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Renewable Generation Plant communications

by

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Introduction:-

There is growing interest in renewable energy around the world. Since most RE sources are intermittent in nature, it is a challenging task to integrate RE resources into the power grid infrastructure. In this grid integration, communication systems are crucial technologies, which enable the accommodation of distributed RE generation and play extremely important role in monitoring, operating, and protecting both RE generators and power systems.

As compare to large power plants, RE plants have less capacity, and are installed in a more distributed manner at different locations. The integration of distributed RE generators has great impacts on the operation of the grid and probes to new grid infrastructure. It is the main driver to develop the smart grid for infrastructure modernization, which monitors, protects, and optimizes the operation of its interconnected elements from end to end with a two-way flow of electricity and information to create an automated and distributed energy delivery network.

Conventional power plants employ synchronous machines, which are well understood by Network Operators and Generators. Synchronous machines assists in maintaining transient stability, good voltage control, reactive power support, frequency control and fault ride-through capabilities, thus being able to meet the connection requirements defined by the system operators.

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The technical and operational characteristics of the power system are determined by the network, by the technical characteristics of the generation, and to a lesser extent, by the loads connected to it. Renewable Energy developers and network operators must work together to define a set of minimum technical performance requirements in order to accommodate significantly greater volumes of renewable generation without destabilization of the grid and to ensure continuing maintenance of network security and hence security of supply while allowing a greater volume of wind farms to be connected to the system .

Drivers of RE development:

RE is a growing component of electricity grids around the world due to its contributions to (1) Reducing climate impact from fossil fuel use (2) long term energy security, and (3) expansion of energy access to new energy consumers in the developing countries like India and China. The challenge is ensuring energy availability and preserving the environment. The key elements behind propagation of renewable energy sources are the following:

1) Meeting electricity supply demand deficit.
2) Reducing climate impact from fossil fuel use and production of clean energy
3) Bringing electricity to the rural and unexplored areas
4) Ensuring Energy security
5) Power quality and secure energy access for all nations
6) Reducing Transportation of electricity from long distances.

RE is implicated in all of these elements, and is critical to transforming energy grids to meet the environmental, economic and social challenges of the future. Globally, RE's share of electricity generation will increase substantially over the next two decades and beyond. Indeed, this is already occurring: governmental action at the international, national and sub-national levels has created a wide variety of laws and policies to promote RE development. These include:

- **Carbon taxes:** Taxation of greenhouse gas emissions, so as to internalize the climate disruption costs of fossil-fuel use;
- **Cap-and-trade systems:** Provision of tradable annual emissions allowances to greenhouse gas emitters coupled with reduction in the quantities of allowances issued each year; RE goals: mandates requiring load-serving entities to source a specified proportion of energy sold from renewable sources;
- **Feed-in tariffs (FiTs):** Guaranteed wholesale prices for RE coupled with a requirement that load-serving entities take renewable power whenever it is available;
- **Tax credits:** credits against taxable income for generation or installation of RE;
- **Development of smart grids:** advances in the architecture, functionality and regulation of electricity grids so as to enable higher penetrations of RE; and

- Removal of long-standing fossil fuel subsidies.
- Generation based incentives (GBI)

Expanding energy access

Energy demand in developing countries is growing rapidly. In addition to the needs outlined in the previous subsections for cleaner energy and more secure energy, the world simply needs *more* energy as more people in the developing world gain access to it. As global energy demand increases, RE provides one means among many of adding energy assets to the system alongside growth of other resources

Necessity of Communication System:

Grid-tied renewable energy systems are quickly becoming a ubiquitous facet of the nation's utility landscape. Accelerated public interest in renewable energy in the India has accompanied sustained, robust market growth of multiple distributed generation technologies over the last few years. At the same time, policymakers are working to address a number of pressing concerns related to the generation of electricity by conventional means, including aging infrastructure, grid congestion, electric rate increases, natural gas price volatility, climate change, diminished air quality and related public-health concerns, reliability issues, energy security and energy efficiency. While the full costs of conventional electricity generation are increasingly being recognized and internalized, the price of distributed, renewable-energy systems continues to decrease.

Many equipment in the grid requires monitoring and control for operation of support systems and applications, such as SCADA, EMS, protective relaying for high voltage lines, data dispatch, distribution feeder automation, generating plant automation, physical security.

A communication system transmits measured information and control signals between RE generators and power systems. For e.g. Well-designed communication systems can better explore the wind potentials and facilitate generation controls, for meeting peak load and providing voltage support for power systems.

Presently RE sources are utilizing mainly wired communications such as PLC, optical fiber etc. for grid integration. Use of wireless communications for distributed monitoring and control can improve RE generation reliability and efficiency, and reduce the life cycle cost.

Communication system can also integrate into solar PV which can sense the voltage, current and temperature of each module, and send the information data to the monitoring interface.

With this system, each solar module status is visible. This can be very useful as most of the solar panels are installed in the areas that are not readily accessible.

Overview of Communications systems for RE sources.

ABT System: Post Electricity Act-2003 in India, The Central Electricity Regulatory Commission (CERC) CERC introduced Availability Based Tariff (ABT) mechanism to attain availability, affordability and grid discipline in the power sector. ABT has been successful in improving the quality of power and curtail the disruptive trends like high frequency deviations and frequent grid disturbances resulting in generators tripping, power outages and grid instability. Additionally, ABT mechanism has also helped in encouraging higher generation availability, economic load dispatch operations and promote energy trading.

Although ABT has brought grid discipline, it has not been able to reduce the increasing peak power shortage experienced by majority of the state utilities. Inter-state ABT is only a partial solution for the problem. Also there are other problems like transmission corridors getting congested while bringing the excess amount of power from the remote location to the load centres. A viable alternative can be generators being located near the load centres and actively promote renewable energy to fill the increasing demand. This will defer T&D expansion, increase the generation, improves the voltage profile of the system and reduces the line loss.

In case of renewable generators, unit size of each RE generator ranges from 350 kw (wind) to 6-8 MW (biomass projects). Because of its nature, renewable energy based generation may not be amenable to scheduling on 'timeblock to timeblock' on day ahead basis. Rather, it needs to be dispatched at all times as and when available in order to maximize generation and optimal utilization of renewable energy generation assets. Some renewable energy generation such as biomass based power plants can be subjected to scheduling & dispatch regime, however, availability of necessary communication and metering infrastructure is essential for such implementation. Most of the small capacity generating stations (<10 MW) present a dispersed generation connected at distribution level (33kv or below) thereby limiting their visibility at SLDC for meaningful command & control operations. In India, small hydro plants with capacity of less than 25 MW are considered as renewable.

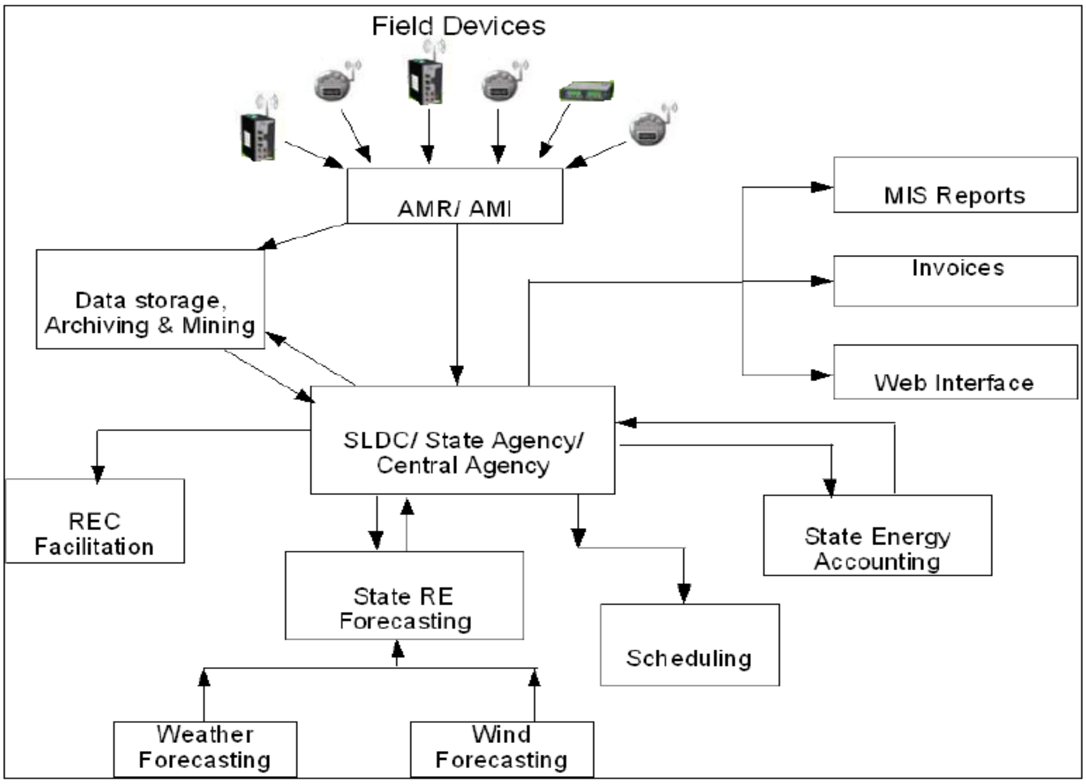
Though all the State Electricity Regulatory Commission's (SERCs) follow the CERC guidelines there are slight variations in the grid codes state wise to adapt with the local conditions in the best possible way. For example as per West Bengal Electricity Regulations (WBERC) all renewable energy power plants except biomass power plants, non-fossil fuel based co-generation plants & Municipal solid waste (MSW) plants with capacity of 10 MW and above is treated as 'Must-Run' power plants & is not subjected to 'merit order dispatch' principles. Must-Run power plants/ open access customers purchasing power from 'Must-Run' power plants should submit a 24 hours day ahead schedule to the Nodal agency on mutually agreed time block (TOD basis) for operational convenience. No Mismatch/ Unscheduled Interchange charges will be payable for such power plants. The biomass power plants, non-fossil fuel based co-generation plants & MSW plants with capacity of 10 MW & above and Open Access Customers of these plants will come under ABT mode of operation to the Nodal agency as per the state grid code. Unscheduled/ Mismatch charges for deviation from the schedule is to be paid weekly as per rate as specified in the tariff regulations. As per KERC order dated June 20, 2006, Projects under 25 MW capacity are not considered under the ABT mechanism.

However, as per Maharashtra Electricity Regulatory Commission (MERC) state grid code 2006, all generating units with capacity of 50 MW & above should be subjected to scheduling & dispatch regime as stipulated under the grid codes and should be subjected to the dispatch instructions issued by RLDC/ SLDC, as the case may be from the point of system security.

Hence, we can clearly see that though the basic framework for the renewable energy followed by the states is in line with the CERC guidelines. However, there may be variations from region to region to adapt to the local conditions. Therefore, there is an imminent requirement of a flexible solution that can adapt to the regulatory variations with flexibility to incorporate the future changes as per the law of the land.

Renewable Energy Communication solution: The complete solution for managing renewable energy in the grid for both LDCs & RE Generators should comprise of three basic things, ABT mechanism, Forecasting & mass Data Storage. However, the solution approach should be different for both LDCs & RE Generators. The system contains various devices like PLC, SCADA, Power Line carriers, HMI Interface, Metering devices, LAN and Network system etc.

A) Load Dispatch Centre (LDC)



LDC system for Renewable Energy Management

The IT solution should perform the following business functions for a LDC :

1. **Scheduling - day ahead & day of operation**

    a. If more than minimum specified generation capacity
    - Boundary conditions are normal
    - Special Cases

    b. If less than minimum specified generation capacity
    - Lumped: Group of wind or solar farms are scheduled together as a single entity

    c. Based on type of source
    - Wind
    - Solar
    - Biomass

2. **State Energy Accounting**

3. **REC Facilitation**
    - Measurement & Data Acquisition

- Validation
- Reporting: Validated RE injection report
- Sending in notified format

4. **Open Access (OA)/ Power Purchase Agreements (PPAs) Facilitation**
There can be RE generators not following REC mechanism & having PPAs or exploring OA opportunities in the grid. There are set of functions of OA to be performed like OA approval mechanism, OA UI calculation, OA charges calculation & bill invoicing

5. **State RE forecast – Solar/ Wind**
- By integration of data received from individual plants/ farms
- By compilation of total availability in the state through data from environmental laboratories, historical data & intelligent algorithm

6. **Data Storage, Archiving & Mining**
   - Enabling Renewable Regulatory Fund (RRF) & Renewable Purchase Obligation (RPO) which includes data exchange in standardized formats among stakeholders like regulatory commissions, RLDC, NLDC, discoms, etc.
   - Enabling informed decisions on RPO, RRF, investments, policy framework, etc - Mass data storage upto 30 years for precise statistical model results

7. **Transmission loss for the state calculation**

8. **Transmission service charges calculation & invoicing**

9. **Interface to AMR Head-end system** – Meter data processing for grouping to measure logistical entities

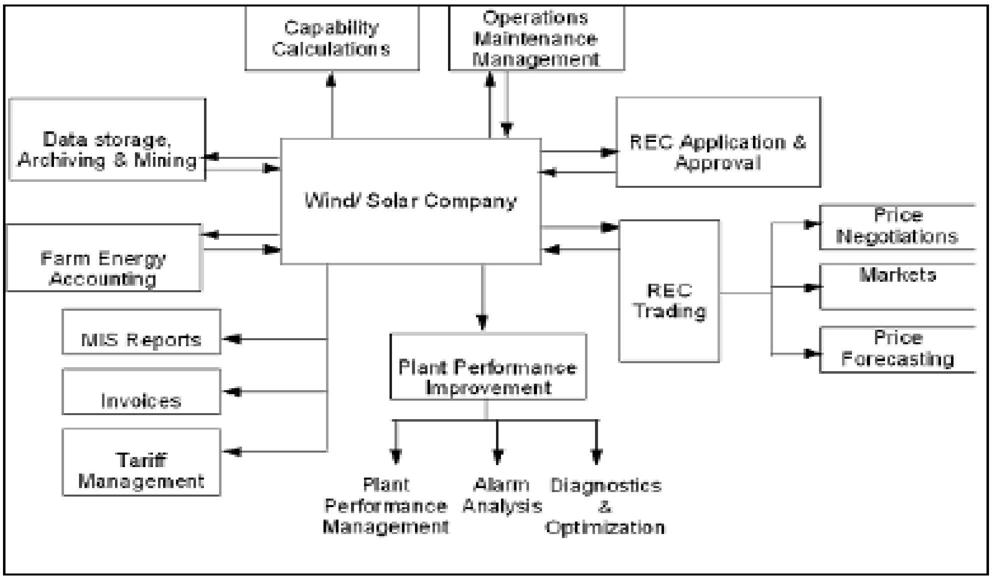
10. **Web based visualization** – Visualization for energy balance, energy transactions at interchange areas, corridor usage, ancillary revenues, technical losses, key violations, etc.

11. **Reporting**

12. **Interactions:**
   - Regional Load Dispatch Centre (RLDC): To get entitlement and send requisition, to get implemented schedule, billing frequency, UI charges invoice
   - State Generating Stations (SGS): To get declared capacity and send dispatch schedule
   - Distribution companies: To send entitlement, get requisition and send drawl schedule

- Open Access Customer: To get application, send approval and send schedule
- Update Load Dispatch Centre Website regularly

B. RE Generators



RE Generator system

The IT solution is applicable to individual wind farms, wind generation companies (eg: Total generation of ABC company in India), individual solar farms & solar generation companies. The solution should perform the following business functions:

1. Data storage, data mining, statistical models & forecasting

- Mass data storage upto 30 years for precise statistical model results
- Through data from environmental laboratories, historical data & intelligent algorithm

2. Capability calculation & declaration

a. If more than minimum specified generation capacity
- The boundary conditions are normal
b. If less than minimum specified generation capacity
- Lumped: Group of wind pr solar farms are scheduled together as a single entity
c. Based on type of source
- Wind - Solar - Biomass

3. Measurement & Data Acquisition

4. Plant Performance Monitoring & Improvement

- Plant Performance Management
- Alarm Analysis
- Diagnostics & Optimization

5. Energy accounting including UI

- Unit/ Plant/ Farm wise energy accounting - UI calculations & accounting

6. REC application & approval process

7. REC Trading through price negotiations

8. REC Trading through markets (including REC price forecast)

Renewable Communication Devices:

A. Power Line Communications

PLC uses existing electrical wires to transport data. PLC can be used for broadband Internet access, indoor wired LAN, utility metering and control, real-time pricing, distributed energy generation, etc.

Power line communications (PLCs) are to use existing electrical wires to transport data.

Recently, new PLC technologies are available that allow high bit rates of up to 200 Mb/s. PLC can be used in several important applications: broadband Internet access, indoor wired local area networks, utility metering and control, real-time pricing, distributed energy generation, etc.

From a standardization point of view, competing organizations have developed specifications, including HomePlug Powerline Alliance, Universal Powerline Association and HD-PLC. ITU-T adopted Recommendation G.hn/G.9960 as a standard for high-speed power line communications.

In IEEE, P1901 is a working group developing PLC medium access control and physical layer specifications. National Institute of Standards and Technology (NIST) has included HomePlug, ITU-T G.hn and IEEE 1901 as “Additional Standards Identified by NIST Subject to Further Review” for the smart grid in the USA .

The primary advantage of PLC arises from the fact that it allows communication signals to travel on the same wires that carry electricity. However, since power line cables are often 4 unshielded and thus become both a source and a victim of electromagnetic interference (EMI).

Another issue is the price. A PLC module is usually more expensive than a wireless module, such as ZigBee, which will be introduced in the next subsection. In addition, wireless is also more practical in some applications, such as water/gas meters powered by batteries without power lines.

B. Wireless LAN

A leading standard for the wireless home network communications is ZigBee. The Zigbee Smart Energy standard builds on top of the ZigBee Home Automation (HAN) standard. HAN provides a framework to automatically control lighting, appliances, and other devices at home.

ZigBee Smart Energy provides a framework to connect HAN devices with smart meters and other such devices. This will enable the energy utility to directly communicate with the end consumers of energy.

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Wi-Fi is often used as a synonym for IEEE 802.11 wireless local area network (WLAN) technologies. Recently, Wi-Fi became a standard for laptops and subsequently phones due to its high data rate. When using it in utilities, however, Wi-Fi’s power consumption is an issue that needs to be considered carefully.

The ZigBee Alliance and the Wi-Fi Alliance also consider collaborating on applications for energy management and networking. The initial goal will be to get Smart Energy 2.0, a standard promoted by ZigBee, to work on Wi-Fi.

C. Wireless Wide Area Networks

Public cell phone can be used to connect household smart meters directly with the utility’s systems. A major advantage is the reduction of the costs. However, since public wireless cellular networks are not specialized in machine-to-machine area, some requirements in utilities may not be met by cellular networks.

Public cell phone carriers have great interest in using wireless wide area networks to connect household smart meters directly with the utility's systems. A major advantage of this approach is the reduction of the costs (by not having to build a new network and by leveraging the expertise of the telecom world). However, since public wireless cellular networks are not specialized in machine-to-machine area, some requirements in utilities may not be met by cellular networks.

Others argue that if the public wireless giants want to get into this business, they will do whatever it takes to meet the requirements to win these large-scale, multi-year utility contracts.

WiMAX is based on the IEEE 802.16 standard, enabling the delivery of wireless broadband communications. Unlike the now-popular wireless networking technologies using unlicensed spectrum (such as those used by Silver Spring and Trilliant), WiMAX uses licensed wireless spectrum, which is arguably both more secure and reliable. The primary disadvantage of using a licensed network is that it is more expensive. In addition, compared to cellular technologies,

WiMAX has yet to be deployed at scale, which means some risks when applied to utilities.

RE grid integration challenges:

Wind and solar generation both experience intermittency, a combination of non-controllable variability and partial unpredictability, and depend on resources those are location dependent. These three distinct aspects, explained below, each create distinct challenges for generation owners and grid operators in integrating wind and solar generation.

Non-controllable variability: Wind and solar output varies in a way that generation operators cannot control, because wind speeds and available sunlight may vary from moment to moment, affecting moment-to-moment power output. This fluctuation in power output results in the need for additional energy to balance supply and demand on the grid on an instantaneous basis, as well as ancillary services such as frequency regulation and voltage support.

Partial unpredictability: The availability of wind and sunlight is partially unpredictable. A wind turbine may only produce electricity when the wind is blowing, and solar PV systems require the presence of sunlight in order to operate. Unpredictability can be managed through improved weather and generation forecasting technologies, the maintenance of reserves that stand ready to provide additional power when RE generation produces less energy than predicted, and the availability of dispatchable load to "soak up" excess power when RE generation produces more energy than predicted.

Location dependence: The best wind and solar resources are based in specific locations and, unlike coal, gas, oil or uranium, cannot be transported to a generation site that is grid-optimal. Generation must be collocated with the resource itself, and often these locations are far from the places where the power will ultimately be used. New transmission capacity is often required to connect wind and solar resources to the rest of the grid. Transmission costs are especially important for offshore wind resources, and such lines often necessitate the use of special technologies not found in land-based transmission lines.

Because the presence of wind and sunlight are both temporally and spatially outside human control, integrating wind and solar generation resources into the electricity grid involves managing other controllable operations that may affect many other parts of the grid, including conventional generation. These operations and activities occur along a multitude of time scales, from seconds to years, and include new dispatch strategies for rampable generation resources, load management, provision of ancillary services for frequency and voltage control, expansion of transmission capacity, utilization of energy storage technologies, and linking of grid operator dispatch planning with weather and resource forecasting. The essential insight to integration of variable RE is that its variability imposes the need for greater flexibility on the rest of the grid, from other (controllable) generators to transmission capacity to loads.

Non-controllable variability: Variability in the context of wind and solar resources refers to the fact that their output is not constant. It is distinct from unpredictability, which we discuss in the following section. Even if operators could predict the output of wind and solar plants perfectly, that output would still be variable, and pose specific challenges to the grid operator, which we introduce here.
On the seconds to minutes time scale, grid operators must deal with fluctuations in frequency and voltage on the transmission system that, if left unchecked, would damage the system as well as equipment on it. To do so, operators may order generators to inject power (active or reactive) into the grid not for sale to consumers, but in order to balance the actual and forecasted generation of power, which is necessary to maintain frequency and voltage on the grid. These ancillary services go by a plethora of names and specific descriptions. Typical services for an impressionistic overview include:
Frequency regulation: occurs on a seconds-to-minutes basis, and is done through automatic generation control (AGC) signals to generators;
Spinning reserves: generators available to provide power typically within 10 minutes
These reserves are used when another generator on the system goes down or deactivates unexpectedly;
Non-spinning reserves: these generators serve the same function as spinning reserves, but have a slower response time;
Voltage support: generators used for reactive power to raise voltage when necessary;
Black-start capacity: generators available to re-start the power system in case of a cascading black-out.

Additionally, grid operators must track loads:
Demand for electricity on the consumption side of the grid and ensure that generation matches load at all times. This *load following* function becomes particularly important at times of day when demand for electricity increases substantially, such as morning, a hot afternoon, or evening. Load following may be provided through a class of ancillary service or through a "fast energy market", depending on the system operator.

These functions are not new. Grid operators have been regulating frequency and voltage, maintaining reserves and following shifts in load since the development of the electricity grid. This is because loads themselves are variable, and even conventional, controllable generation experiences problems and cannot perform as scheduled all of the time. Consumers demand electricity in ways that, while predictable, are not controllable and have some degree of variability. Thus wind and solar generation does not introduce entirely novel problems with which operators have never grappled. Indeed, at low penetrations, the integration challenges are primarily device and local-grid specific, such as subsynchronous resonance and harmonics, which the turbine itself may cause.

However, high penetrations of wind and solar generation will add *more* variability to the energy system than grid operators have traditionally managed in the past, and thus increase demand for ancillary services and balancing energy overall. It is more difficult, and sometimes impossible, to manage such challenges at the device level, and so grid-level actions, technologies and strategies are often needed. Wind and solar resources in sufficient amounts may also complicate load following functions when large demand shifts coincide with weather events that alter power output from wind or solar resources. Grid operators located in more remote regions and serving smaller loads may have less flexibility to provide ancillary services and load following than their larger counterparts. Compounding matters, plentiful RE resources are often located in these remote locations. The IEA and other bodies have recommended consolidation of grid operators, in order to integrate RE sources over larger areas and so reduce the variance of the power produced, as well as easing of market restrictions on sales of ancillary services as a solution to this problem.

Partial unpredictability: Partial unpredictability, also called uncertainty, is distinct from variability. The variability of wind and solar generation is ever-present, a result of reliance on the ever-changing wind and sun, and affects the system at the moment-to-moment time scale as a cloud passes over a PV plant or the wind drops. Partial unpredictability, on the other hand, refers to our inability to predict with exactness whether the wind and sun will be generally available for energy production an hour or a day from now. This hour-to-day uncertainty is significant because grid operators manage the great majority of energy on the grid through "unit commitment", the process of scheduling generation in advance, generally hours to a full day ahead of time, in order to meet the expected load. When actual production does not match the forecast, the grid operator must balance the difference. RE generation increases the cost of this function by increasing the spread between predicted and supplied energy, a cost that is ultimately borne by consumers. Unit commitment at present is largely deterministic, meaning that once a generator is scheduled to run, its full capacity is expected to be available for use. This practice reflects the relative predictability and controllability of traditional coal, gas and hydropower generation resources. Operators ensure the availability of reserves generators that withhold the supply of energy and so stand ready to balance the system in an emergency, so as to protect against a potential transmission line or generator outage.

But the process of unit commitment and the calculation of reserves needed to ensure reliability becomes more complex when dealing with *stochastic* (uncertain) generation, whose output at the committed time carries some degree of uncertainty. *Forecasting* technologies aim to predict weather and thus generation output from wind and solar resources at various timescales more accurately, and communicate those predictions to grid operators in a manner that allows the operator to more effectively schedule and dispatch resources. Properly anticipating wind and solar output levels allows the operator to modify the scheduling of other generators so as to more optimally utilize all assets under the grid operator’s purview. The operator must, for example, ensure that reserves are available not only to cover transmission line or generator outages, but also to respond to still unanticipated changes in wind and solar output. Assisting the operator in this process are *advanced unit commitment methods*, which aim to prepare the system for multiple potential and uncertain outcomes that cannot be predicted by the forecasting technologies.

Unlike deterministic unit commitment processes, advanced unit commitment methods must take into account the stochastic nature of wind and solar generation and their relative concentration on the system in recommending the scheduling of other resources. Ultimately, the goal of advanced unit commitment is to cost-effectively maintain sufficient flexibility on the system, such that the integration of RE resources neither exposes the system to unacceptable reliability risks nor overschedules reserves in a way that unnecessarily burns fuel and emits pollution.

Locational dependency: Far removed from the day-to-day management of the grid is its long-term planning, specifically the siting and utilization of new transmission lines. Here RE generation plays a significant role and introduces new challenges. Because wind and solar resources are often located in remote locations, far from load centres, developing sufficient transmission to move RE to markets is critical to their integration.

Transmission planning processes are highly varied, and tend to be influenced by regional politics. For example, a transmission line may provide capacity for energy produced in one country or state, passed through another, and consumed in yet another. These disparities in generation capacity, transmission location and load size between locations can make the development of transmission for RE contentious and complex, particularly with respect to cost allocation. Because new transmission lines built out to RE generation resources will carry primarily renewably generated, variable and partially unpredictable electricity, technical needs arise regarding the transmission technology to be used.

On the other hand, distributed energy resources provide for an alternative vision of the future grid, where energy is generated and used locally on a *micro-grid*, avoiding the cost of line losses and the high capital cost of transmission lines. In such a schema, the electricity grid could be conceptualized as a collection of independent micro-grids with vastly reduced long-distance energy transmission needs.

Operational technologies and practices

This section focuses on operational technologies and practices related to wind power, since wind power generation is currently the most widely deployed large-capacity RE generation and has significant impacts on power system operations. Much has been done to address these impacts by researchers and grid operators worldwide. Similar technologies and practices can also be used for PV and solar thermal power generation. For the operation of power systems with high penetration of large-capacity RE generation, RE power forecasting is critical for grid operators to carry out operational planning studies and ensure that adequate resources are available for managing the variability of RE output.

Power forecasting and methods

Based on the time scale of the forecast, wind power forecasting can be classified as ultra short- term forecasting, short-term forecasting and medium/long-term forecasting. Short-term forecasting is currently the most widely used, with a time scale up to 48-72h. Present methods for short term wind power forecasting generally include physical methods, statistical methods, and a hybrid of the two.

- **Physical methods** start with a numerical weather prediction (NWP) model, which provides the expected wind speed and direction at a future point in time. Further steps include the application of the NWP model results to the wind farm site, the conversion of the local wind speed to power, and the further application of the forecast to a whole region.
- **Statistical methods** first establish the relationship between the historical NWP data and the historical power output data of wind farms via one or more learning algorithms, and then predict the wind farm power output based on this relationship.

Forecast accuracy

The accuracy of wind power forecasting can be measured by different indices. Root mean square error (RMSE) normalized to the installed wind power is most commonly used. Regardless of the forecasting method used, the forecast error (RMSE) for a single wind farm is between 10 % and 20 % of the installed wind power capacity for a horizon of 36 hours. Spatial aggregation greatly reduces forecast errors, just as it reduces variability.

As we have seen, integrating more large capacity RE into the grid brings variability and uncertainty. At the same time, there will continue to be unexpected disturbances stemming from load variation, grid faults and conventional generation outages. Worldwide studies and experience in recent years have shown that new technical solutions are needed to address this conjunction of difficulties. The new solutions will include new technologies, methods and practices, applied in order to provide more flexibility and improve the efficiency of power systems, constantly balancing generation and load. Only this will make the power systems reliable and maintain security of supply, i.e. avoid any interruption in the supply of power. The required power system flexibility can be achieved on the generation side, from both RE generation and conventional generation. It should first be pursued using grid-friendly RE generation. This means mitigating the impacts of RE generation on the power system, enabling it to contribute to system reliability and stability by improving its design and control technologies. However, the amount of flexibility which can be achieved by this approach is limited. Flexibility from conventional generation is currently the major source of power system flexibility, and is generally referred to as "generation flexibility".

Flexibility can also be achieved from the load side through demand response, and from energy storage that can act as either generation or load). In addition to adding new flexibility, existing flexibility can be better exploited by operational enhancement within a balancing area, and can be shared in wider geographic footprints by cooperation between, or consolidation of, smaller balancing areas, supported by transmission expansion.

Grid-friendly RE generation

Need for grid-friendly RE generation

At the beginning of its development RE generation technology focused more on tapping the maximum power from RE resources. It neglected to make any contribution to power system reliability and stability and in the absence of standards and incentives was not designed to operate in a coordinated fashion with the rest of the system. As long as RE penetration is low this is manageable and can be accepted by power system operators. But as RE generation penetration grows, and especially as the capacity of RE power plants becomes larger and larger, this will have a serious impact on system operation. Therefore it is becoming increasingly important that RE generation should play a greater role in helping to maintain system reliability and stability, and this may be increasingly required by interconnection standards. Technologies have been developed and are continuously improving at the generating unit, plant and plant cluster level to make RE generation more predictable, controllable and dispatchable, or in other words more grid-friendly.

Advanced characteristics of RE generating units and plants

Development of power electronics and mechanical engineering technologies, as well as the design of proper control strategies, have enabled wind generating units to possess performance comparable or even superior to those of conventional thermal or hydro generating units. Some advanced operational capabilities of wind generating units and the methods to achieve them are cited below. Most of these capabilities can also be achieved for solar PV generating units since they share many technical characteristics with wind turbine generators, especially the inverter-based ones.

a) Voltage/Var control and regulation

Reactive power support and power factor control can be provided either through a built-in capability or through a combination of switched capacitor banks and power electronic based transmission technologies such as static var compensator (SVC) and static synchronous compensator (STATCOM).

b) Fault ride-through

The ability is needed to survive (ride through) specific low and high voltage/frequency ranges and durations caused by faults or disturbances in the power system. Voltage ride-through can be achieved with all modern wind generating units, mainly through modifications to the controls.

c) Active power control, ramping and curtailment

This can be achieved through unit control mechanisms for wind turbine units with activestall or pitch control, or discrete tripping of units.

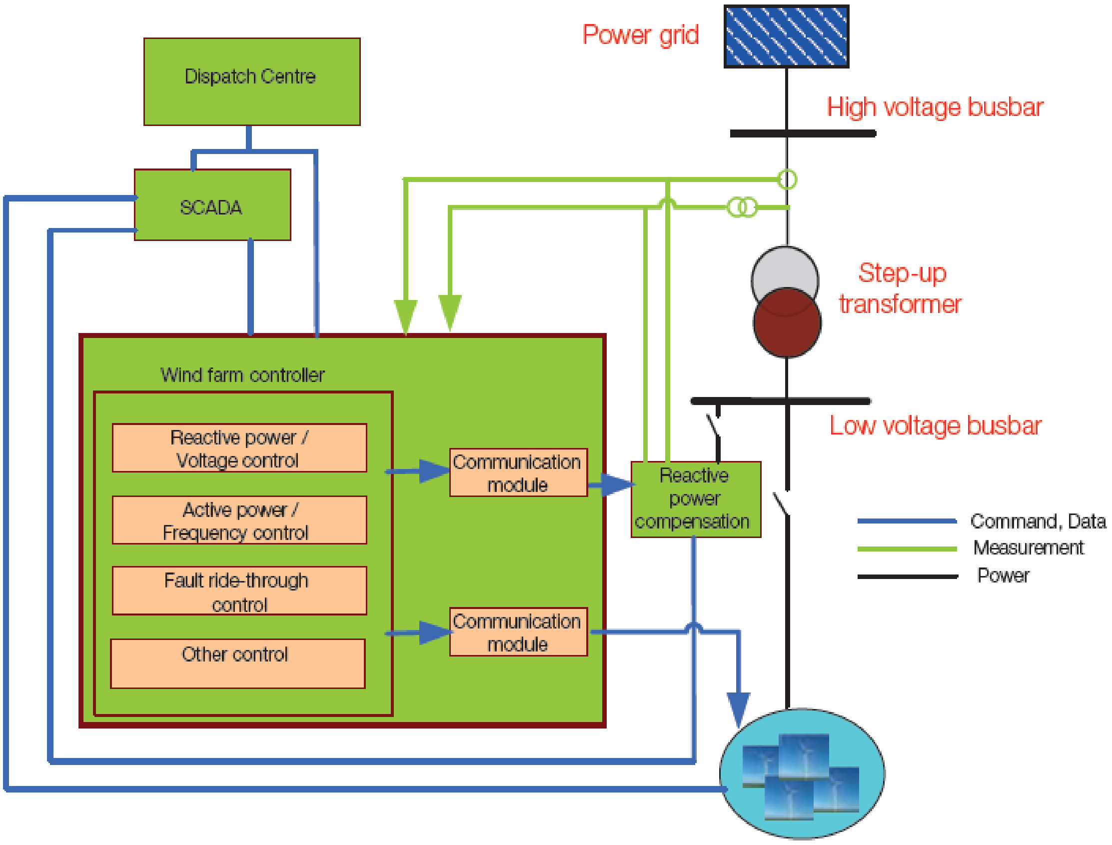
d) Primary frequency regulation

Primary frequency regulation can be supplied by all units that are equipped with some form of pitch regulation (i.e. active-stall or pitch control).

f) Short-circuit current control

All inverter-based variable generators have a builtin capability to limit the fault current to a level that does not exceed 150 % of the full load current.

For grid integration it is important to view RE generation at the plant level. An RE power plant is not just a simple collection of RE generating units, but is also supported by many other components and systems so as to function like a conventional power plant. Based on advanced generating units, these characteristics can also be achieved at the plant level. Plant-level reactive power compensation, accurate RE generation output forecasting, the presence of monitoring, control and data communication systems, as well as properly designed relay protection schemes all help to improve the predictability, controllability and dispatchability of RE power plants.



Typical structure of a wind power plant

Centralized control of an RE plant cluster

The areas with the best RE resources may see the development of RE power bases with many RE power plants located adjacent to each other. The control of the RE power plants in such a cluster must be coordinated if operational problems are to be avoided. There have been numerous reports of one or more plants at maximum reactive power output while neighbouring plants are absorbing reactive power. To avoid this kind of situation, centralized cluster control is an attractive solution. A centralized cluster control system, configured in a multi-layer structure, can be used to coordinate the active and reactive power control of a RE power plant cluster, just as cascaded hydro power plants on a river are controlled.

Improvements in modelling RE generation

In order to represent accurately the static, dynamic as well as short-circuit performance of RE generators, plants and clusters and their impacts on power systems, appropriate models of the different types of RE generation are needed. Up to now, most RE generation modelling efforts have been carried out at the generator level. Although RE generator manufacturers have long been developing and refining models to improve their generator design – these are typically user-written proprietary models on commercial software platforms – it has now been recognized that publicly available industry-standard models, similar to those available for conventional generation, are needed for planning studies. Efforts to develop generic models for PV have also begun. However, regarding RE generator modelling, a great deal of research still needs to be carried out, e.g. to determine the short-circuit contribution of different types of RE generators, and to represent the more advanced and rapidly developing control characteristics of RE generation.

Transmission system for Renewable Power Plants

Although on a system-wide level RE power plants generate electricity just like any other power plants, RE power has quite distinctive characteristics in generation, transmission and operation technology when compared to conventional generation. Understanding these distinctive characteristics and their interaction with the other parts of the power system is the basis for the integration of large-capacity RE power in the grid. In this chapter, the state of the art of the technologies and practices related to large capacity RE integration is described to facilitate the understanding of their interaction with the power grid. This discussion is further divided into the RE generation technology itself, the transmission technology and the operational technology and practices.

Transmission technology

Large-capacity RE generation plants are usually far from load centres, and they therefore need long-distance power transmission. Up to now, AC transmission has been used for large capacity RE power transmission, and voltage source converter high voltage DC (VSC-HVDC) transmission has been used for offshore wind power integration.

AC transmission

AC transmission is a mature technology. The capacity of an AC transmission line is proportional to the square of the voltage level and inversely proportional to the impedance of the line, which increases with the transmission distance. To achieve a large increase in the transmission capacity of long-distance AC lines, a natural way is to raise the voltage level. For small-tomedium scale RE power plants, transmission lines below 330 kV are usually used. For largescale, long-distance RE power, transmission lines above 500 kV are usually needed.

VSC-HVDC transmission

IGBT-based VSC-HVDC differs from the conventional thyristor-based current source converter HVDC (CSC-HVDC, also known as line commutated converter HVDC (LCCHVDC)) in that it is self-commutated via control circuits driven by pulse-width modulation, while CSC-HVDC is line-commutated, i.e. switched off when the thyristor is reversely-biased from the AC voltage. Compared to CSCHVDC, VSC-HVDC offers among others the following major advantages:

a) It can rapidly control both real and reactive power, independently, within its rated MVA capacity. As a result, it can transmit very low and even zero active power, which is suited to the frequent and wide-range output fluctuation of RE generation, while CSC-HVDC is limited by minimum startup power. VSC-HVDC terminals can generate or absorb a given amount of reactive power as instructed or according to the voltage level of the connected AC grid, providing excellent voltage support, while CSCHVDC terminals always absorb reactive power when working, requiring large amounts of reactive power compensation.
b) It can rapidly reverse the reactive power direction merely by reversing the current direction, without changing the voltage polarity as CSC-HVDC requires. It therefore needs no changes in the topology and strategy of the converter station control system.
c) It does not require support from the connected AC grid for commutation as CSC-HVDC does, and can therefore be connected to weak or even passive AC grids, while CSC-HVDC requires the connected AC grid to be sufficiently strong.

Transmission expansion

Needs for transmission expansion

Accommodation of large-capacity RE generation needs large-scale transmission grid expansion and reinforcement for the following reasons:
a) Grid expansion and inter-regional connection are needed to transmit the energy generated by large-capacity RE sources, which are generally located far from load centres and the existing grid.
b) Through grid expansion, the geographic diversity of RE generation can be exploited to smooth out their aggregated variability and uncertainty and to reduce the RE power forecast error.
c) Grid expansion and reinforcement can support interconnection between balancing areas, hence facilitating their cooperation or consolidation to share flexibility resources.

Application of new transmission technologies

a) Higher voltage level AC transmission: UHVAC

UHVAC transmission lines with rated voltage levels of 1150 kV or 1 000 kV were built and commissioned by the former Soviet Union and Japan in the 1980s and 1990s, but then operated at a 500 kV voltage level for practical reasons.
China is now leading the research and application of 1000 kV UHVAC transmission, which seems a desirable technology to meet the need for largescale, long-distance power transmission from the large coal, hydro, wind and solar energy bases in the northern and western regions to the central and eastern regions with huge and still fast-growing electricity demand.
A single-circuit 1000 kV AC line can transmit 4 000 MW to 5 000 MW over an economic distance of 1 000 km to 1 500 km. Compared to 500 kV AC transmission, 1 000 kV AC transmission has many advantages in improving transmission capacity and distance, reducing power loss, reducing land use and saving cost, as shown in Table 4-2 [sin06] [tgy06]. For RE

energy transmission, UHVAC is mainly suitable for transmitting power from on-shore RE plants using overhead lines.

2) More flexible AC transmission: FACTS

Based on advanced power electronic technologies and innovative designs, FACTS equipment can be applied to improve the capacity, stability and flexibility of AC transmission, making it more capable of transmitting large-capacity RE. For example, thyristor controlled series compensators (TCSCs) can be installed in transmission lines to reduce electrical distance, increase damping and mitigate system oscillation; SVC, STATCOM and controllable shunt reactors (CSRs) can be shuntinstalled on substation buses to solve the reactive power compensation and voltage control problems which are common in RE integration due to their output fluctuation. SVCs or STATCOMs may also be used to improve the performance of RE power plants to meet integration requirements on reactive power and voltage control, while keeping the design of RE generators relatively simple.

3) Higher voltage level DC transmission: UHVDC

CSC-HVDC is a conventional HVDC transmission technology that is relatively mature and has long been used for long-distance, large-capacity power transmission without midway drop points, as well as for the interconnection of asynchronous power networks. Compared to AC transmission, it has advantages such as lower loss, lower line cost, narrower corridor and rapid power control capabilities. Like AC transmission, DC transmission is also progressing in the direction of ultra-high voltage levels for larger-capacity and longer-distance power delivery.

4) More flexible DC transmission: from VSC-HVDC to MTDC and DC grids

The major advantages of VSC-HVDC as compared to conventional CSC-HVDC is, it not only suitable for application in RE integration, but also more convenient to form multi-terminal DC (MTDC). Three or more converter stations are linked to each other with DC lines, each interacting with an AC grid, which facilitates flexible multi-grid interconnection and even DC grids. These will be useful in future RE integration where multiple resource sites and multiple receiving ends are involved.

For short distances and relatively low power high voltage alternating current (HVAC) technology will suffice. As power as well as distance increases, HVAC should be augmented with FACTS devices in order to compensate for HVAC losses and to provide stability support. In order to connect remote offshore wind power plants to a grid, VSC-HVDC technology is preferred.

Developments in transmission planning

a) Current practice in transmission planning

Up to now, transmission planning has mainly been based on expert judgment and *deterministic simulations* based on *mathematical models* of the power network and its components. For one scenario of load forecast and generation portfolio for the year studied, transmission alternatives are first proposed by planning experts, then extensive simulations are performed, including power flow, stability and short-circuit studies, among others, under typical normal and contingency situations (generally “worst cases”), to verify whether the deterministic planning criteria can be met. If not, modifications are made to the alternatives and simulations are re-run. For technically viable alternatives, economic comparisons may be made to find the best one. In some cases, in order to account for uncertainty, several scenarios of load forecast and generation portfolio may be considered as a so-called “sensitivity analysis” or “scenario method”.

b) Towards probabilistic transmission planning

The necessity of probabilistic transmission planning has been acknowledged in the research and industry community, following the realization that deterministic planning methods may not be able to reflect the probabilistic nature of outage and system parameters, and that the widely used *N-1* security criterion may be insufficient to capture the real “worst case”, for which a corresponding risk analysis is necessary. As the separation of generation and transmission planning resulting from power market restructuring has made deterministic transmission planning less meaningful, the increasing uncertainty introduced by large capacity RE integration is making the need for probabilistic transmission planning more urgent rather than replacing traditional deterministic transmission planning, probabilistic planning is called to complement it by adding probabilistic planning criteria and evaluation in the planning processes.

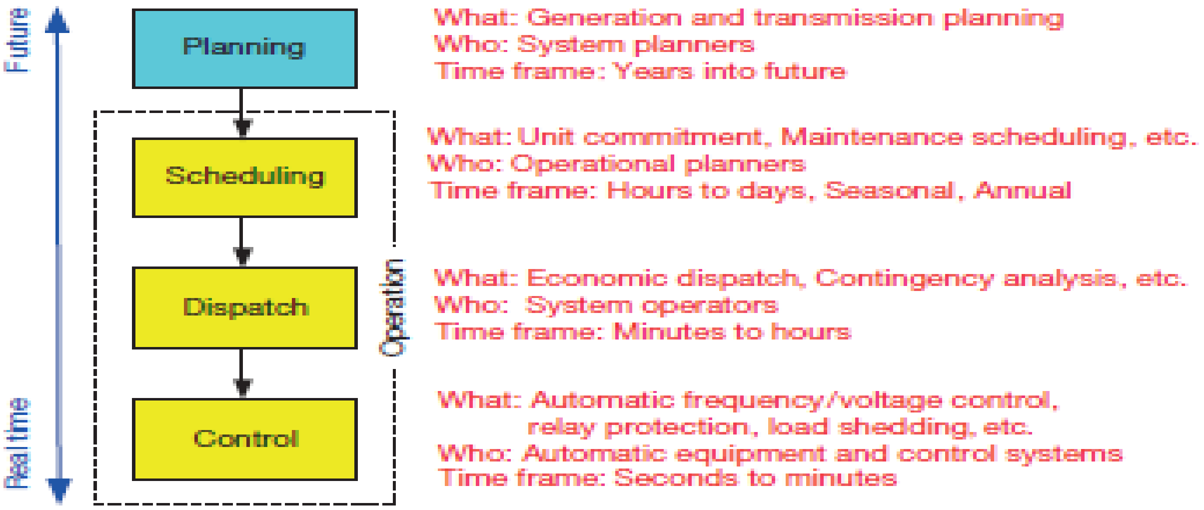
Operational enhancement

Need for operational enhancement

When resource capacity and flexibility as well as transmission availability have been determined by the planning process, it is operations’ responsibility to manoeuver all the system capabilities to cope with the variability and uncertainty resulting from the integration of large capacity RE generation. The operations process, as a broad concept distinct from planning, can be further divided into scheduling, dispatch and control processes. The operation of modern power systems is supported by a physical layer supervisory control and data acquisition (SCADA) system and an application layer energy management system (EMS). The SCADA system covers most of the spread-out elements in a power system, with sensors to monitor their operational conditions and report them to the operations centre through communications channels. The EMS residing in the operations centre exploits the information collected by the SCADA system to analyze the situation and reveal any problems in the power system, make security and economic dispatch and control decisions, and send real-time commands to control the relevant system elements through the SCADA system. Since modern power systems rely heavily on computerized communications and control for operations, they have evolved into cyber-physical systems.

Typical processes of power system planning and operation involves following steps:

- Planning
- Scheduling
- Dispatch
- Control



Historically, various operational tools (EMS applications) have been developed and deployed to successfully address the existing variability and uncertainty in power systems. As variability and uncertainty increase substantially due to the integration of large-capacity RE generation, enhancements have to be made to major operational tools as well as some operational practices; the development and incorporation of more accurate RE power forecasting is critical to most of these enhancements. The integration of large-capacity RE generation may also pose more challenges to cyber-security.

More accurate RE power forecasts

As described in section 3.4.1, many wind power forecast methods and programs have been developed in the last two decades, and the forecast accuracy has been significantly improved, especially for short-term forecasts. However, the forecast accuracy is still low as compared to load demand forecasts, especially for day-ahead and longer time horizons. In addition, the need to forecast significant weather events and provide probabilistic information along with forecast results is not well addressed. Listed below are some directions for improving forecast accuracy and the value of forecasting in operations.

a) Model and data improvement

Improvements in atmospheric observation and numerical weather prediction models are critical for improving RE power forecast accuracy; here, a promising avenue is collaboration among related sectors at national and international levels to improve boundary-layer weather forecasts. Collection and processing of high quality meteorological and electrical data from RE power plants, both historical and real-time, is also essential, and for this purpose four dimensional data assimilation technology may play an important role.

b) Centralized forecast and ensemble forecast

Centralized forecasting at system level can improve forecast accuracy as compared to plant-level forecasts. It is also beneficial for error reduction that the single centralized forecasting system should receive input data from several commercial forecast providers and combine them to form a single ensemble forecast.

c) High-resolution plant-level forecast and nodal injection forecast

While centralized forecasting is the best approach for system-level forecasts, highresolution separate forecasts at different RE power plants are also very important for RE generation dispatch, and for determining the power injected into each delivery node in the power system for managing transmission congestion.

d) Ramp events forecast and situational awareness

Forecasting of ramp events, sudden and large RE generation output changes caused by severe weather events, is of great importance to provide situational awareness to grid operators and help decision-making. However, the definition and forecast methods of ramp events need more research before ramp event forecasts can be integrated into forecasting products.

e) Human forecast

System operators may become good human forecasters after accumulating years of experience. They sometimes outperform advanced forecasting tools. More research is needed into how best to combine human forecasts with computed forecasts.

f) Probabilistic forecast

By providing not only the value but also the probability of expected RE power production or ramp events, probabilistic forecasts could become very valuable for system operations.

Enhancement of operational tools and practices

Power system operation is the field that sees the most prominent and direct impacts of large-capacity RE integration. Briefly cited below are some major enhancements related to EMS applications. The underlying principle behind these developments is to improve operators' situational awareness by evaluating potential events and their impacts, and to provide operators with guidance on possible mitigating measures.

a) Unit commitment

Detailed unit commitment (UC) studies are normally conducted one day ahead, to determine what amount and types of conventional generation units should be available at what time to ensure the desired generation capacity, and also enough flexibility to address system variability and uncertainty. With increased levels of RE generation it is recognized that UC will not be effective unless the RE power forecast is taken into account, and that it should be run more frequently, say every 4 to 6 hours or at even shorter intervals, or alternatively each time a new RE power forecast is provided.

b) Contingency analysis

Contingency analysis (CA) assesses the impacts of potential contingencies, which are normally outages of different grid components, under certain operating conditions. With increased levels of RE generation, the contingency set must be augmented to include those extreme ramp events which are due to RE and outages of RE power plants. Information from the RE power forecast is needed to determine potential contingencies.

c) Online dynamic security analysis

Online dynamic security analysis (DSA) has been implemented in many power system control centres to help operators make the right operational decisions. It evaluates system security and stability limits based on near-realtime network topology and operating conditions, such as the transmission line thermal limits and the system voltage/transient/frequency stability.

By incorporating the RE power forecast and modelling, an online DSA system can be adapted to cope with the operational risks and challenges resulting from increased levels of RE generation.

d) Security constrained economic dispatch

Security constrained economic dispatch (SCED) determines how to dispatch generators to produce electricity at the lowest cost subject to reliability requirements and operational limits on generation and transmission facilities. It is now evolving to accommodate two major directions of power system development: the increase in high penetration RE generation and the development of demand response and smart grid applications.

e) Automatic generation control

AGC is a centralized system designed to ensure real-time generation/load balance and frequency stability, by regulating the power output of selected generation units and exchanging power on tie-lines between different power systems or control areas. Existing AGC algorithms need to be modified so that, based on RE power forecasts, they may address the variability and uncertainty of RE generation.

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f) Stochastic operations and risk-based decision making

To address the increased uncertainty, including that related to RE power forecasts, many researchers believe that future EMS applications should make greater use of stochastic modelling techniques. Stochastic UC, stochastic SCED and stochastic optimal power flow, for example, should be feasible by taking advantage of the greater computing power now available. Risk-based decision making techniques are also needed to improve the current deterministic and binary decision making process; for this, research on how to quantify the relevant operational risks and the severity of contingencies such as extreme ramp events is critical.

g) Security and defence generally

“Security” in DSA and SCED mainly refers to the physical aspects of power system security, or security of supply. As a cyber-physical system, the power system also faces cyber-security challenges, including the reliability of the communications systems serving the power system, and protection of critical information related to power system monitoring and control as well as confidential customer information. Failures in cyber-security, especially those caused by malicious cyber attacks on the control system, may damage power system elements and endanger the physical power system’s security of supply. Since large-capacity RE power plants are usually remotely located and consist of many widely-distributed, small-capacity generating units, the cyber-security of their control systems may require more attention. SCADA and EMS, cyber vulnerability is still a salient problem, and is becoming even more complex with the development of smart grids. Moreover, as power systems, meteorological systems, communications networks, water, commerce, etc., the so-called “critical infrastructures”, become more closely integrated, it becomes increasingly important that the security protocols in one sector are considered within the broader context of the security protocols in connected sectors, as well as the security needs of the country and region. This issue involves harmonization of cyber-security policies both vertically (e.g. from system operation down to individual wind turbine control) and horizontally (e.g. from the power grid to emergency services and telecommunications). With regard to RE integration, this would suggest a need for integrated security policies between weather forecast systems and power system operation, specifically dispatch. For example, a highly secure power grid system with high RE concentrations could still be quite vulnerable to an attack that targets the country’s weather forecasting service, either disrupting forecasting or providing false forecast data. A grid operator who relied on such data might find himself in serious trouble, beyond simple variations in forecast.

Conclusion:

In draft stage

Interoperability of Different Communication Systems

Without a framework of interoperable standards for communications, it would be very difficult to integrate renewable energies into the grid. Since the potential of system is very large and complex, interoperable standards adoption is challenging.

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