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STUDY COMMITTEE D2
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Mysore – KARNATAKA - INDIA

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SYNCHROPHASORS: IMPLEMENTATION, TESTING AND OPERATIONAL EXPERIENCE

By

Uttam Mishra

Protection Application Engineer
Doble Engineering Company

ABSTRACT

As the electric power grid continues to expand and as transmission lines are pushed to their operating limits, the dynamic operation of the power system has become more of a concern. Synchrophasors provide power system information and facilitate a variety of applications. Phasor measurements are continuously streamed information. They provide actionable quantities to give clarity during a rush of events. This is important during line outages, generation changes, voltage fluctuations and other complex operating conditions. It is desirable to have PMU over traditional state estimators that provide lagging and inaccurate system information when the system is experiencing an event.

This paper will review the application of synchrophasors to observe power system dynamic phenomena and how they are useful in the real-time control of the power system with operational examples and case studies. The paper will also explain the PMU testing methods and analysis of results.

Key word: Synchrophasor, Phasor measurement unit, WAMS

INTRODUCTION:-

. The conventional power system monitoring, protection and control system are based on local measurements. However, it is quite difficult to maintain the stability and security of the system on the whole, if only local measurements are utilized in the monitoring, protection and control schemes. One promising way is to provide a system wide protection and control, complementary to the conventional local protection strategy. While it is not possible to predict or prevent all contingencies that may lead to power system collapse, a wide-area monitoring and control system that provides a reliable security prediction and optimized coordinated action is able to mitigate or prevent large area disturbances. The main tasks, which can be accomplished through PMUs are early recognition of large and small scale instabilities, increased power system availability through well coordinated control actions, operation closer to the limit through flexible relaying schemes, fewer load shedding events and minimization of the amount of load shedding. The main disadvantage of the present conventional methods of system monitoring is the inappropriate system dynamic view, or the uncoordinated local actions, like those in decentralized protection devices. Solution to the above can be achieved through dynamic measurement system using synchronized phasor measurement units i.e. PMU. Phasor measurement unit (PMU) is a device, which can extract phasors with respect to a time synchronized reference signal. In addition, it could be able to determine analogue measurements such as frequency, rate of change of frequency (ROCOF) and power as well as digital measurements such as circuit breaker status. With new advances in processing and equipments, PMU can be a stand-alone unit as well as a functional unit within another physical unit such as a protective relay or a power system data recorder. A system comprising synchronized phasor measurements and performing the tasks of stability assessment with adaptive relaying is called a Wide-Area Monitoring, Protection and Control (WAMPAC) system.

* 2nd floor Suvidhi Pride, Gorwa Refinary Road, Vadodara, Gujrat (India)
Fax: + 91 265 2290995 e-mail: umishra@doble.com

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PMU APPLICATIONS

PMUs are a very promising technology for the protection applications of the future. There are some wide area protection schemes, such as load shedding, which are in use today. For normal protection, PMU technology has some limitations. Though steady-state requirements of a PMU are well-defined, transient behavior of a PMU is not well-defined, and various units operate differently under transient conditions. Due to the slow response time of PMU technology, it has been applied mostly for backup protection applications. The backup applications where present PMU technology has been applied are power system stability, two ended fault location algorithms, system diagnostics, distributed bus bar protection, load shedding, line reclosing selectivity, and wide area frequency monitoring. Some of the applications are described in this paper.

POWER SWING DETECTION

One of the most promising applications of PMU is in the power swing detection. When a fault occurs on a system, the power transfer between two buses where the fault occurred increases. At each end of a line that connects separate buses, voltages can become unstable and continuously change at both ends. The change in bus voltages is caused by power swing, and the angle between the buses will oscillate. By observing the angle and applying equal area criteria to the power curve, it can be determined whether it is a recoverable power swing (stable power swing) or unrecoverable power swing (unstable power swing). If it's a recoverable power swing, which can be determined by measuring the angle swing between the two buses, appropriate actions can be taken. If it is determined to be an unrecoverable power swing, a different set of actions or criteria can be determined to isolate the problem. Some power swing conditions, whether stable or unstable, can be determined by using a special algorithm. This is only possible by making real-time measurements and making decisions in real-time, which is provided by the PMU technology.

SPECIAL INTEGRITY PROTECTION SCHEME (SIPS)

Special Integrity Protection Scheme, such as load-shedding schemes, requires measurement of voltage and current throughout the system. Based on the system wide measurements, appropriate actions can be taken. Traditional schemes were based upon predetermined sequences of actions based on assumed extreme conditions. The extreme conditions and actual system conditions are different so the effectiveness of the SIPS scheme is somewhat compromised. PMUs provide actual data in real-time, which can determine corrective actions to keep the system intact. Wide area stability and voltage control systems can use PMU data to make intelligent decisions and prevent wide area blackouts. This is the biggest area of potential growth of PMU applications today.

DISTANCE TO FAULT LOCATION

Distance-to-fault location calculation is another area that is very promising. Single-ended algorithms for detecting fault locations have been readily available technology for several years, but having a double-ended algorithm, determined by information provided by PMUs placed throughout the power system is a very desirable application. Thanks to today's communication technology advancements and accurate time-stamped power system values provided by PMUs, system performance can be measured and verified to help determine fault locations. Using negative sequence values provided by most PMUs, it is very easy determine distanced to fault location for all types of fault except three phase fault. For three-phase faults, positive sequence values are used. Following figure indicates the equivalent power system network for the fault condition.

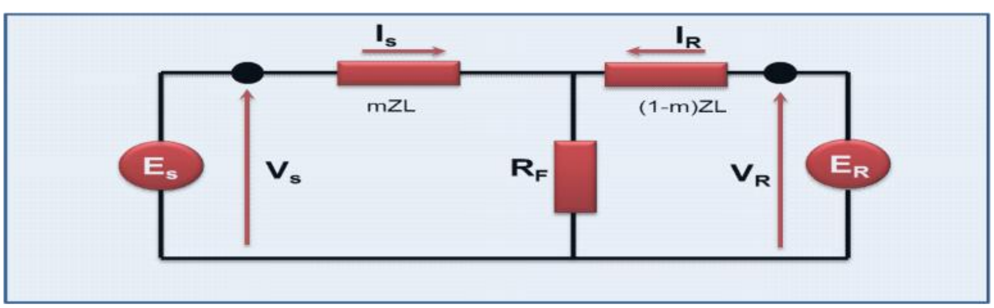


Figure 1

In the above figure, Vs and VR are the sending and receiving end voltages respectively measured by protection at each end. RF is the fault resistance and "m" is the distance to fault (0.5 for 50% of fault). ZL is the positive sequence impedance of the line.

The equivalent negative sequence network is as shown in the following figure.

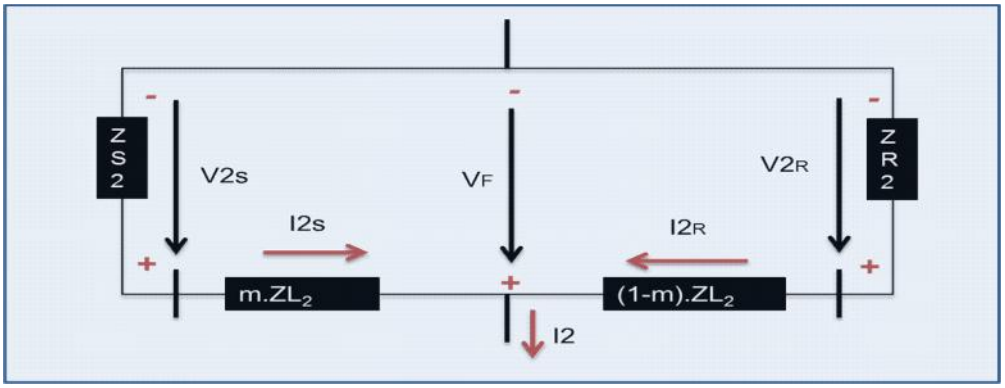


Figure 2

Using PMU at both end of the line, it provides all the data of voltages and currents seen at each end of the line. The above figure allows us to calculate value of 'm" as shown below.

- $V2_S - I2_S*mZL_2 + V_F = 0$ & $V2_R - I2_R*(1-m)ZL_2 + V_F = 0$
- $V_F = I2_S*mZL_2 - V2_S$ & $V_F = I2_R*(1-m)ZL_2 - V2_R$
- $I2_S*mZL_2 - V2_S = I2_R*(1-m)ZL_2 - V2_R$

Figure 3

From the above equation, the value of "m" can be calculated as shown below.

$$m=\frac{I2_R*ZL_2+V2_S-V2_R}{ZL_2*I_2}$$

Figure 4

Using PMU data the distance to fault calculation can be done with high accuracy as data from both end of the lines are available. With the single ended fault locators the errors in the calculations are quite high. Lack of information provided from the other end provides as much as 10 to 15% error in fault calculations. Three terminal line applications can have as much as 38% error. Since 2008, Taiwan power employs PMUs based on double-ended algorithms for fault locations. PMUs are installed on 345 kV and 161 kV power systems. There have been 40 events evaluated to date. The fault location accuracy, using PMU technology with a two terminal lines algorithm, is 1.878%, compared to the 10 to 15% with single-ended fault location algorithms. Accuracy of three terminal line PMU algorithm applications is 1.35%, compared to 40% for single ended fault location algorithms.

In addition to fault location calculations, real-time decisions of reclosing functions can be made when there is a mix of overhead lines and underground cables. If the distance to fault location suggests faults in the overhead section, reclosing can be initiated while if the fault location algorithm indicates fault in the cable section, reclosing can be blocked.

PMU Testing:-

Goal: under various conditions, make sure that the reported each PMU data message matches the expected values for each Phasor Vector, Frequency Deviation and Rate Of Change Of Frequency (ROCOF). Highly precise protection test sets with versatile time synchronization features can cover a significant range of test cases. Protection test sets are different than other general purpose laboratory testing equipment for time, voltage and current. They are perfectly adapted to the domain of three phase electrical power systems and allow the specification of the test signals in familiar terms.

Why it is required?

- Errors in station sensors (CTs, PTs)
- Time synchronization accuracy (GPS receiver clocks – crystal used, drift, ageing, etc)
- Inherent error in the PMU device over time

How it is achieved?
– Standard test set
• Capable of generating GPS based synchronized signals
• Accurate GPS clock capable of generating both IRIG-B and 1PPSsignal output
• Stable system frequency generation and or compensation
• Should have at least 10th of accuracy as mentioned in compliance of C37.118 for each conditions

Synchrophasor technology enables a new generation of monitoring and controls. Testing is challenging but standards for measurement and test will provide common ground to all. Test data and experience will lead to improved PMUs, standards, and measurement systems.

Standard requirement:

- Steady state tests
  - Frequency
  - Voltage
  - Current
  - Phase (discrete or continuous)
  - Harmonic Distortion
  - Out of band interference
- Dynamic tests
  - Phase and Amplitude Modulation
  - Phase Modulation
  - Linear Frequency Ramp
- Transient tests
  - Magnitude step
  - Phase step

Test Set up:

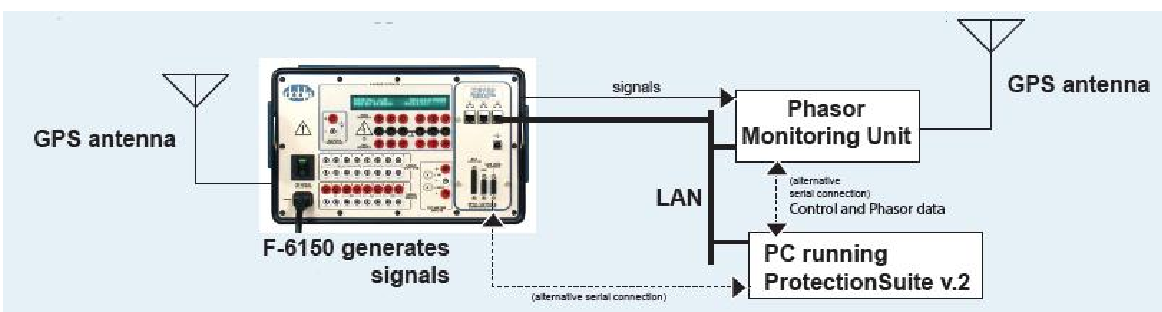


Figure 5

(PC, F6150 and PMU each have IP addresses)
Protection Suite → F6150: Waveform definitions, start time
Protection Suite → PMU: Request configuration, start transmission
F6150 → PMU: Generated waveforms
PMU→ Protection Suite: Configuration response, phasor data stream

OPERATIONAL EXPERIENCES:

Case Study-1: Automatic Generator Shedding Using Synchronized Measurement

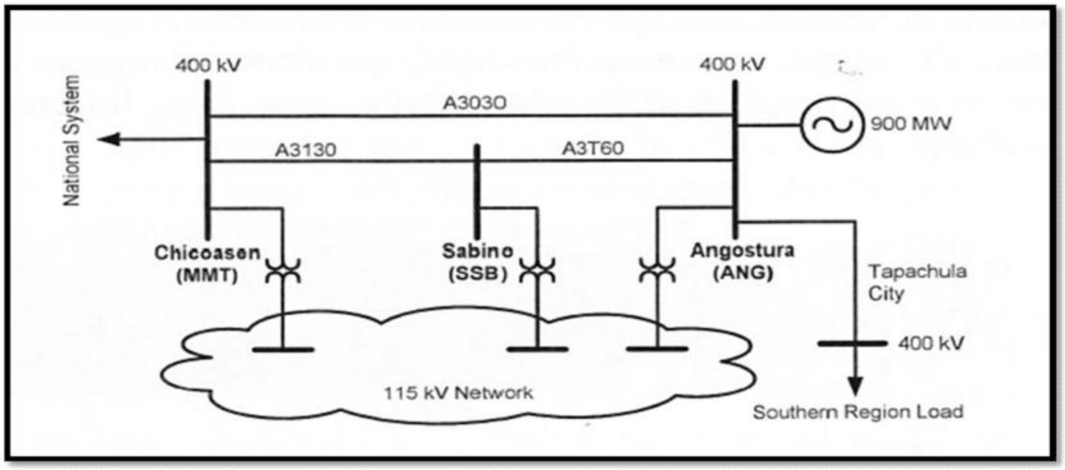


Figure 6

In Mexico, most of the generation is at one end of the country, while most of the load is in the center of the country. The power is transmitted over 400 KV network. The network is shown in the diagram above. It was observed from the simulation that loss of a 400 KV line could put this system in out of step conditions. So to protect against it, the scheme needed to measure the angle of the separation and make sure it trips the generation, when necessary. By carrying out experiments, it was determined that, when both lines are out of service, the angle separation between bus and generator is 14°. When one line is out of service, the angle of separation is 7°. CFE implemented an automatic generation shedding scheme (AGSS) to implement a scheme to shed the generation when the angle of separation reached 10° or greater.

Case Study-2: The Europe Power System Disturbance happened on November 4, 2006

On Saturday, November 4, 2006 the interconnected power systems of the UCTE synchronous area were affected by a serious system disturbance originating from the North German transmission grid. The disturbance had its starting point in Germany, but subsequently large parts of the European power systems interconnected in the UCTE synchronous area suffered from it. After the tripping of many high voltage lines the UCTE grid was divided into three areas (West, North East and South East). This resulted in significant power imbalances and frequency deviations in each area.

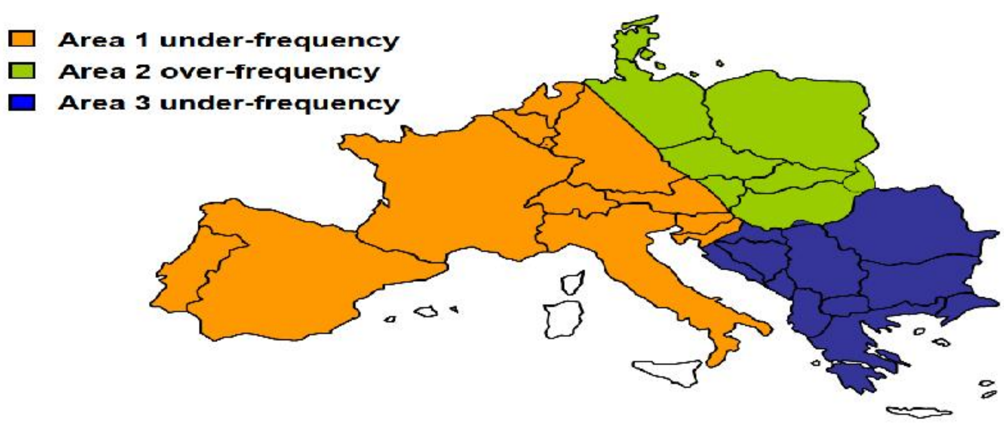


Figure 7

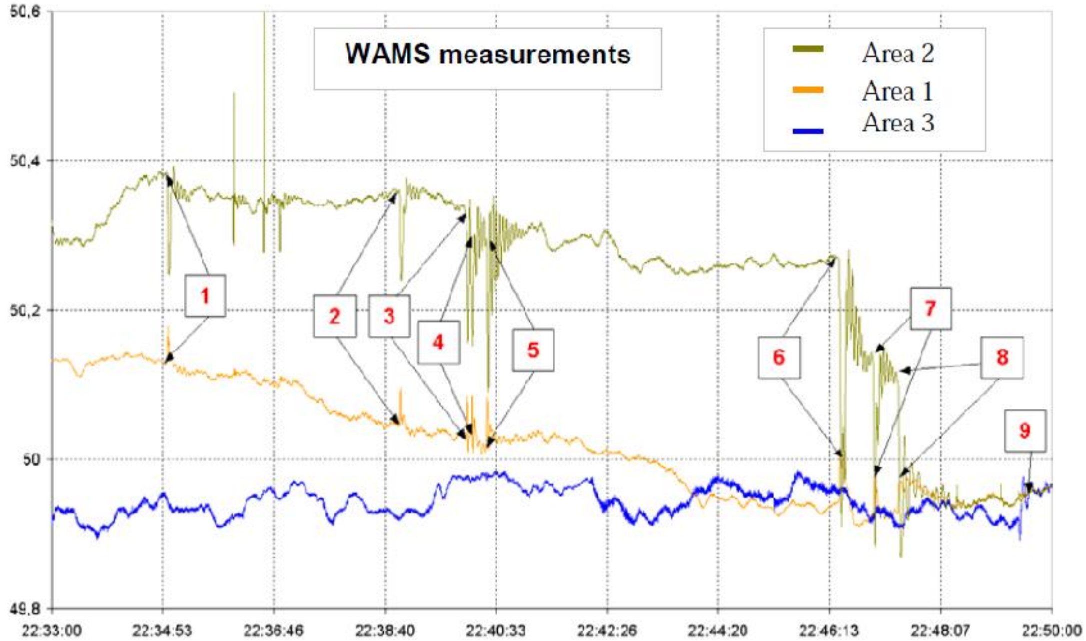


Figure 8

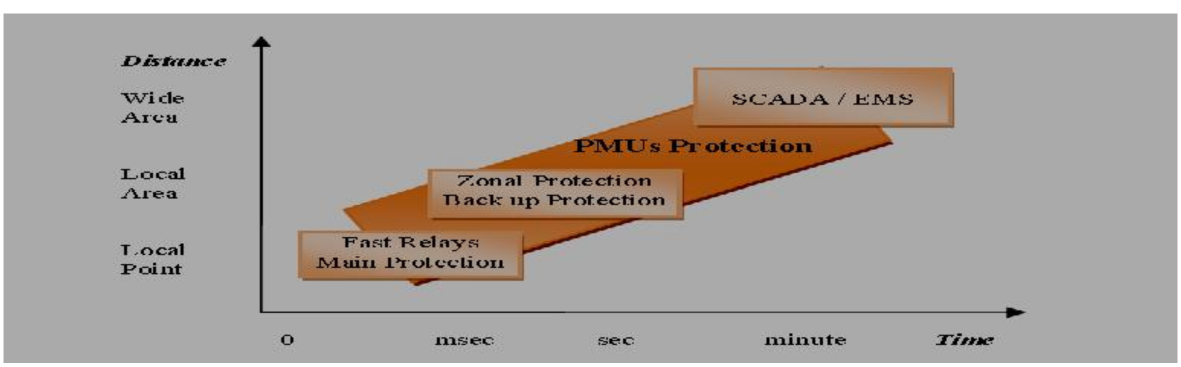
PMU-based Wide Area Measurement System (WAMS) was installed in UCTE system. With the help of Wide Area Measurement System in UCTE system, transmission system operators perform resynchronization actions immediately after having awareness about the system splitting. The whole system restored in record time as folloing:

- Full resynchronization of the UCTE system was completed 38 minutes after the splitting.
- The Transmission System Operators (TSO) were able to re-establish a normal situation in all Europe countries in less than 2 hours.
- The final report about the facts and analyses on the root causes of the disturbances as well as finial conclusion and recommendations came out in 87 days.

In conclusion, practical experience has proven that the application of PMU in power system significantly speeds up the system restoration process and technically simplifies the event analysis process.

CONCLUSIONS

PMUs and WAMS enable a new dimension of monitoring power grid operation. Synchrophasors solve the problem of time incoherency required for wide-area power system control. With the ability to use time-synchronized measured values from across power systems, new protection and control schemes like those described in this paper are being implemented today. Synchrophasors can be put as following in power system protection and control.



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