SARI- EI has envisaged an exercise which provide empirical evidence that South Asian Regional Power Exchange (SARPEX) could massively improve the welfare of each country as well as the South Asian region as a whole. This exercise has also yielded major distributive benefits in terms of consumer and producer surplus for each country and price signal to region. This paper is describing the rational for having a day ahead market platform in the South Asian region, and what fruitful outcome the region may accrue from this platform.

The results from the Mock Exercise provide evidence that SARPEX is not only desirable but also very much feasible. The access to SARPEX regardless of the mode of operation not only helped BBIN in management of demand supply balance on a day ahead basis but also allowed the countries to buy/sell power at a price less than/greater than their marginal willingness. The operating mode however slightly impacted the overall regional surplus which was higher in the Unified mode as compared to the Sequential mode. But, the choice of operating mode didn't have any significant bearing on the total Surplus in BBIN.

KEY WORDS- Power Exchange, Day Ahead Market, Cross- Border Electricity Trade, Regional Cooperation, BBIN, Term Ahead Market, South Asian Regional Power Exchange, SARPEX

1. Introduction to Current Cross Border Electricity Trade in the South Asian Region

South Asian Countries (SACs) (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka) are the home for nearly one-quarter of world's population (~1.7 billion[1]) (Bank, 2016) today. Such a huge population is significantly lagging behind in economic and human development indices. Inadequate economic development due to the power supply deficit for which, inadequate power generation and grid connectivity considered to be the main hindrances.

SA region's per capita electricity consumption (563 KWh) is significantly low compare to world per capita electricity consumption (2977 KWh)[2] (Verma, 2016). All South Asian countries aspire to become fully developed nations by the middle of this century and rapid industrialization is important to achieve this goal. For this, access to adequate and affordable electricity is a prerequisite and also a better human development indices. Currently, South Asian countries has Transmission capacity of more than 2300 MW.

2. Power Exchange for South Asian Region – A missing link

The cross-border trade in South Asian Region is agreement based, mostly medium and Long-term power trade (Ray, Jain, & Nikhil, 2017). Some of the power trade is through traders like PTC and NVVNL. There is exchange based power trade of the Region where. This set-up can only fructify the privilege of resource complementarities but the South Asian Nation do not get the benefits that can only be accessed through Exchange Based trading. India is the only country which has power exchange platforms as a part of its power market. Indian Power exchanges offers a transparent and neutral platform at national level which provides a framework for efficient price recovery of electricity. These and other benefits of a power exchange can be extended to the other nations which are connected to the Indian grid also. The manner in which this can be achieved has been elaborated further in this paper.

3. Power Exchange

Power Exchange (PX) is a platform on which buyers and sellers come together to transact. It is not the market but a host to the market. Its core function is to ensure fair and transparent transactions as well as efficient dissemination of price information to its stakeholders. The importance of energy/power trading through exchange has grown rapidly in Europe and elsewhere due to increased energy consumption and market integration. The range of products a power exchange offers can serve market participants on daily and weekly basis. Some of the power exchange products are: Day Ahead Spot Contract (DAS), Day Ahead Contingency Contract (DAC), Week Ahead Contract, Intra Day Contract, and Renewable Energy Certificates (REC) (Power Exchange India Limited , 2018).

Power Exchange in India offers different products with discrete features .A participant can use this as per there requirement and strategy. Some of the products are Day-Ahead Market (DAM), Term –Ahead Market (TAM), Intra-Day Market etc. Broadly it follow a sequence of steps: Bidding, Matching, Transmission Corridor and funds availability, scheduling, confirmation and result (Indian Energy Exchange, 2018) . To process these bids, the country area in divided into 13 zones.

As per the international experiences, typically power exchanges/power pools started operations in one or two countries. Subsequently, they expanded their operations to other countries turning into a regional

[1] http://data.worldbank.org/region/south-asia

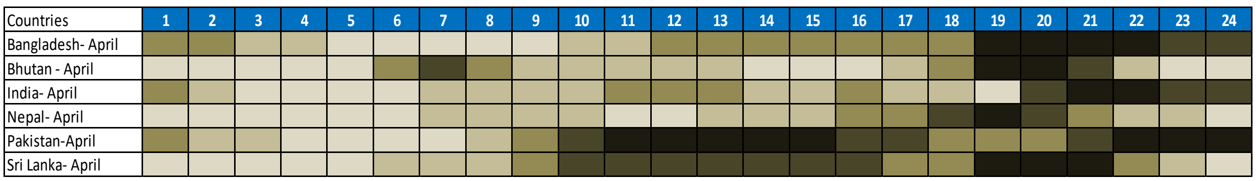
[2] https://www.worldwidejournals.com/paripex/file.php?val=June_2016_1466078018__37.pdf

exchange. The biggest advantage of open market place is that it is less open to manipulation, compared to non-market mechanisms based on negotiations. There is also no room for vested interests and political influence to set prices at inefficient levels.

4. Drivers for Regional Exchange platform in South Asian Region

4.1 **Hourly Complementarities:** The member countries has variation in daily demand curve and to feed that reliable supply is required. Efficient utilization of domestic resources could be a possible option, if adequate storage capacity is used .But using storage has a disadvantage of conversion losses, which could be saved given economic benefit. This daily demand curve variation is substantial (This representative figure 1 has been prepared based on hourly variations in the SACs as on 1st April 2014.) and can be dealt by using day-ahead and intra-day kind of power market products.

Figure 1 : Peak and off-peak hour's difference between the countries



Color Coding	Range	
	Min	Min+ (Max-Min)*20%
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	Min+ (Max-Min)*40%	Min+ (Max-Min)*60%
	Min+ (Max-Min)*60%	Min+ (Max-Min)*80%
	Min+ (Max-Min)*80%	Max

4.2 Seasonal Complementarities

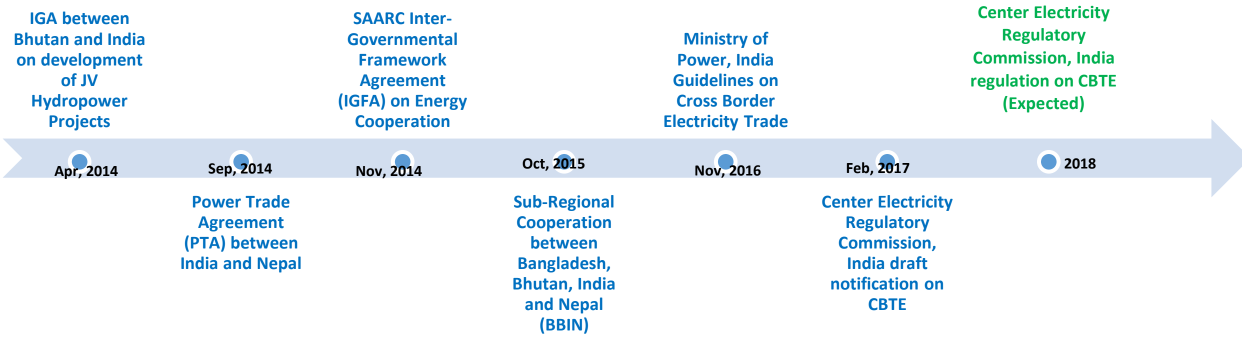
The SA countries also has significant seasonal variation in demand. High electricity demand in Bangladesh can be seen in the month of May where as in other member countries it's low or medium. Such dynamic seasonal variation in demand across the countries provide opportunities for optimal utilization of resources across the borders.

5. Recent Developments in encouraging for Exchange Based Power Trading in South Asian Region

The recent development of CBET related as shown in the figure 2 are indicating that the South Asian country's government inclination towards cross border electricity trade. After having experience of various different type of bilateral CBET, India has allowed power exchange platform based trade for Term Ahead Market (Power, 2016).3 However DAM accounts for more than 95% of power exchange based trade in India.

[3] http://powermin.nic.in/sites/default/files/webform/notices/Guidelines%20for%20Cross%20Boarder%20Trade.pdf

Figure 2 : Recent Cross Border Trade of Electricity Development in the SAR



6. A case for Power Exchange platform for South Asia

A regional power exchange for south Asian nations has been a topic of discussion since very long. In the past study has been conducted, which concluded exchange based trading as a solution for power sector issues (Wijayatunga, Chattopadhyay, & Fernando, 2015). After reviewing the available literature on this subject, it was felt that it is necessary to create a road map for the proposed South Asian Regional Power Exchange (SARPEX). A road map was accordingly developed (Ray & Jain, 2017).

In line with the roadmap, (South Asia Regional Power Exchange: SARPEX) was conducted under the flagship of USAID/SARI/EI program in 2016-18. The exercise focused on ascertaining the feasibility and desirability of SARPEX by quantifying the possible volume in regional market, the surpluses generated for the Region and individual Nations etc. Additionally, the following outputs were also generated from the mock exercise:

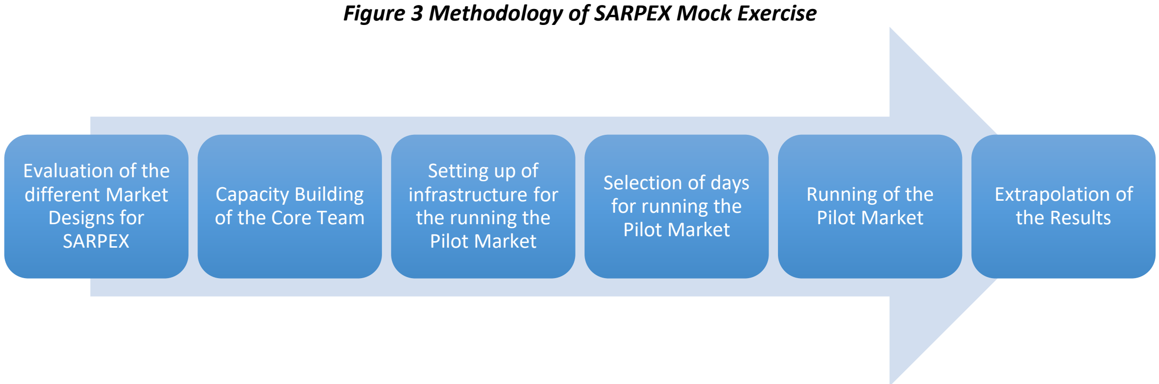
- A set of market design and rules of a SA regional electricity market.
- Capacity building of relevant officials from the SA countries on the functions of a power exchange.

6.1 Approach & Methodology of SARPEX- Mock Exercise:

The Methodology followed to conduct the exercise is shown in figure below. Core team members were nominated by the respective Government/ Organizations of the three countries which are connected to the Indian Grid at present, that is, Bangladesh, Bhutan and Nepal. Additionally professionals from Ministry of Economic Affairs (Bhutan), Bhutan Power Corporation, Power cell (Bangladesh) , Bangladesh Power Development Board ,Power Grid Corporation of Bangladesh, Nepal electricity Authority, Central Electricity Regulatory Commission (CERC),Central Electricity Authority (CEA), Power System Operation Corporation (POSOCO) etc. from India were also involved at various stages.

The approach and methodology adopted for the SARPEX Mock Exercise can be divided into following components as show case in the below figure 3.

Figure 3 Methodology of SARPEX Mock Exercise



6.2 Evaluation of the different Market Designs

The key market design and rules for running the mock exercise was based on the existing power trade and market structure in South Asian region along with the learnings from various existing Regional Power Exchanges. After the mock exercise, the same was revised and recommended as the market rules and design of SARPEX. These market design and rules covers many aspects such as Market Clearing, Congestion Management, Settlement system, Bid aggregation and submission, Modes of operation etc.

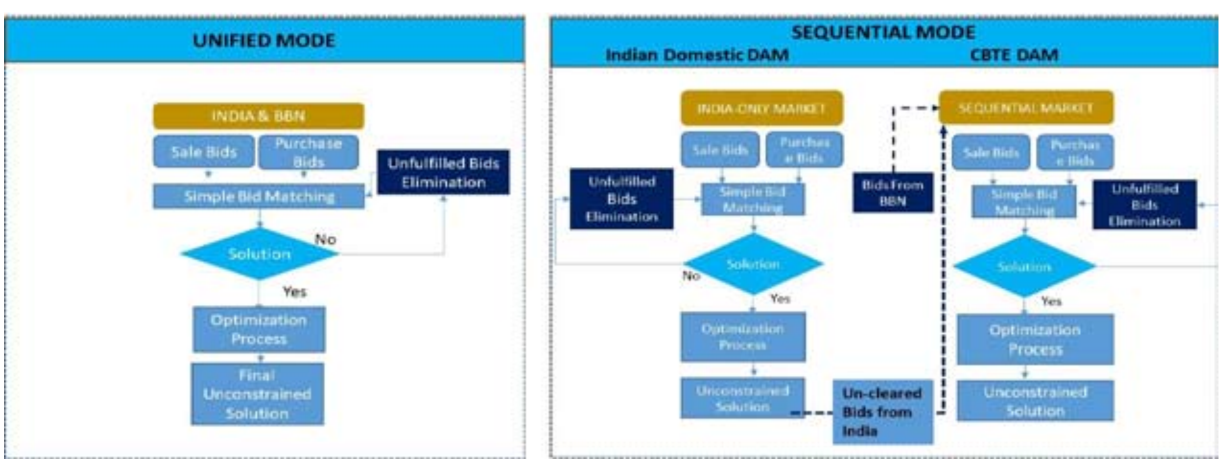
The following two modes of operation were evaluated in the SARPEX Mock Exercise

Unified Mode: In this case, the bids from both the Indian participants and BBN were cleared simultaneously to have a single Unconstrained MCP for the entire region. In doing so, the key features of the DAM as prevalent in the Indian Exchanges today were kept unaltered for Indian entities.

Sequential Mode: In this case, the bids from the Indian participants and BBN countries were cleared in a sequential manner to cause the least disruption to the Indian domestic exchange due to other participating countries. In the first stage, the MCP was determined for India and the un-cleared sell bids from India were aggregated with the buy and sell bids of BBN for determining the MCP of the second stage.

For the purpose of understanding, it may be noted that India only mode mentioned here represent the currently Operational DAM in India.

Figure 4 Unified and Sequential mode of operation



6.3 Capacity Building of the Core Teams

For conducting the Mock Exercise, core teams were nominated from the concerned authorities of BBN In order to ensure proper involvement of the core team members in the Mock Exercise, it was important to develop the necessary skills pertaining to trading on a Power Exchange. To facilitate this, the core teams were trained on the various skills required for power trading on an Exchange including bidding.

6.4 Infrastructure for running the Mock Exercise

To facilitate the uploading of bids by BBN, a web portal[4], mimicking an exchange based platform was created where the bidders could submit their bids and see the results for their bid submission. The web portal was designed in such a manner that after the bid submission, the web-application interacted with the Market Clearing Engine software at the back end to generate and view the results. This allowed for an environment that could maintain confidentiality of bids and transparency of results.

6.5 Selection of Sample Days for Mock Exercise

As it was not practically possible to run the simulations for all the days of FY16, therefore it was imperative to select sample days representing the year for simulating the DAM for a Regional Power Exchange. The results from the sample days were then extended to cover the entire year.

Accordingly 71 sample days were selected using Hierarchical Clustering by grouping the data into clusters such that the objects lying within a cluster have similar characteristics defined through a set of variables.

6.6 Submission of Bids

The core team members that were nominated in each country were entrusted with the task of preparing the buy/sell bids for the selected days after the training was imparted to them in the capacity building workshop. The bids were submitted them by logging in to the web portal just as in case of an operational exchange. The Indian bids were extracted from the information available in public domain.

6.7 Extrapolation of Results

The results obtained from the simulations of 71 days were extrapolated to cover all the days of FY16 to assess the impact of SARPEX on each country, in terms of the key metrics discussed earlier. The methodology used for extrapolation is explained below.

The representative days for the mock exercise were selected using clustering. Thus, each of the selected days in the sample were associated with a particular cluster. The days falling within the same cluster by design had similar characteristics, regardless of the calendar month. Thus in order to aggregate the results at a monthly level, the results for the days falling within the same cluster were averaged to arrive at a ‘typical characteristic day’ for that cluster and such typical characteristic days of each cluster were then averaged over a month (weighted by their frequency) to arrive at the total (extrapolated) monthly figures.

7. Outcomes of SARPEX- Mock Exercise:

The Mock Exercise for FY16 indicated that the initiation of SARPEX would result in an overall surplus of INR 323.63 Billion and INR 323.24 Billion (Including the Surplus if the current Indian Domestic DAM) in the Unified and Sequential mode respectively compared to the overall surplus of INR 313.53 Billion in the India Only mode. The additional surplus, to the tune of about INR 10 Billion could in turn bring higher economic activity and associated increase in the economic welfare of the respective countries.

[4] Web portal link- http://mocksarpex.ga/

The Mock Exercise finds that the BBIN can make significant gains in both modes of operation.

Table 1 : Total Surplus (including Indian DAM) in Unified and Sequential mode (in INR Billion)

	Regional Surplus	Surplus Gain to Bangladesh	Surplus Gain to Nepal	Surplus Gain to Bhutan	Surplus Gain to India $
India-Only	313.53	N.A.	N.A.	N.A.	313.53
Unified	323.63	8.85	0.7	0.3	313.78
Sequential	323.24	8.23	0.63	0.42	313.96

$ Figures are inclusive of the Surplus gain to India from the current DAM market of India
*Surplus gain to Bangladesh and Nepal is mainly accounts for Consumer Surplus
*Surplus gain to Bhutan mainly accounts for Producer Surplus
*Surplus gain to India accounts for both Producer and Consumer Surplus
* N.A. - Not Applicable

It can be seen that the total regional surplus and individual surplus to BBN differed across the two modes. As shown in Table 1 above, the surplus gain to India and Bhutan was higher in the Sequential mode while Bangladesh and Nepal accrued higher surplus in Unified mode. This is because Bangladesh and Nepal are predominantly buyers and prices in the Sequential mode were slightly higher than that of the Unified mode (up to 20 to 35 Paisa) in most cases. A higher purchase price and hence relatively lower cleared buy volumes results in a slight drop in surplus for the buying countries, though the differences are very small in terms of the overall gains to each country from participation in DAM on SARPEX. However, it was noted that the differences were not really significant.

8. Conclusion:

The results from the Mock Exercise provide enough evidence backed up by numbers, that SARPEX is not only desirable but also very much feasible. The introduction of DAM in SAR could immensely improve the producer and consumer welfare in each country as well as the region as a whole. Additionally, SARPEX could also yield efficient price signals, transparency and major distributive benefits in terms of increased fuel diversity, diversified supply mix and decreased overall costs. Therefore, setting up of SARPEX backed by an efficient market design in the form of either Unified or Sequential mode is crucial for enhancing and sustaining cross border trading between the countries.

The access to SARPEX regardless of the mode of operation not only helped BBIN in management of demand supply balance on a day ahead basis but also allowed the countries to buy/sell power at a price less than/greater than their marginal willingness. The operating mode however slightly impacted the overall regional surplus which was higher in the Unified mode as compared to the Sequential mode. But, the choice of operating mode didn't have any significant bearing on the total Surplus in BBN.

The operating mode had an impact on India as its consumer surplus in Unified mode reduced as the new market entrants i.e. Bangladesh and Nepal with higher willingness to pay displaced some of the low cost Indian buyers. However, the situation was completely nullified in the Sequential mode as by virtue of its design, it didn't impact the existing operations of the Indian participants. However, in terms of the total surplus, India gained in both the Unified and Sequential mode because the un-cleared sell bids were cleared through purchase bids of Bangladesh and Nepal, thereby making it symbiotically beneficial to all the countries.

Further, it was also found that adequate inter country transmission capacity is critical for ensuring higher Surplus in the region. The Surplus Gain to BBIN witnessed in FY16 was far higher than the annual transmission charges of the interconnecting transmission lines. Thus, any investments for enhancing the transmission capacity could result in huge dividends in terms of increased economic gains and social welfare. Therefore, strengthening of inter-country transmission capacity could permit more volumes on SARPEX resulting in further increase in surplus due to a larger and efficient market size.

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Bibliography

Bank, W. (2016). World Bank. Retrieved from https://data.worldbank.org/region/south-asia

Central Electricity Regulatory Commission. (2017). Report on Short-term Power Market in India:2016-17. New Delhi.

Indian Energy Exchange. (2018, May 15). https://www.iexindia.com/products.aspx?id=15&mid=2. Retrieved from https://www.iexindia.com: https://www.iexindia.com/products.aspx?id=15&mid=2

Power Exchange India Limited . (2018, May 18). https://www.powerexindia.com/PXIL/insidepage.aspx?id=10. Retrieved from https://www.powerexindia.com: https://www.powerexindia.com/PXIL/insidepage.aspx?id=10

Power, M. o. (2016, December). Guidelines on Cross Border Trade of Electricity. India.

Ray, S. K., & Jain, G. (2017). Roadmap for South Asian Regional Power Exchange. New Delhi: SARI/EI.

Ray, S. K., Jain, G., & Nikhil. (2017). Development of Regional Electricity Markets. In S. M. Khasru, Connectivity and Trading in Power & Energy : A Regional and International Dimension (pp. 123-136). Dhaka: IPAG.

Verma, R. (2016). Cross Border Electricity Trading in SAARC Countries. Indian Journal of Research-PARIPEX.

Wijayatunga, P., Chattopadhyay, D., & Fernando, P. N. (2015, August). Cross-Border Power Trading in South Asia: A Techno Economic Rationale. Cross-Border Power Trading in South Asia: A Techno Economic Rationale. Manila, Philippines: Asian Development Bank.

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