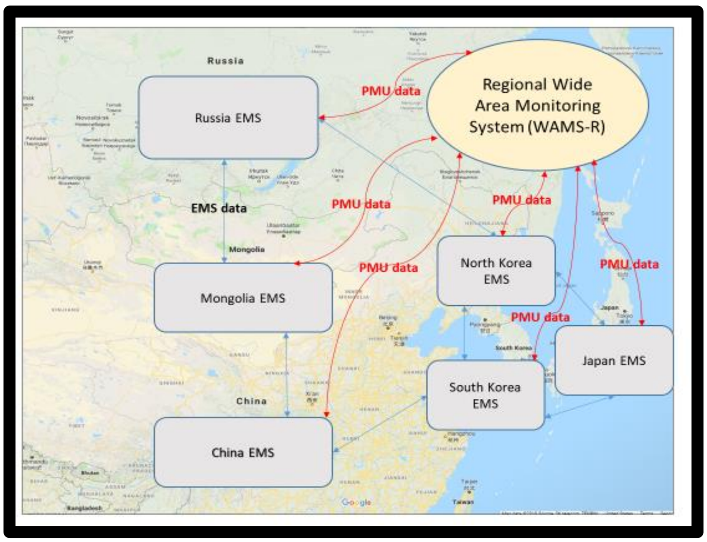
NAUTILUS INSTITUTE

NAPSNET SPECIAL REPORT

DATA AND MODELING REQUIREMENTS FOR ELECTRICITY GRID INTERCONNECTIONS



JAY GIRI

MAY 9, 2019

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I. INTRODUCTION

In this essay, Jay Giri "describes real-time grid management, control center EMS functions and inter-utility data exchange. It also describes the benefits and challenges of inter-utility grid management and examples of international utilities working together. It specifically addresses modeling requirements for international inter-utility operation. Finally, it describes an innovative emerging solution for more effective inter-utility grid operations that helps improve management of the entire interconnection." The paper prefigures a regional Wide Area Monitoring System using synchrophasors in Northeast Asia.

Jay Giri is an Independent Consultant with GGM Consulting

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The views expressed in this report do not necessarily reflect the official policy or position of the Nautilus Institute. Readers should note that Nautilus seeks a diversity of views and opinions on significant topics in order to identify common ground.

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II. NAPSNET SPECIAL REPORT BY JAY GIRI

DATA AND MODELING REQUIREMENTS FOR ELECTRICITY GRID INTERCONNECTIONS

MAY 9, 2019

Summary

Large electrical interconnections consist of many individual electric utilities whose primary responsibility is to manage just their portion of the grid. The utility is typically connected to many other utilities in the interconnection. Actions taken within one's own portion of the grid have an influence on its neighbors. Hence it is vitally important to coordinate one's own electric utility grid management actions with all the neighbors since they could be potentially impacted.

Utilities have a control center with grid operators to manage their portion of the grid round the clock. These centers continually monitor real-time grid conditions in their portion of the grid to assess current status, potential threats and vulnerabilities. Operators take appropriate actions when needed to preserve the reliability and security of the grid. The goal is to ensure that the lights always stay on for all customers.

Control centers primarily consist of a hardware and software platform called an Energy Management System (EMS). These centers also communicate real-time data and operational information with neighboring control centers.

Today, uncertainties in the grid are rapidly increasing due to the growth of less predictable renewable generation resources, demand response programs, distributed generation, microgrids, potential cyber-security issues, and in some cases the aging infrastructure.

Therefore, today, it is of greater importance to have utilities cooperate with each other by sharing real-time information and data, in order to work jointly together as a single team, to preserve the integrity of the entire interconnection.

This paper describes real-time grid management, control center EMS functions and inter-utility data exchange. It also describes the benefits and challenges of inter-utility grid management and examples of international utilities working together. It specifically addresses modeling requirements for international inter-utility operation. Finally, it describes an innovative emerging solution for more effective inter-utility grid operations that helps improve management of the entire interconnection.

Contents

1. INTRODUCTION

Electricity is invisible — and omnipresent in most parts of the world.

In 1881, Thomas Edison created the first electric power company (in New York City, in the United States) to generate power and supply it to customers. Power then was transmitted as direct current (DC) via what we today term a micro-grid: a small, self-contained system of generation, transmission, and consumption. By the 1930s, power transmission had evolved to alternating current (AC) interconnected systems. Over time, these power companies started connecting with their neighbors for support during emergencies and to benefit from cheaper power from neighbors. This has led to large electrical interconnections which consist of many individual power companies.

The modern power grid is a large electrical interconnection and one of the most complex engineering machines in existence. Millions of components comprise the electricity supply chain, from generation to the end consumer. All these components must work reliably, 24-hours-a-day, seven-days-a-week, to power our homes and businesses.

Grid conditions are continually changing. Changes in electricity demand necessitate instantaneous changes in electricity production. Consequently, voltages, currents, and power flows in lines, transformers and generators are constantly changing around the clock.

The grid management challenge is to ensure that these changing power system operating conditions always stay within safe limits, including for potential, probable future contingencies.

In 2000, the U.S. National Academy of Engineers (NAE) selected Electrification as the "most significant engineering achievement of the last century."

This paper focuses primarily on the high voltage transmission grid. It describes the following topics:

- The Electricity Supply Chain
- Real-time Transmission Grid Management
- Control Center EMS functions
- EMS Data modeling
- Inter-utility Data Exchanges
- Practical Examples of Inter-Utility Data Exchanges
- Prospects for International Data Exchange in Far East Asia
- Innovative Multi-Utility Future Grid Management
- Proposed Innovative Solution for Far East Asia Grid Management

2. THE ELECTRICITY SUPPLY CHAIN

Alternating Current (AC) is the form in which electricity is delivered to customers. AC is the form of energy that consumers use when they plug home appliances, televisions, fans and electric lamps into a wall socket.

AC current periodically reverses direction, in contrast to Direct Current (DC), which flows only in one direction. A battery in a flashlight is an example of DC energy.

AC frequency varies by country, and generally either power is generated at either 50 or 60 cycles per second (or Hertz—Hz). AC is 3-phase (3 transmission lines) and DC is 2-phase (2 transmission lines).

The major advantages of AC over DC for widespread geographical deployment are:

- AC power transmission and distribution can be easily interrupted, since the current crosses zero (shifts from positive to negative current) many times per second.
    - Hence practical affordable circuit breakers (CBs) have been built, which can de-energize AC lines quickly
    - Hence complex multi-terminal, meshed AC networks can be easily managed
- DC cannot be easily interrupted, since current does not cross zero.
    - Hence special complex logic is needed to artificially force current to zero in order to disconnect and de-energize the line.
    - Hence it is not easy to build meshed or multi-terminal networks
        - Hence most DC high voltage lines are long distance point to point (a sending end and a receiving end)
- AC voltages can be easily and affordably increased or decreased using AC transformers.
- DC voltages cannot be changed easily and require complex inverter/converter schemes

Therefore, over time, electric power grids have evolved and grown worldwide as AC networks. DC is used typically in special cases, for large-scale point-to-point power transfers.

The AC electricity supply chain consists of:

- Generation
- Transmission
- Distribution
- Customer Loads

Figure 1 is a simple illustration of the electricity supply chain.

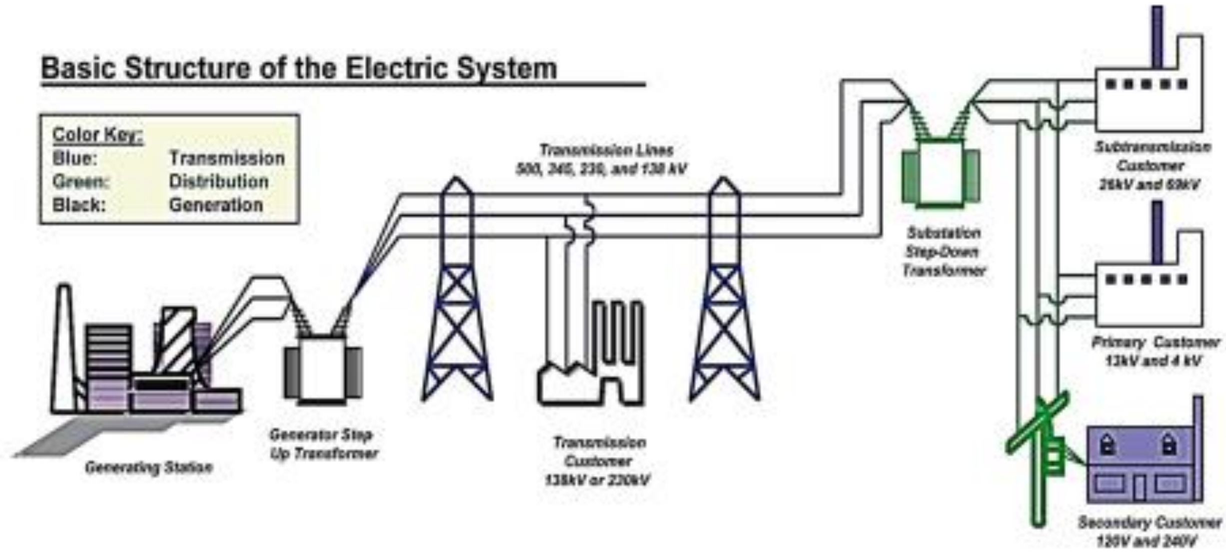

Figure 1: The Electricity Supply Chain

Source: US Federal Energy Regulatory Commission, US Department of Energy, Office of Electricity Delivery and Energy Reliability.

The generation system produces power at a relatively low voltage and high current. This voltage is increased (and current is decreased) using transformers in order to efficiently transfer power over long distances. By reducing current we reduce losses which are equal to I squared R — where I is the current and R is the resistance of the conductor. The high voltage system is called the transmission system or transmission grid. The voltages are then reduced at the customer locations and the lower voltage distribution system or grid carries the power to the end-user or customer loads. The power is delivered to customers at the lower safe voltages.

The amount of electricity or ‘electric power’ delivered is equal to voltage (V) multiplied by current or V*I — and is measured as volt amps (VA) — or as mega volt amps (MVA) for high voltage AC (HVAC) systems. MVA consists of active power or MW (where V and I are in phase) and reactive power or MVAR (where voltage and current are 90 degrees out of phase). Active MW power is the power that is useful and consumed by the grid’s loads. MVAR is a by-product and there is no net transfer of energy to loads.

Facilities that generate electricity are typically, but not always, in remote locations. The supply chain typically covers vast geographical areas and consists of millions of pieces of equipment working together, to provide customers with electricity 24/7/365, around the clock. It is one of the most complex real-time engineering machines in existence today!

This scenario is becoming somewhat different and more challenging with the recent rapid growth of renewable energy resources, since they are unpredictable and cannot be easily controlled.

3. REAL-TIME GRID MANAGEMENT

When demand for electricity (or "load") changes, generation needs to react immediately in order to maintain system frequency. If demand increases, generation needs to increase; if demand decreases, generation needs to decrease. Electricity cannot be easily stored for retrieval later, hence this generation load mismatch needs to be continually monitored and adjusted in real-time.

Electricity cannot be intentionally routed along a preferred transmission path; it follows the path of least electrical resistance, as dictated by the laws of physics.

In addition to second-by-second changes in customer demand, events such as lightning strikes, short circuits, equipment failure, accidents, also disrupt flow in the electricity supply chain.

Maintaining power grid system frequency within a certain normal range is essential to ensure system integrity. This simple operational objective requires a vast infrastructure of hardware, protection and control equipment and advanced software tools.

3.1 Electric utilities of an interconnection

Large electrical interconnections have evolved over time, by the interconnection of smaller power grids with their neighbors. The primary objectives being:

- Share economical generation with each other, both to serve loads and to reduce the need for reserve capacity; and
- Provide support to each other during system emergencies.

Today's interconnections typically consist of numerous independent electric utilities that own and operate their own portion of the grid — or each is responsible for a small subsystem of the large interconnection.

The goal of each utility grid operator is to keep the power flowing for their own customers without interruption — "keep the lights on." Each utility has visibility and control of only their portion of the interconnection. Yet any action implemented by a utility potentially affects their neighbors since the systems are all connected — electrically and physically.

3.2 Control Center — Energy Management Systems

In order to manage their portion of the transmission grid, utilities have implemented control centers. These consist of integrated systems of real-time functions to monitor and control the transmission grid. The first centralized control centers were established in the 1950s based on analog technology.

These control centers used and use a software and hardware system called an Energy Management System (EMS). Based on a centralized command and control paradigm, EMS have evolved over the past six decades into much larger and more complex systems. Nevertheless, they have the same simple mission as before: "Keep the lights on for all customers around the clock."

The modern Energy Management System (EMS) based on digital computers was developed in the 1960s to maintain the integrity and security of the power grid. Over the past five decades, EMS capabilities have continued to evolve. Today, most utilities have an EMS that focuses on real-time management of the transmission grid.

The EMS receives measurements from various substations in the grid every 2-4 seconds. These measurements include voltages of busbars, line and transformer flows (MW, MVAR) and AC frequency. These measurements do not have time tags and have unknown, variable latencies; they are also noisy and not necessarily accurate.

The EMS applications were originally designed to handle these not-perfect measurement characteristics. The applications use these measurements to monitor the state of the grid and display them to the grid operator.

Today's grid management paradigm is basically reactive — the operator monitors and reacts to measurements of current conditions, in order to make decisions for the immediate future. *It is like driving an automobile and making steering decisions <u>by only looking at the dashboard</u>.* The driver is like the grid operator who makes decisions to ensure the grid is secure, so that customers' lights stay on. 'Driving by dashboard' becomes particularly challenging when the road ahead is not necessarily straight and flat.

The grid operator's tasks focus on situation awareness (SA) and implementing actions. SA is more comprehensively defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." For the grid operators, taking action means implementing changes to their own grid equipment and working with neighbors as needed to implement system-wide actions.

The specific operator functions are:

- **Real-time monitoring**
    - A continual round the clock activity
- **Synthesizing actionable information**
    - Numerous times of the day, when alerts from disturbances are detected and need to be investigated
- **Implementing actions**
    - A less frequent activity — performed only when needed, to avert a potential problem

Figure 2 below shows the suite of real-time and off-line functions that comprise a modern control center.

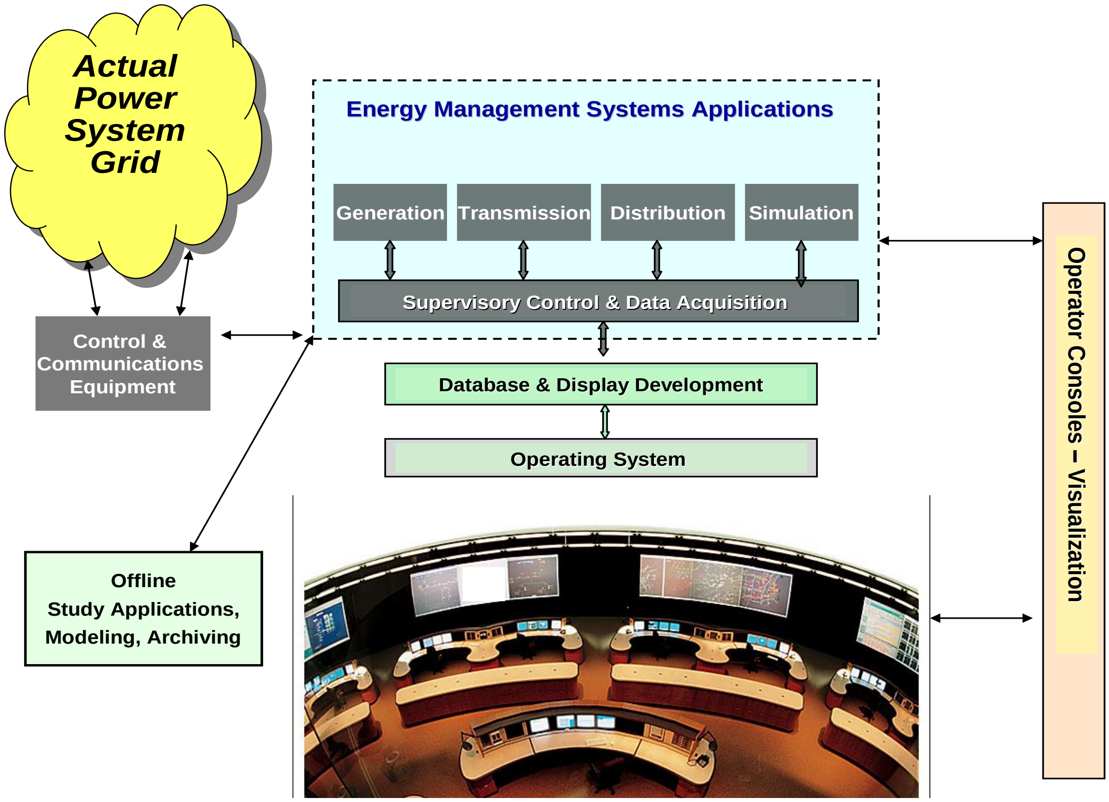

Figure 2: Control Center Applications Overview

Source: GE Grid Solutions

3.2.1 Real-time Grid Measurements — SCADA

The first EMS application implemented in control centers was Supervisory Control and Data Acquisition (SCADA) systems. SCADA systems retrieve live grid data typically every 2 to 4 seconds.

SCADA allows the operator to visually monitor grid conditions from a central location and serves as the eyes into the grid. SCADA also allows operators to implement actions manually, if needed. SCADA provides continual measurements from key locations of the grid to allow the operator to monitor grid conditions and recognize overloads and emergencies. The operator can also remotely switch selected transmission components in or out of service to alleviate overloads or mitigate problems. The components that could be switched included voltage support equipment, sections of a line, transformers, and generators. Operators can also shed customer load (or intentionally turn off electricity to customers) as a last resort in order to preclude a widespread grid collapse.

3.2.2 Maintaining System Frequency — LFC

Load Frequency Control (LFC) automatically maintains system frequency as load changes, by immediately changing (increasing or decreasing) generation accordingly. LFC typically runs every 4-10 seconds.

LFC is one of the first “smart grid” applications implemented to automatically help the operator with the objective of keeping the lights on. It is the only closed-loop application that works round the clock with minimal operator intervention.

3.2.3 Minimizing Electricity Production Costs — ED

Economic Dispatch (ED) determines optimal generator outputs in order to minimize total generation cost. ED typically runs every minute.

LFC combined with ED is called Automatic Generation Control (AGC). AGC simultaneously satisfies multiple objectives: maintaining normal system frequency, maintaining tie-line contractual flows, and dispatching generators to minimize the total system generation cost.

3.2.4 Monitoring Grid Network Conditions — SE

State Estimation (SE) calculates current network conditions using SCADA data with a user-defined model of the grid network. The grid model consists of a detailed model of one’s own utility as well as some portions of the immediate neighbors in the interconnection. SE typically runs every minute.

SE calculates the “best guess” of system conditions across the entire network, especially for network nodes not measured by SCADA — or it fills in the gaps for what SCADA does not measure. This provides a comprehensive holistic view of all the modeled grid substations. SE also provides alerts of overloads on lines and transformers.

3.2.5 What-If Studies — CA

Contingency analysis (CA) uses SE to do a series of “what-if” contingency studies. Meaning, if these contingencies were to occur, will the grid remain secure? CA assesses the strength and resiliency of the grid to potential vulnerabilities.

Contingencies are potential outages of transmission lines, transformers, generators, loads or even entire substations. CA processes a list of predefined contingencies to determine if any will result in overloads or more severe problems. Operators make decisions on what might occur in the immediate future.

CA typically usually runs after every other SE run, or about every two minutes.

CA is a very important operator function. Typically, one computer display monitor at the control center is dedicated to continually display these updates.

3.2.6 Optimization of Grid Operating Conditions — OPF and SENH

Optimization techniques to minimize transmission system losses — optimal Power Flow (OPF) — and to determine corrective and preventive control recommendations to alleviate the impacts of potentially harmful contingencies — Security Enhancement (SENH), are included in many of the modern EMS. These run typically at some multiple of the SE cycle.

They employ advanced algorithms such as linear programming and mixed integer programming on very large-scale matrix systems.

3.2.7 Dynamics of the Grid — DSA

Dynamic Security Assessment (DSA) simulates the dynamics of the grid when a fault or an unplanned event occurs. These are called grid stability applications. They assess grid vulnerabilities due to transient instability and voltage instability. They are computationally challenging since they involve the iterative solution of a large number of nonlinear differential equations (the generator dynamic models) with the solution of another large number of nonlinear algebraic equations (the electrical network). Stability applications have become another important tool for the grid operator, and they provide alerts to potential instability due to the dynamic behavior of the grid.

3.3 EMS Subsystem Overviews

Figure 3 illustrates the scope of SCADA and SE that provides the grid operator with a wide-area view of real-time conditions. SCADA monitors one's own system. SE models one's own transmission system as well some of the immediately neighboring systems — this is because CA (which use the SE results as its base case) solutions are affected by the neighboring transmission system network.

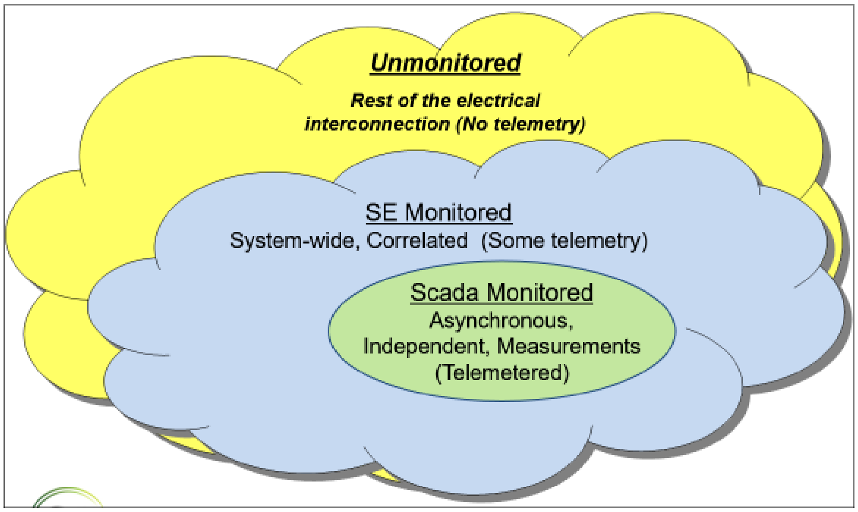

Figure 3: Grid monitored regions

Source: GE Grid Solutions

Figure 4 is an overview of the EMS monitoring and analytical functions.

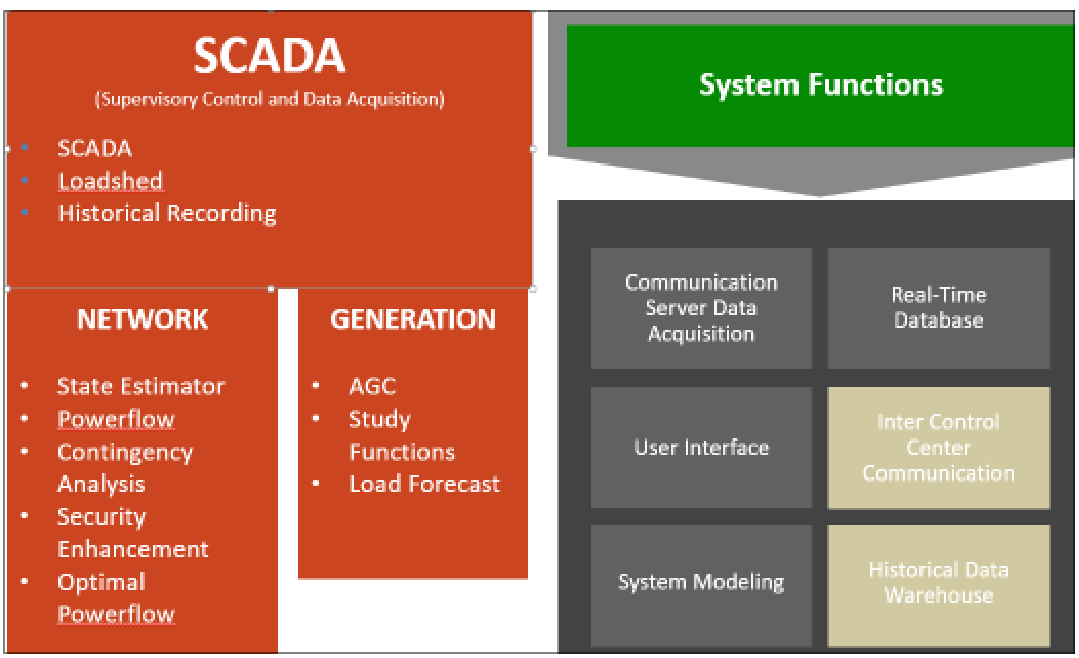

Figure 4: Main EMS software subsystems

Source: GE Grid Solutions

Figure 5 shows how the different EMS functions monitor and analyze the grid. SCADA, AGC, SE, and CA are used and related as follows:

- SCADA is the eye of the EMS. It provides an asynchronous, uncorrelated view of the grid based on remote terminal unit (RTU) data from the nodes (generators, substations, switches, and other components) of the grid. Without SCADA, the EMS has no visibility of the grid.
- AGC is the energy balance or frequency view. It monitors generation-load imbalances at the SCADA scan rate and monitors system frequency and tie-line flows.
- SE and CA provide an analytically-correlated view of grid conditions. Some substations may not be monitored since they do not have RTUs, or communications to the control center. SE uses the available SCADA data and fills in the blanks for these un-monitored substations. SE provides a comprehensive assessment of conditions (voltages, line flows) at all substations, by using a best fit algorithm with the available SCADA measurements.

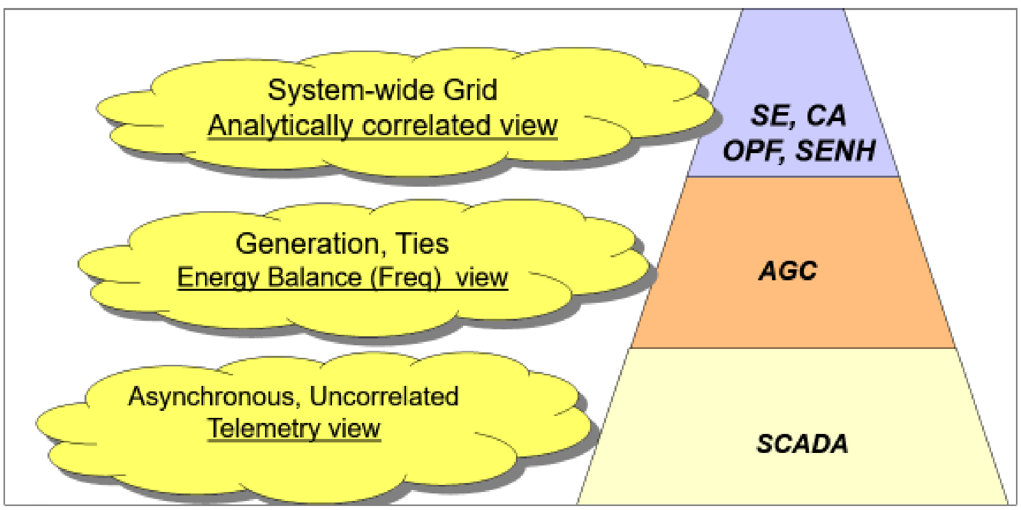

Figure 5: EMS applications perspectives

Source: GE Grid Solutions

Figure 6 shows a typical SCADA one-line diagram from which the operator can perform supervisory control actions such as opening or closing circuit breakers in the field. Circuit breakers are shown as small red squares (closed) or green squares (open).

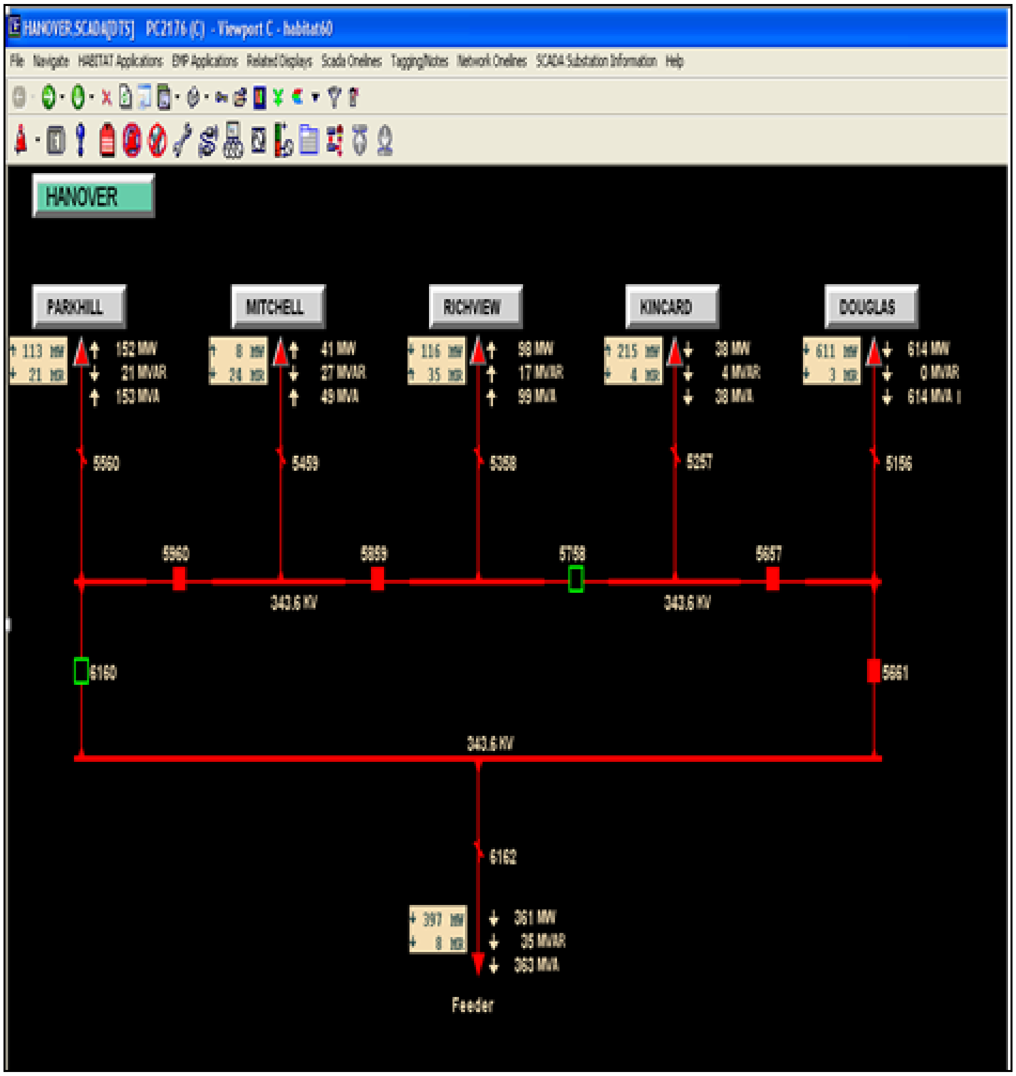

Figure 6: Typical SCADA substation one-line diagram

Source: GE Grid Solutions

4. EMS DATA MODELING

The different types of grid equipment that are modeled in the EMS are:

- **Transmission System:**
  This includes transmission lines, transformers, shunt capacitors and reactors, phase-shifting transformers, static VAR compensators (SVC), and high-voltage dc (HVDC) transmission systems.

- **Generating Units:**
  This includes the entire spectrum of supply resources — hydro, steam, gas, and geothermal generation, as well as wind and solar power plants.
- **Loads:**
  Representing the electrical loads in the system, which range from simple light-bulbs to large industrial facilities.

4.1 EMS Models

The EMS model is a comprehensive representation of all the transmission grid equipment owned by the utility.

Figure 7 depicts how the network model is represented in the EMS. The model is a **'node-breaker model'**. Nodes are junctions of substation components. Breakers are circuit breakers which connect equipment, such as lines, transformers, generators and loads.

All substations are represented by node-breaker models to describe the complete interconnected topology of the grid.

In **Figure 7**, the nodes are numbered 20, 21, 23, 232, etc. Circuit breakers are the symbol between nodes 231–232 and 20–21, etc. Circuit breakers are either open or closed. Transformers are the symbol between 21 and 231 (21 is at one voltage and 231 a different voltage). Generators and loads are symbols connected to node 21 and 23 respectively. Lines are connections between substations — such as connected to node 232 in this substation and another node at the other substation.

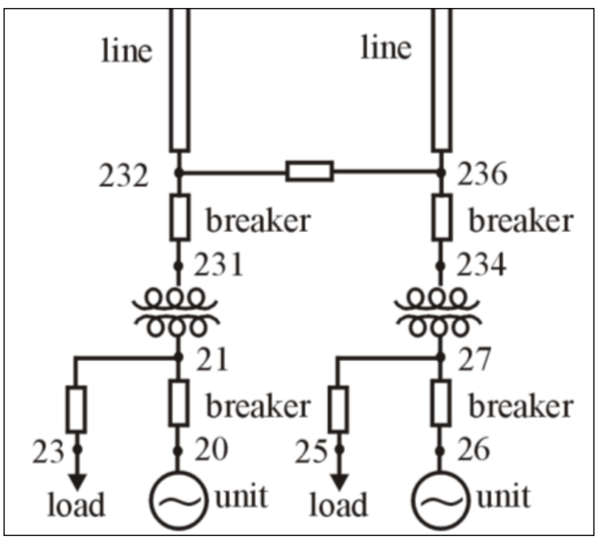

Figure 7: EMS node breaker model

Source: M. Papic, Idaho Power

The EMS model topology is conglomeration of such node-breaker models for all the substations in its jurisdiction.

Grid equipment are defined with specific models and specific model parameters — such as resistance, reactance and capacitance, etc.

Each grid equipment has a steady state model (where the grid is relatively stable, and frequency is close to normal) and a dynamic model (for when the grid is in a disturbed state, and frequency is oscillating, and is not uniform across the grid).

4.1.1 Steady-state EMS Models

Each of the grid equipment (transmission elements, generators, and loads) are represented by a steady-state model.

For transmission lines, transformers, and shunt capacitors/reactors, model development is accomplished by an accurate calculation of the impedances, MVA capacity ratings. For generation, steady-state models represent real and reactive power (MW and MVAR) capability and remote voltage control buses. Loads are represented as constant real and reactive power; or constant current; or constant impedance.

These model parameters are calculated based on information from the original equipment manufacturers. The manufacturers also provide safe operating limits or ratings for each component — such as maximum allowable MVA capacity.

The individual component models are then combined into a complete system model for representing steady-state behavior of an entire interconnection. This model is known as the "power flow" model. For some studies, remote parts of a large interconnection sufficiently distant from the locations of interest are represented using reduced-size models known as "equivalents."

4.1.2 Power flow models of transmission systems represent only positive sequence quantities. Dynamic EMS Models

Models that represent the dynamics of equipment are also used for each of the categories of equipment listed above.

For stability studies, the characteristics of concern typically have time constants in the range of a few tens of milliseconds to many seconds. Thus, dynamics models represent the behavior of power plants and their controls, certain types of loads, and various power electronic devices — such as Flexible AC Transmission systems (FACTs) and HVDC.

Equipment modeled in the steady state model have corresponding dynamics models.

5. INTER-UTILITY DATA EXCHANGES

Large electrical interconnections consist of many individual electric utilities. A utility is typically physically connected to many other utilities in the interconnection. The flow of electricity in the interconnection is dictated by physics and not jurisdictional utility boundaries. Hence utility operators whose primary responsibility is to manage 'just their portion' are not in full control of 'just their portion' of the grid. Actions taken by neighbors affect their portion of the grid and vice versa.

Hence it is very important to coordinate one's own operation with neighbors, since they could be affected.

By increasing inter-utility cooperation and information exchange across the entire region, the holistic benefits to the overall interconnection are:

- Safer grid operation
- Improved security of supply
- More sustainable supply
- Easier access to market participants
- Easier sharing of economic power as and when needed
- Improved socio-economic welfare in the region
- Improved situational awareness across borders

5.1 Confidentiality of Data Exchanges

Utilities are typically hesitant to be totally transparent with their neighbors, since they might lose their competitive advantage. So, they typically share just a subset of their grid data based on mutual agreements, in order to help improve the neighbors' real-time grid operations.

Typically, task forces are created, with all utilities involved, to discuss the kinds of data sharing that would be beneficial, and the rate at which they should be shared. The objective is to help each other, so that one can manage their grids more effectively and securely — while being careful to not divulge confidential information that could hurt their business.

A data sharing document is typically developed jointly, to clearly articulate:

- Type of data to be shared,
- How often it should be shared,
- Why it is needed,
- Which applications will use these data,
- How applications' results will be shared,
- A guarantee to preserve the confidentiality and intellectual property of the data, and that it will not be used for any other purposes.

5.2 Types of EMS data exchanges

The following are the types of data that are exchanged between utilities:

- **Real-time conditions at major substations**
  - These are real-time power system condition such as voltages and power flows on lines, transformers or generators.
  - These are typically exchanged on regular periodic basis — from every minute to every day
  - These could be for just a few major substations that may impact neighbors
- **Network topology changes**
  - These are planned or unplanned outages of major grid equipment
  - There are typically exchanged when they occur, on a ‘report by exception’ basis
  - These also are for just a few major grid equipment that may impact neighbors
- **Network model parametric data**
  - These are the numerical parameters of steady state and dynamic network models
  - These are reported quite infrequently — like when they perform joint analytical studies across multiple utilities
  - Once again, this typically represents a subset of their network model — for example just their higher voltage networks

5.3 Protocols for Inter Utility Real-time Data Exchanges

Inter-utility real time data exchange has become critical to the operation of interconnected systems in most parts of the world. At the top level there is typically a system operator with coordination responsibilities for dispatch and overall system security. Below this are regional transmission companies that tie together distribution companies and generating companies. In continental power systems, there is now considerable interconnection across international borders.

SCADA manufacturers developed their own proprietary “closed” protocols for communicating from a control center to equipment in the field. These were followed by the development of “open” industry-standard protocols such as DNP3 (Distributed Network Protocol) and IEC (International Electrotechnical Commission) 61850. However, none of these communication protocols were suited to the requirements of communicating between control centers.

5.3.1 ICCP

A joint EMS vendor initiative in the United States was development of ICCP (Inter Control Center Protocol). ICCP began as an effort to develop an international standard for real-time data exchange within the electric power utility industry. In the US, ICCP networks are widely used to tie together groups of utility companies, typically a regional system operator with transmission utilities, distribution utilities and generators. ICCP is based on client / server principles. Data transfers result from a request from a control center (client) to another control center (server). Control centers may be both clients and servers.

5.3.2 ICCP TASE-2

The second ICCP protocol version — TASE.2 — is the version that has become the most popular. The Telecontrol Application Service Element (TASE) protocol — also known ICCP — allows for data exchange:

- Across wide area networks
- Between utility control centers of an interconnection.
- Within a utility's hierarchies of control centers, and non-utility generators.

Data exchanges include real-time data and historical power system monitoring data.

5.4 Grid Model Data Exchange — Common Information Model CIM

The Common Information Model (CIM) was originally developed to support the integration of multi-vendor applications at control centers. This describes a common format that all utilities can use to exchange **network model data**. The data includes network topology and parametric data of grid equipment.

CIM standards are used to:

- Facilitate the exchange of power system network data between organizations
- Allow the exchange of data between applications within an organization
- Exchange market data between organizations.

The Common Information Model (CIM) has been officially adopted by the IEC to allow control centers to exchange grid model parameter information. IEC Standards 61970-301, 61968-11, and 62325-301—are collectively known as the CIM for power systems.

6. PRACTICAL EXAMPLES OF INTER-UTILITY DATA EXCHANGES

The following are just a few of the major inter-utility data exchanges that have been implemented around the world. They have been in successful operation for many years.

6.1 PJM — USA

Transmission Owners (TOs) and Generator Owners (GOs) are responsible for providing the information and data needed by PJM to accurately model their electrical system. They have been successfully exchanging real-time and model data for many decades.

PJM (the Pennsylvania/New Jersey/Maryland grid in the Eastern United States) models have multiple data attributes, including modeling the physical devices, appropriate limits, substation and network connectivity, telemetry to support State Estimation (SE), SA, etc.

The data and information to be submitted includes, but is not limited to, the following:

- Substation topology
- Equipment names or designations
- Facility physical characteristics including impedances, transformer taps, transformer tap range, transformer nominal voltages, etc.
- Facility limits and ratings
- Recommended contingencies to be studied
- Real-Time analog and equipment status telemetry for transmission and generation elements, including, but not limited to:
    - Breaker, switch, or other equipment status required to determine connectivity
    - MW, MVAR power flow for lines, transformers, loads, generators

6.2 Europe: ENTSO-E

European Transmission System Operators (TSOs) are entities operating independently from the other electricity market players and are responsible for the bulk transmission of electric power on the main high voltage electric networks.

TSOs provide grid access to the electricity market players (i.e. generating companies, traders, suppliers, distributors and directly connected customers) according to non-discriminatory and transparent rules. In order to ensure the security of supply, they also guarantee the safe operation and maintenance of the system. In many countries, TSOs are responsible for the future development of the grid infrastructure as well.

Figure 8 shows the 43 TSOs from the 36 countries who are members of ENTSO-E (the European Network of Transmission System Operators for Electricity).

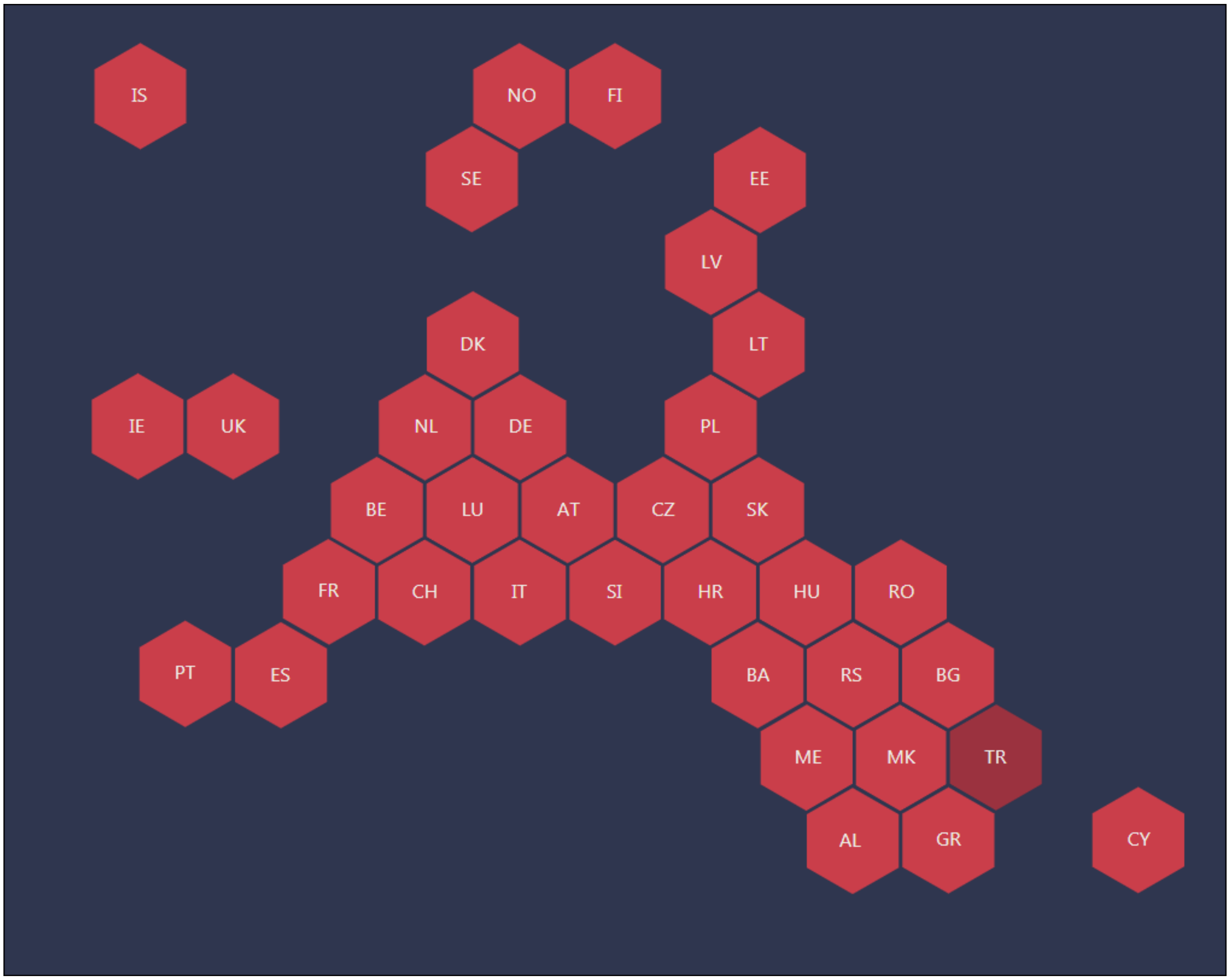

Figure 8: European Countries of the ENTSO-E

Source: ENTSO-E website, https://www.entsoe.eu/about/inside-entsoe/members/

In 2015, the members of ENTSO-E signed a multi-lateral agreement on the coordination of operational planning and derived services. They voluntarily agreed to outsource to regional security coordinators five services that were so far performed on a national or control area basis. The first and core coordinated service is the common grid model. The common grid model is a multi-national mathematical model of the grid.

TSOs need to share their individual grid models with the other TSOs and the regional security coordinators1 (RSC). RSCs are responsible for merging the different grid models of the TSOs and issue common grid models. These are then shared with the TSOs for their operational purposes.

6.3 India

The Power Grid Corporation of India Ltd. (PGCIL), which oversees operation of the national grid, is one of the largest power transmission utilities in the world. The country is one single electrical interconnection. The peak load demand is over 100 GW.

Figure 9 provides an overview of the Indian EMS hierarchy. It consists of four EMS levels: national (entire country), regional (geographical groups of states), state, and SCADA systems within a state. Today, the Indian EMS consists of over 450 computers communicating with other each other hierarchically, to gather data from various locations of the grid every few seconds to monitor grid conditions across the country.

In 2013, India embarked on a new project to deploy over 1800 PMUs (Phasor Measurement Units), across the interconnected national grid. This provides sub-second, instantaneous visibility of real-time conditions across India.

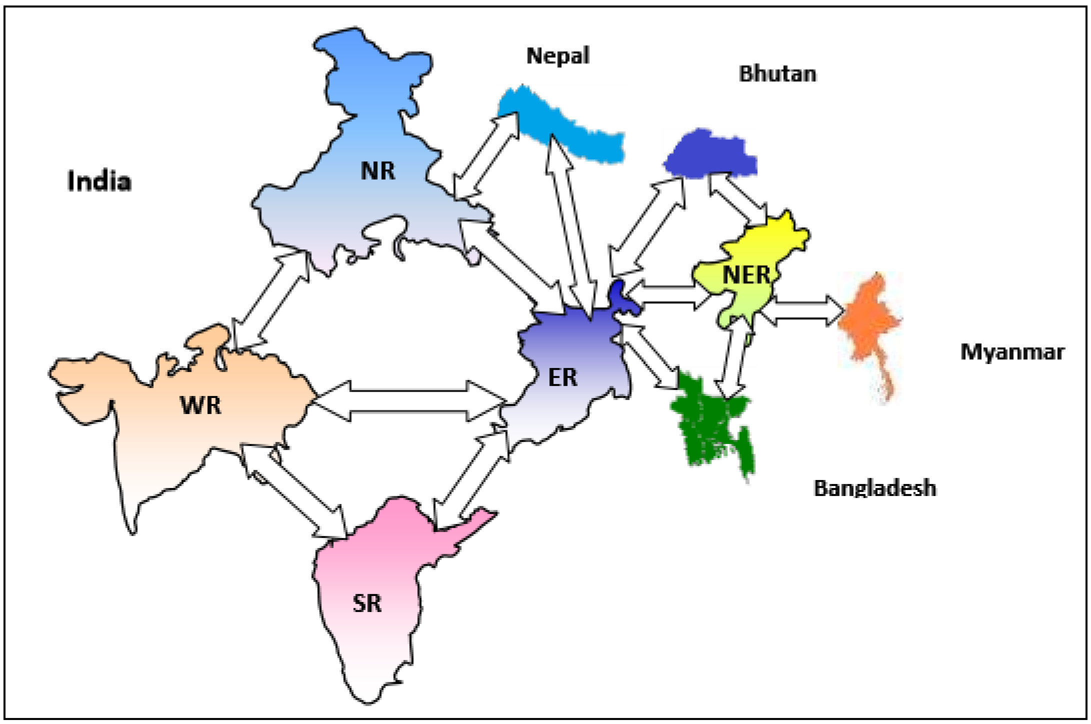

Figure 9: India's Regional Interconnections

Source: PGCIL, India

The power sector in India and its neighboring countries in the South Asian Region must grow rapidly in order to sustain the high level of economic growth in the region. Against this backdrop, strengthening of cross-border electricity cooperation can prove beneficial for all in terms of providing adequate and reliable electricity supply. There are complementarities in electricity demand and resource endowments among these countries that can be leveraged to meet the growing energy requirements of the region while optimally utilizing resources. Furthermore, increased electricity cooperation and trade among these countries can also bring economies of scale in investments, strengthen electricity sector financing capability, enhance competition, improve sector efficiency, and enable more cost-effective renewable energy penetration.

Recognizing the importance of electricity in promoting economic growth & improving the quality of life in the region and envisaging the need for a stronger cross-border electricity cooperation, the South Asian Association for Regional Cooperation (SAARC) organized a cooperative framework for electricity exchanges **(**see **Appendix-SAARC).** Eight countries have signed the SAARC Framework Agreement Energy Cooperation (Electricity). The Framework allows the member states to carry out Cross Border Trade of Electricity subject to laws, rules, and regulations of the respective member states.

The objectives of the framework include:

- Facilitate cross border trade of electricity between India and neighboring countries;
- Promote transparency, consistency and predictability in regulatory approaches across jurisdictions and minimize perceptions of regulatory risks;
- Meet the demand of the participating countries by utilizing the available resources in the region;
- Ensure reliable grid operation and transmission of electricity across the borders;
- Evolve a dynamic and robust electricity infrastructure for cross border transactions.

Figure 10 provides a schematic of power exchanges between India and four neighboring countries.

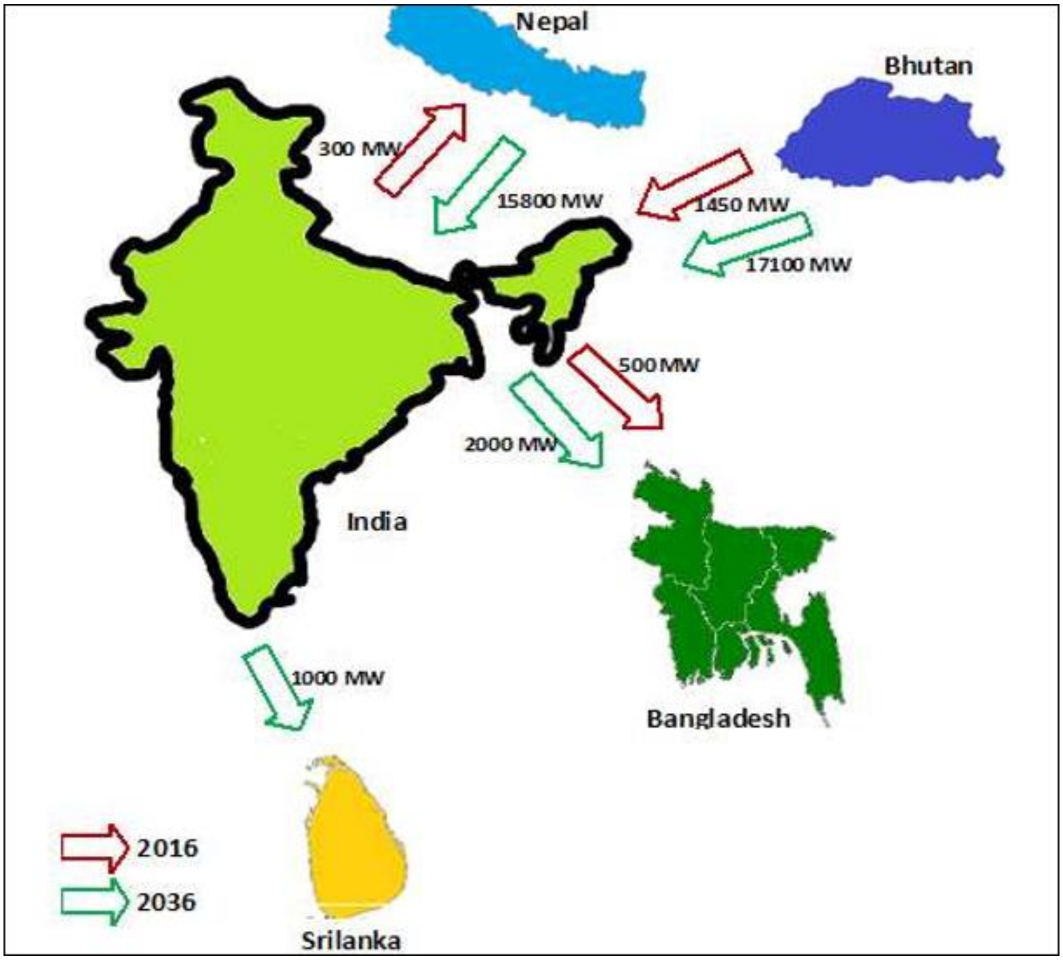

Figure 10: India's International Interconnections

Source: PGCIL, India

6.4 Turkey

Figure 11 shows how Turkey is interconnected with the European ENTSO-E grid and its neighbors. Turkey's stated strategic plan is to continue to strengthen connections in order to improve grid reliability and reduce costs of grid operation.

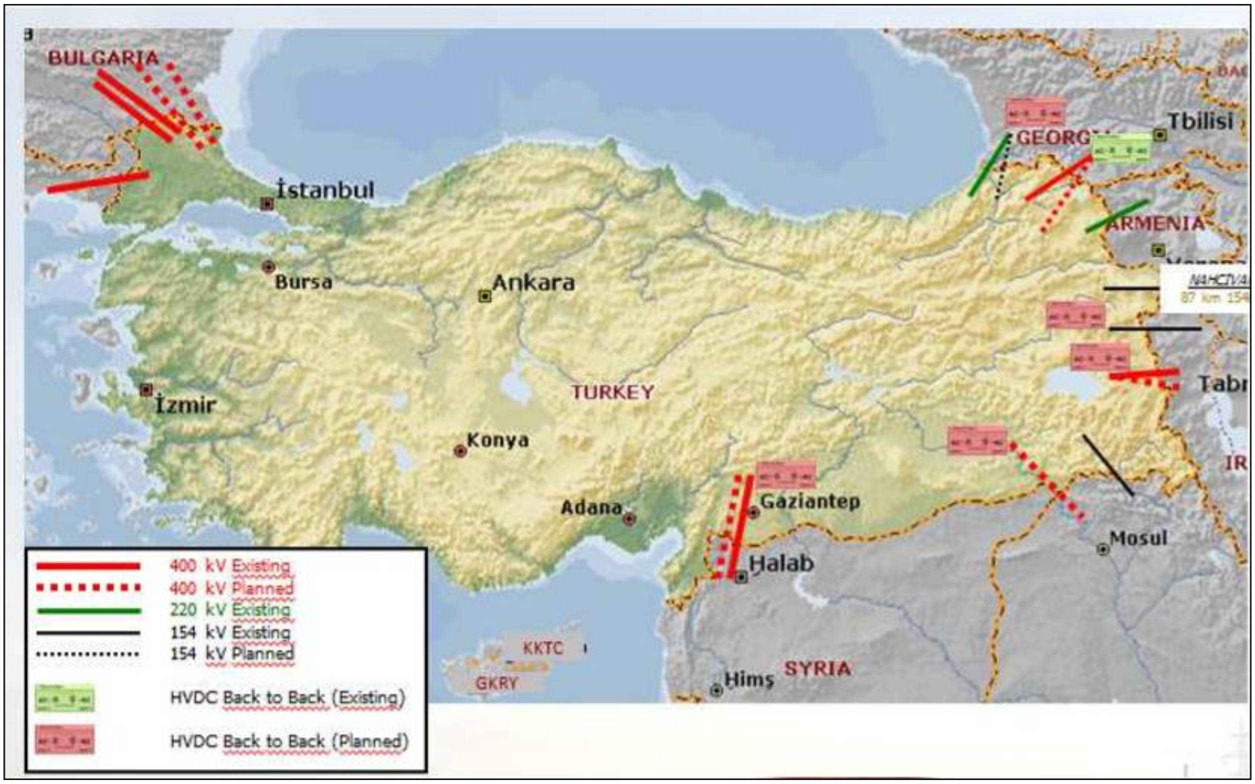

Figure 11: International Interconnections of Turkey

Source: Network Assessment Workshop Athens, Greece March 2017

7. PROSPECTS FOR INTERNATIONAL DATA EXCHANGE IN FAR EAST ASIA

Figure 12 pictorially depicts different national control centers of the Far East Asia region. Each EMS manages their own national grid. Each nation has interconnections with neighboring nations. Each nation has its own EMS vendors, with implementations of different vintages, and differing complexities of real-time applications and capabilities. Some may just have a small subset of EMS applications, some may have a full set. Some may have a hierarchy of control centers with the national center at the top. Some countries may operate at a different frequency than their neighbors.

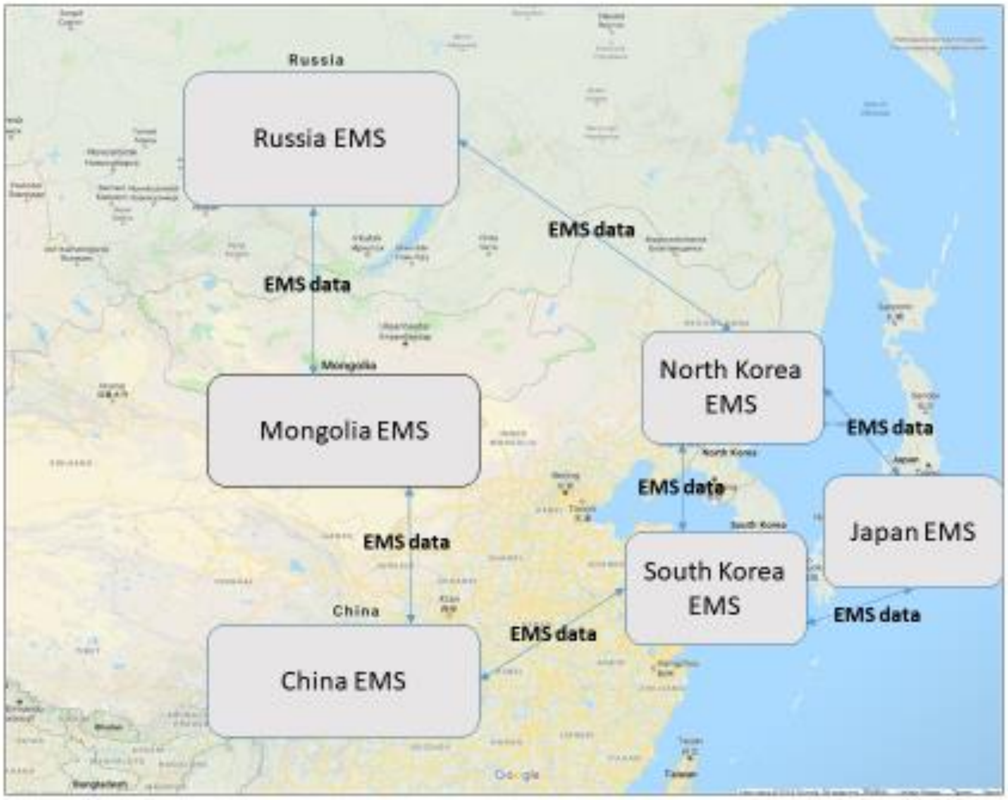

Figure 12: International Control Centers of Far East Asia

Source: GGM Consulting

In order to exchange real-time data, they will need to implement inter control center data exchange protocols, as described in an earlier section. Sharing real-time information from neighboring countries' major substations will help each country operate its grid in a more effective and secure manner. This is especially beneficial with the growth of cheap renewable resources in the different countries. Generation from renewables are constantly changing and cannot be easily predicted. With strong interconnections, economic power can be quickly shared with neighbors.

The growing diversity of power generation portfolios in the different countries, due to the rapid development of renewable energy sources (RES) could result in greater interdependence across the Far East region. Renewables are connected to the grid with inverters. They typically do not provide support during emergencies since they have minimal inertia and inadequate voltage support. Today there are smart inverters that provide artificial inertia and voltage support during emergencies.

Therefore, transmission system design must look beyond national boundaries and move towards multi-national regional solutions. This could include DC transmission overlays on the AC system. If we need to connect systems with different operating frequencies (say 50 Hz and 60 Hz), AC/DC/AC back-to-back converters are a solution. HVDC lines could be used to economically transfer large amounts of power across a great distance.

Many of these solutions are already in operation and/or under development in many nations of the Far East grid.

Figure 13 shows China's HV transmission network today and the future.

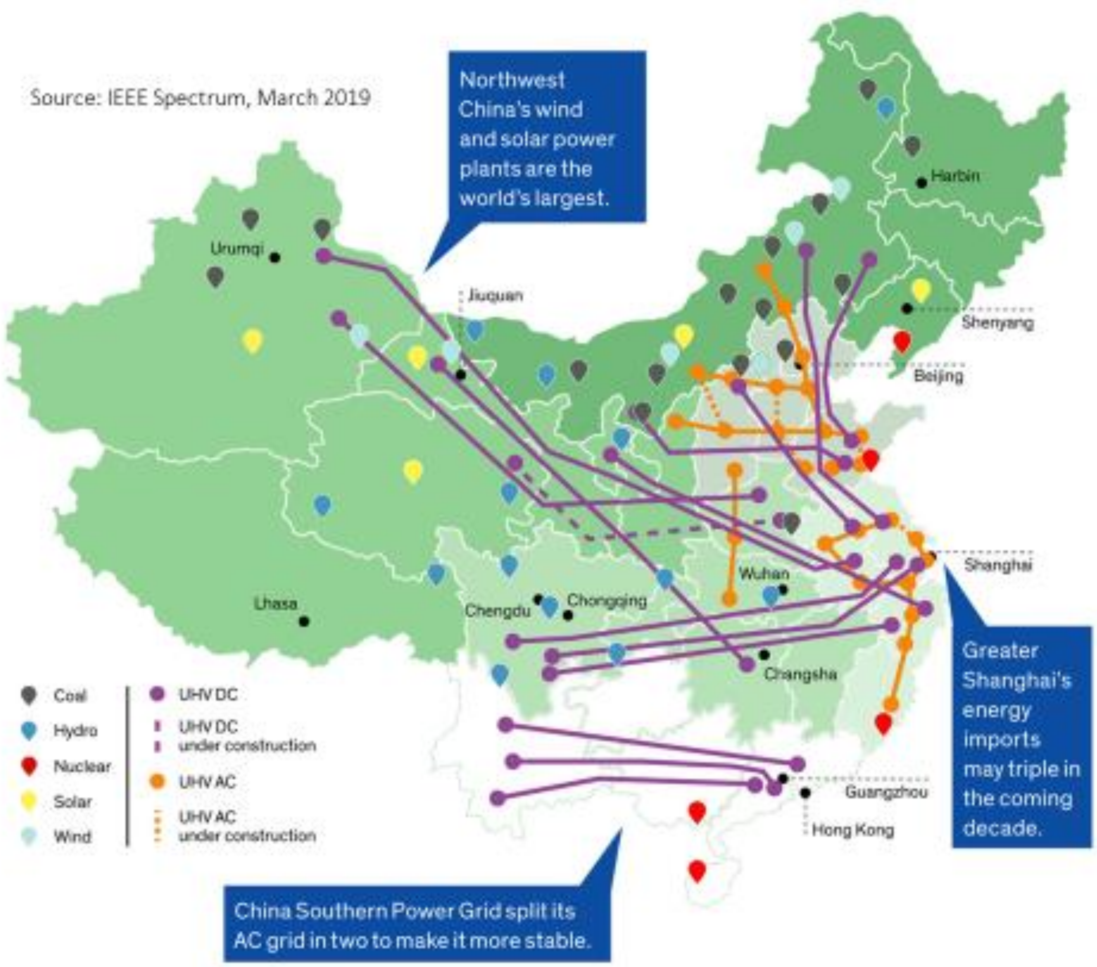

Figure 13: China's National Grid Plans

Source: IEEE Spectrum, March 2019
http://spectrum.ieee.org/energy/the-smarter-grid/chinas-ambitious-plan-to-build-the-worlds-biggest-supergrid

National electricity system expansion plans have in the past been primarily focused on operation of their own national grids. These will need to be augmented now, with overall international regional objectives in mind. Cooperation in joint planning and operations of the different nations is required to achieve more effective operations and to improve overall regional reliability, security and cost efficiency.

Recommended data exchanges include:

- **Real-time conditions at substations**
    - This could be a small subset of critical high voltage substations
    - At a regular, periodic rate of say minutes to hours
- **Network topology changes**
    - This could be only for major critical grid equipment
    - Report on an exception basis — or only when their status changes
- **Network Model changes**
    - This could be just for the grid network that is close to neighbors' boundaries
    - Report on an exception basis — or only when major changes are made

8. AN INNOVATIVE SOLUTION TO FUTURE MULTI-UTILITY GRID MANAGEMENT — EMS-WAMS

8.1 Introduction

Managing the future grid will require creative, innovative solutions. Uncertainties in the grid are increasing due to the growth of less predictable renewable generation resources, demand response programs, distributed generation, microgrids, potential cyber-security issues, the retiring workforce and the aging infrastructure.

Recently there has been a sudden growth in the deployment of a new type of grid measurement technology in installations all around the world. These measurement devices are called synchrophasors.

"Synchrophasors are precise grid measurements now available from field device monitors called phasor measurement units (PMUs). Measurements includes voltage and current — magnitudes and angles — frequency, rate of change of frequency and status data. PMU measurements are typically 30-120 observations per second — compared to every 2-4 seconds using conventional EMS technology. Each measurement is precisely time-stamped using a common time reference. Time stamping allows synchrophasors from across the grid to be time-aligned (or "synchronized"). Together, they provide a precise and comprehensive snapshot of the entire interconnection. Synchrophasors provide an immediate indication of grid stress, and can be used to trigger corrective actions to maintain reliability."

Synchronized phasor measurements (synchrophasors) provide a phasor representation of voltage and current waveforms, representing a sinusoidal signal simply as a magnitude and phase angle, with an associated timestamp. Synchrophasor analytics extract information from the PMU data streams and do not need a grid model.

Today, EMS capabilities are poised to be enhanced quite dramatically with the integration of the growing number of synchrophasor PMU measurements.

8.2 The Modern EMS with Synchrophasors: EMS-WAMS

Today, many EMS control centers are receiving sub-second PMU data. PMUs generates very high volumes of synchrophasor and synchroscalar measurement data. This massive amount of data is used to provide additional useful information for grid operators. The modern EMS is evolving into a vast, diverse conglomeration of monitoring devices and advanced computer and communications technology that measures power system field conditions at sub-second rate.

Sub-second data rates mean the dynamic behavior of the grid can be readily assessed at the EMS; this was not possible in the past. Also, accurate GPS time-stamping allows voltage phase angle differences to be compared at two different parts of the grid providing a summary indicator of power system stress.

Figure 14 illustrates the modern EMS (EMS-WAMS) control center functions and tools. They include the new sub-second Phasor Measurement Unit (PMU) measurement data and analytics.

The functions on the left of the represent the traditional EMS that is based on a user-defined model of the transmission system.

The functions on the right are called WAMS (wide area monitoring systems). These are new analytics that augment the EMS with sub-second monitoring; these do not need a model of the power grid, the actual power grid is the model. WAMS analytics includes:

- Angular Separation
    - precisely indicates grid overloads or outages
- State Measurement
    - sub-second tracking of substation voltages
- Stability Monitoring
    - oscillatory, voltage and transient
- Disturbance Location Identification
- Island detection and re-synchronization

Some of the benefits of a modern EMS-WAMS include:

- Faster identification of grid problems — prompt operator alerts and alarms.
- Monitoring of grid oscillations — to detect those that impact grid operations.
- Voltage and angular grid stability analysis in real time.
- Identification of grid disturbances outside one’s own SCADA purview.
- Fast detection of grid separation and partial grid blackouts
- Tools for reconnecting portions of the grid that are separated or de-energized
- Faster disturbance event analysis — provide information on what just happened.
- More robust and accurate SE solutions.

d

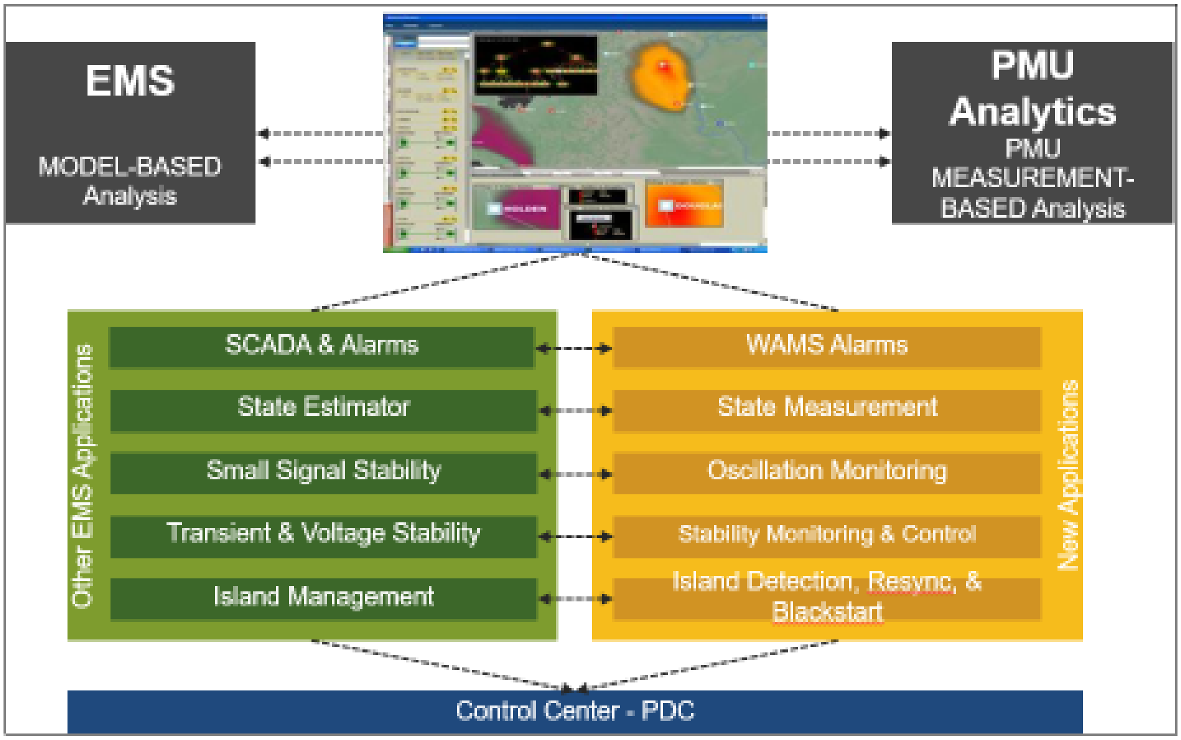

Figure 14: Modern EMS-WAMS control center

Source: GE Grid Solutions

These EMS-WAMS capabilities provide grid operators with a wide-reaching visibility into the status of the grid, as well as, provide the ability to predict and plan for potential problems that may be lurking around the corner. Speed is of the essence when it comes to assessing the cause of grid problems — and more importantly, implementing quick, corrective actions.

9. PROPOSED INNOVATIVE SOLUTION FOR THE FAR EAST ASIA GRID

A new WAMS control center could be created at the Far East interconnection level that uses PMU data from across the grid.

Figure 15 shows a proposed regional WAMS (WAMS-R) and its connections with the national control center EMSs.

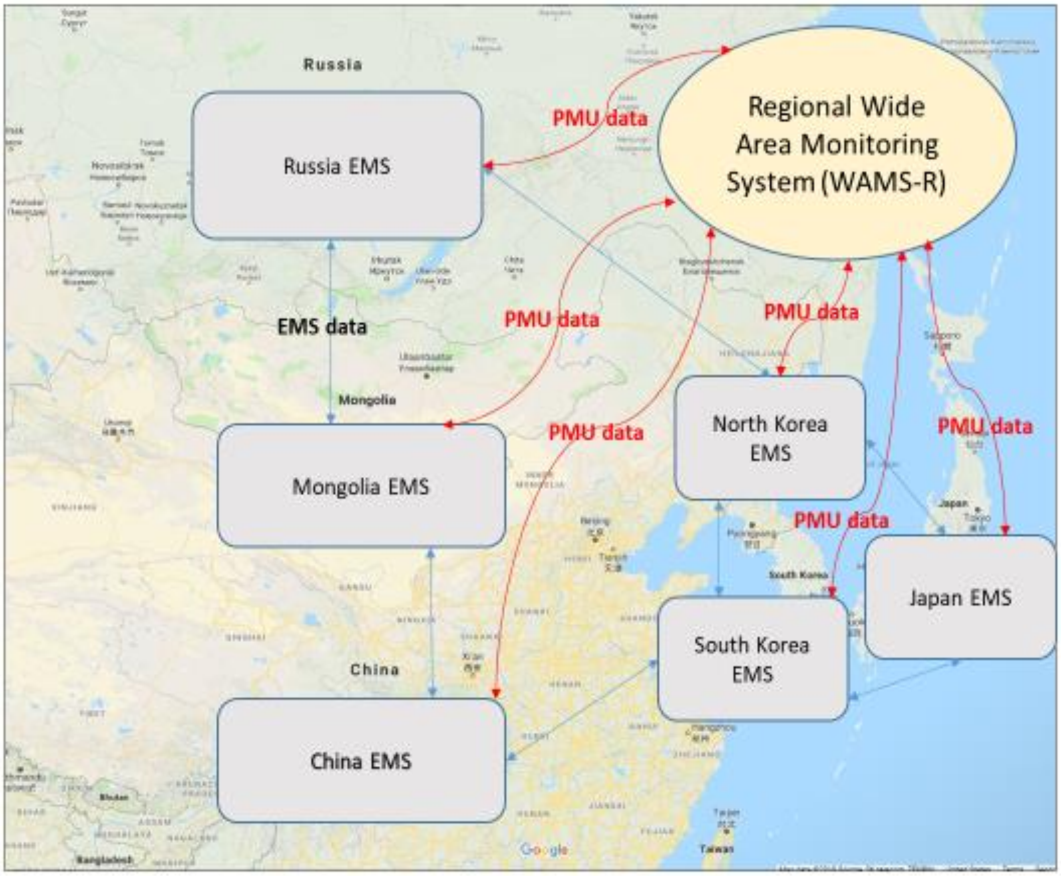

Figure 15: Wide Area Monitoring of Far East Asia — WAMS-R

Source: GGM Consulting

Building WAMS-R in Far East Asia would be a major technical, business and political effort. It will involve significant cooperation of all nations involved.

A suggested time-line and plan of action is:

1. If PMU data are available at any of the EMSs, integrate them to create an EMS-WAMS
2. Add new PMUs and bring their data into the EMS
3. Integrate the new PMUs into the EMS
4. Add new WAMS analytics to use all the PMU data
5. Create a new regional WAMS (WAMS-R) control center for the Far East Asia region

a. Send PMU data from all the national EMS to WAMS-R
b. Add new PMU analytics to WAMS-R
c. Add new operator displays and monitoring in WAMS-R
d. When WAMS-R detects violations immediately alert all national EMSs
e. Work with the national EMSs to develop corrective action plans when necessary

10. CONCLUDING THOUGHTS

Electrical interconnections typically consist of millions of grid components. These are monitored and managed in real-time by numerous electric utilities. These utilities are independently responsible for just subsets of the interconnection. Grid management decisions made by one utility may affect neighbors due to the physics of electricity. Hence it is important for utilities to work together, to address problems, and to jointly develop corrective plans.

The recent rapid growth of renewable energy resources and distributed energy resources pose additional grid management challenges. These cannot be controlled by the utility grid operator and are not easily predictable — adding new challenges for the operator to overcome.

One way to mitigate future grid challenges is to have all grid operators in the interconnection work together, by sharing real time data with each other, and by jointly developing corrective solutions.

Increasing real-time transparency with neighbors will improve effective management of the overall interconnection. This will also allow for utilities to share energy with one another, in a mutually beneficial economic manner which results in reduced costs to customers in the region.

More recently, synchrophasor PMU analytics have been introduced at control centers, which significantly improves the utility operators' capabilities. EMS-WAMS control centers at the higher interconnection level can immediately share grid alerts with all utility operators to ensure all have the same information. This will enable development of an interconnection-wide, holistic, shared, transparent corrective action plan, for the entire region.

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APPENDIX — ICCP

ICCP — Real-time Data Exchange between Control Centers

The EMS data objects that are exchanged between control centers are defined in various parts of IEC 60870-6.

Data Examples include:

- Periodic System Data: Status points, analog points, quality flags, time stamps, etc.
- Exception reporting
- Information Messages: Simple text and binary files.
- Device control requests: on/off, trip/close, raise/lower etc. and digital setpoints.
- Event Reporting
- Scheduling, accounting, outage and plant information.
- Historical Time Series Data

APPENDIX — SAARC

South Asian Association for Regional Cooperation (SAARC)

SAARC was founded on 8 December 1985.

Excerpts extracted below from Source: http://www.saarc-sec.org/saarc-charter/5/

CHARTER

We, the Heads of State or Government of BANGLADESH, BHUTAN, INDIA, MALDIVES, NEPAL, PAKISTAN and SRI LANKA;

1. Desirous of promoting peace, stability, amity and progress in the region through strict adherence to the principles of the UNITED NATIONS CHARTER and NON- ALIGNMENT, particularly respect for the principles of sovereign equality, territorial integrity, national independence, non-use of force and non-interference in the internal affairs of other States and peaceful settlement of all disputes;

2. Conscious that in an increasingly interdependent world, the objectives of peace, freedom, social justice and economic prosperity are best achieved in the SOUTH ASIAN region by fostering mutual understanding, good neighbourly relations and meaningful cooperation among the Member States which are bound by ties of history and culture;

3. Aware of the common problems, interests and aspirations of the peoples of SOUTH ASIA and the need for joint action and enhanced cooperation within their respective political and economic systems and cultural traditions;

4. Convinced that regional cooperation among the countries of SOUTH ASIA is mutually beneficial, desirable and necessary for promoting the welfare and improving the quality of life of the peoples of the region;

5. Convinced further that economic, social and technical cooperation among the countries of SOUTH ASIA would contribute significantly to national and collective self- reliance;

6. Recognising that increased cooperation, contacts and exchanges among the countries of the region will contribute to the promotion of friendship and understanding among their peoples;

7. Recalling the DECLARATION signed by their Foreign Ministers in NEW DELHI on August 2, 1983 and noting the progress achieved in regional cooperation;

8. Reaffirming their determination to promote such cooperation within an institutional framework.

OBJECTIVES

The objectives of the ASSOCIATION shall be:

a) to promote the welfare of the peoples of SOUTH ASIA and to improve their quality of life;

b) to accelerate economic growth, social progress and cultural development in the region and to provide all individuals the opportunity to live in dignity and to realise their full potentials;

c) to promote and strengthen collective self-reliance among the countries of SOUTH ASIA;

d) to contribute to mutual trust, understanding and appreciation of one another's problems;

e) to promote active collaboration and mutual assistance in the economic, social, cultural, technical and scientific fields;

f) to strengthen cooperation with other developing countries;

g) to strengthen cooperation among themselves in international forums on matters of common interests; and

h) to cooperate with international and regional organisations with similar aims and purposes.

PRINCIPLES

1. Cooperation within the framework of the ASSOCIATION shall be based on respect for the principles of sovereign equality, territorial integrity, political independence, non-interference in the internal affairs of other States and mutual benefit.
2. Such cooperation shall not be a substitute for bilateral and multilateral cooperation but shall complement them.
3. Such cooperation shall not be inconsistent with bilateral and multilateral obligations.

III. NAUTILUS INVITES YOUR RESPONSE

The Nautilus Asia Peace and Security Network invites your responses to this report. Please send responses to: nautilus@nautilus.org. Responses will be considered for redistribution to the network only if they include the author's name, affiliation, and explicit consent