A Vision of Smart Transmission Grids

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***Abstract*—Modern power grid is required to become smarter in order to provide an affordable, reliable, and sustainable supply of electricity. Under such circumstances, considerable activities have been carried out in the U.S. and Europe to formulate and promote a vision for the development of the future smart power grids. However, the majority of these activities only placed emphasis on the distribution grid and demand side; while the big picture of the transmission grid in the context of smart grids is still unclear. This paper presents a unique vision for the future smart transmission grids in which the major features that these grids must have are clearly identified. In this vision, each smart transmission grid is regarded as an integrated system that functionally consists of three interactive, smart components, i.e., smart control centers, smart transmission networks, and smart substations. The features and functions of each of the three functional components as well as the enabling technologies to achieve these features and functions are discussed in detail in the paper.**

***Index Terms*—Smart control center, smart substation, smart transmission grid, vision**

I. Introduction

The electric power transmission grid has been progressively developed for over one century [1], from the initial designed local DC network in low voltage level, to three-phase high voltage AC network, and to modern bulk interconnected networks with various voltage levels and plenty of complex electrical components. It was the development of human society and economic needs that continuously drove the revolution of transmission grids stage by stage with the aids of the innovative technologies. As the backbone to deliver electricity from points of generation to consumers, the need of transmission grid revolution has been highly recognized to deal with more diversified challenges than ever before. In this paper, we summarize the challenges and needs for future transmission grid in four aspects:

a) *Environmental challenges*. The traditional electric power production, as the largest man-caused CO_2 emission source, must be changed to mitigate the climate change [2]. The solid and gas emission pollution must be controlled. Additionally, the shortage of fossil energy resources has been foreseen in the next few decades. The natural catastrophes, such as hurricane, earthquake, etc., can destroy the transmission grids easily. The available and suitable space for future expansion of transmission grid has decreased remarkably.

b) *Market/customer needs*. Increasing competition in power market requests highly transparency and liberty, which needs the technical supports of the transmission grid operation, mature market regulation and policies. Customer satisfaction with high quality/price ratio and freedom to interact with the grid in electricity consumption becomes more important.

c) *Infrastructure challenges*. The existing infrastructure for electricity transmission has been in suffering of aging components and insufficient investments. With the pressure of increasing load demands, the network congestion is becoming worse. The fast online analysis tools, wide-area monitoring, measurement and control, and fast and accurate protections are highly needed to improve the reliability of the networks.

d) *Innovative technologies.* On one hand, the innovative technologies, including new materials, advanced power electronics, communication technologies, etc, are not yet mature or commercially available for the revolution of transmission grids; on the other hand, the existing girds lack enough compatibility to accommodate the implementation of spear-point technologies in the practical networks.

Whereas innovation of transmission grid driven by technologies in the past, the current power industry is being modernized and tends to deal with the challenges more smartly by using the state of art technology advances in the areas of sensing, communications, control, computing and information technology [3]-[7]. The shift in the development of transmission grid to be more intelligent has been summarized as "smart grid", and several other terminologies as "Intelligrid", "GridWise", "FutureGrid", etc. The related research programs also have been provided.

The IntelliGrid^{SM} program, initiated by Electric Power

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978-1-4244-4241-6/09/$25.00 ©2009 IEEE

Research Institution, Inc. (EPRI), is to create the technical foundation for a smart power grid that links electricity with communications and computer control to achieve tremendous gains in the enhancements of reliability, capacity, and customer services [8]-[9]. This program provides methodologies, tools and recommendations for open standards and requirement-based technologies with the implementation of advanced metering, distribution automation, demand response, and wide-area measurement, etc. The interoperability is expected to be enabled between advanced technologies and power system.

The SmartGrids program, set up by the European Technology Platform (ETP) in 2005, created a joint vision for the European networks of 2020 and beyond [10]-[11]. The objective features were identified for Europe's electricity networks as flexible to customers' requests, accessible to network users and renewable power sources, reliable for security and quality of power supply and economic to provide best value and efficient energy management.

A Federal Smart Grid Task Force was established by the U.S. Department of Energy (DoE) under Title XIII of the Energy Independence and Security Act of 2007. In its Grid 2030 vision, the objectives are to construct the 21st century electric system to provide abundant, affordable, clean, efficient, and reliable electric power anytime, anywhere [1]. The expected achievements through smart grid development will not merely enhance reliability, efficiency and security of the nation's electric grid, but contribute to the climate change strategic goal of reducing carbon emissions.

There are also remarkable research and development activities undergoing in both the industry and academia [12]-[20]. References [12] and [13] presented smart grids for future power delivery. Reference [14] discussed the integration issue in the smart grid. In [15], Tsoukalas presented some interesting and promising concepts such as energy internet. Some specific technologies such as smart metering infrastructure were presented in [16].

The majority of previous work has placed great emphasis on the distribution system and demand side as wide range of emerging technologies was applied to them. The big picture of the whole transmission grid in the context of smart grids is still unclear. This paper presents a unique vision for the future smart transmission grids by identifying the major smart characteristics and performance features to handle the challenges. The vision regards the power transmission grid as an integrated system that functionally consists of three interactive parts: control centers, transmission networks, substations, and takes into account all the fundamental. The paper is organized as follows. Section II will present the general framework and major characteristics of the proposed smart transmission grid. The features and enabling technologies of three functional components, smart control centers, smart transmission networks, and smart substations, will be discussed in details in Sections III through V. Further discussions and conclusions will be given in Section VI.

II. Framework and Characteristics of Smart Transmission Grids

The vision of a smart transmission grid is illustrated in Fig. 1. The existing transmission grid is in the significant pressure of diversified challenges and needs from environment, customer and market, existing infrastructure issues, etc. These challenges and needs are more important and urgent than ever before to drive the current transmission grid to expand and improve its characteristics and functions towards smart features with the leverage of rapid developing technologies. In the roadmap of research and development, the smart features of transmission grid are envisaged and summarized in this paper as digitalization, flexibility, intelligence, resilience, sustainability, and customization. With the smart features, the future transmission grid is expected to deal with the challenges in the identified four aspects.

A. Digitalization

The smart transmission grid will employ a unique, digital platform for fast and reliable sensing, measurement, communication, computation, control, protection, visualization, and maintenance of the entire transmission system. This is the fundamental feature facilities the realization of the other smart features. This platform is featured with user-friendly visualization for sensitive situation awareness and high tolerance of man-made errors.

B. Flexibility

The flexibility for the future smart transmission grid is featured in four aspects: 1) expandability for future development with the penetration of innovative and diverse generation technologies; 2) adaptability to various geological/geographical locations and climates; 3) multiple control strategies for the coordination of decentralized control schemes among substations and control centers; 4) seamless compatibility with various market operation styles and plug-and-play capability to accommodate progressive technology upgrades with hardware and software components.

C. Intelligence

Intelligent technologies and human being's expertise will be incorporated and embedded in the smart transmission grid. Self-awareness of the system operation state will be available with the aid of online time-domain-based analysis such as voltage/angular stability and security analysis. Self-healing will be achieved to enhance the security of transmission grid via the coordinated protection and control schemes.

D. Resiliency

The smart transmission grid will be capable to deliver electricity to customers securely and reliably in case of any external or internal disturbances or hazards. A fast self-healing capability enables the system reconfigure itself dynamically to recover from attacks, natural disasters, blackouts, or network component failures. On-line computation and analysis will enable the fast and flexible network operation and controls such as intentional islanding or even sectionalizing in emergency.

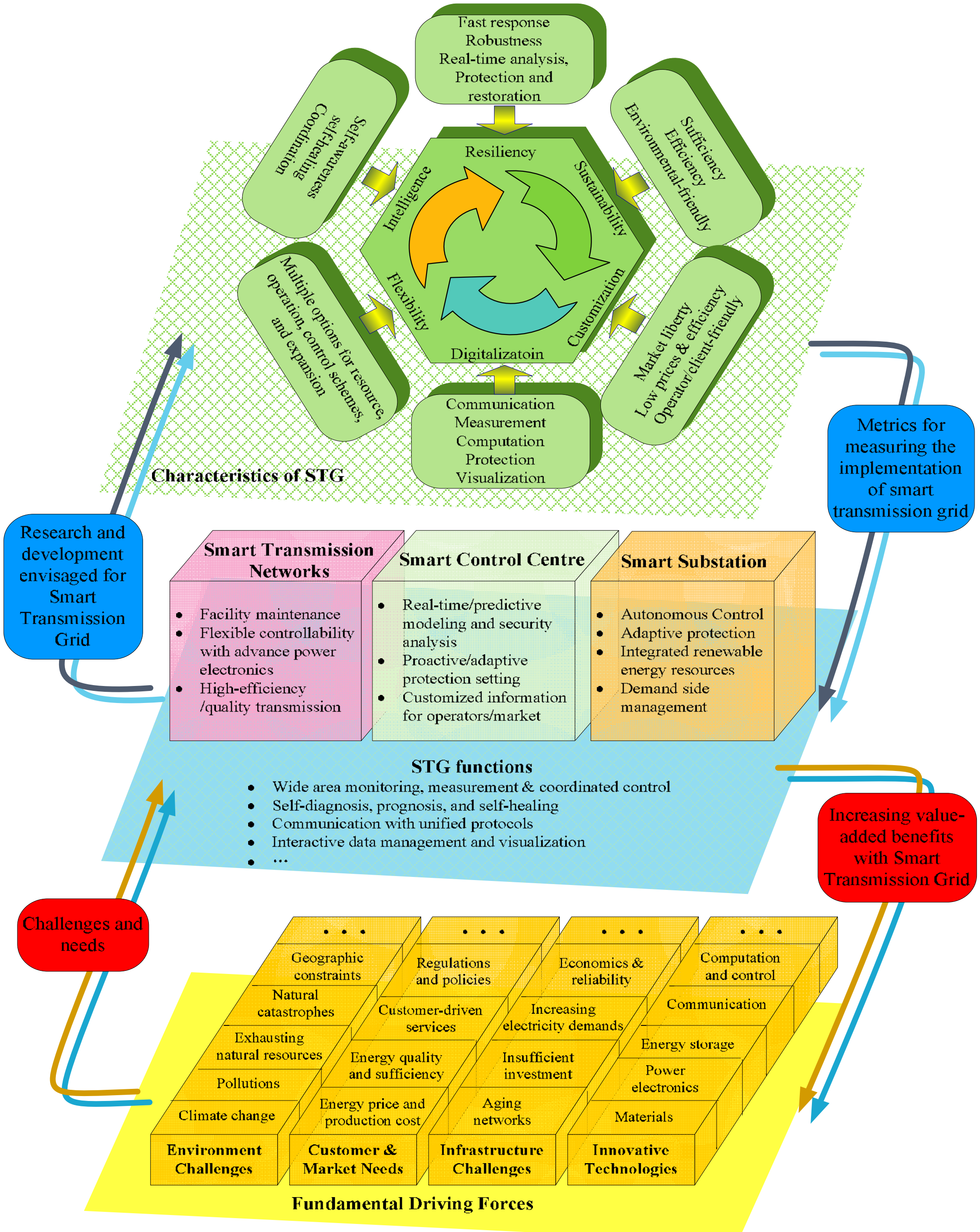

Fig. 1. Vision of a smart transmission grid

E. Sustainability

The sustainability of the smart transmission grid is featured by sufficiency, efficiency and environment-friendly. The growth of electricity demand should be satisfied sufficiently with the implementation of affordable alternative energy resources, increasing energy saving technology in the electricity delivery and system operation, and mitigation of network congestion. Innovative technologies to be employed should have less pollution or emission, and decarbonizes with the consideration of environment and climate change.

F. Customization

The design of the smart transmission grid will be client-tailored for the operators' convenience without the loss of functions and interoperability. It will also cater to customers with more energy consumption options for high quality/price ratio. The smart transmission grid will further liberate power market, increase transparency, and improve competition for the market participants.

To achieve the aforementioned smart features and characteristics, the enabling technologies include:

1) *New materials and alternative clean energy resources.* Application of new materials and devices in power systems will improve the efficiency of power supply by increasing power transfer capabilities, reducing energy losses, and lowering construction costs. High penetration of alternative clean energy resources will mitigate the conflicts between the human society development and environment sustainability.
2) *Advanced Power electronics and devices.* Advanced Power electronics will be able to greatly improve quality of power supply and flexibility of power flow control.
3) *Sensing and measurement.* Smart sensing and measurement and advanced instrumentation technologies will serve as the basis for communications, computing, control, and intelligence.
4) *Communications.* Adaptive communication networks will allow open-standardized communication protocols operated on a unique platform. Real-time control based on fast and accurate information exchange in different platforms will improve the system resilience by the enhancement of system reliability and security, and optimization of transmission asset utilization.
5) *Advanced computing and control methodologies.* High performance computing, parallel and distributed computing technologies will enable real-time modeling and simulation of complex power systems. The accuracy of the situation awareness will be improved for further suitable operation and control strategies. Advanced control methodologies and novel distributed control paradigms will be needed to automate the entire customer-centric power delivery network.
6) *Mature power market regulation and policies.* The mature regulation and policies should improve the transparency, liberty and competition of the power market. High customer interaction with the electricity consumption should be enabled and encouraged.
7) *Intelligent technologies.* Intelligent technologies will enable fuzzy logic reasoning, knowledge discovery, and self-learning, which are important ingredients integrated in the implementation of the above advanced technologies to build the transmission grid smarter.

The application of the technologies will be discussed in details with smart control center, smart transmission and smart substation in Section III to V, which are the three functional components of smart transmission grid.

III. Smart Control Centers

A. Monitoring /Visualization

The present monitoring system in a control center depends on state estimators, which are based on data collected via SCADA systems and remote terminal units (RTUs). In the future control center, the system-level information will be obtained from the state measurement modules based on Phasor Measurement Units (PMUs) [21]-[22]. The PMU-based state measurement is expected to be more efficient than the present state estimation since synchronized phasor signals give the state variables, in particular, voltage angles. As a comparison, the present state estimation demands more running time and is less robust, since the data collected from RTUs are not synchronized and significant effort must be taken for topology checking and bad data detection.

The present visualization technology displays the system configuration with one-line diagrams that can illustrate which buses are connected with a specific bus. However, it is not exactly matched to the geographic location. In addition, it is typical that only buses in the control area, together with some boundary buses, are displayed in the monitoring system. In the future, the results from state measurement shall be combined with a wide-area geographical information system (GIS) for visual display on the screens of the control center. The wide-area GIS shall cover a broad region including the control center's own service territory as well as all interconnected areas, and even the whole Eastern Interconnect or WECC system. This will increase the situational awareness across a very broad scope and prevent inappropriate operations when neighboring system is not fully known.

Since the future visualization and monitoring technology will cover a much broader scope, increased information exchange is needed. The present technology for inter-area communications includes a mix of obsolete and current technologies, such as telephone lines, wireless, microwave, fiber optics, etc [23]. In the future, the communication channels are expected to be more dedicated such as employing a fiber optic network for communications with Qualify of Service (QoS) implemented. Not surprisingly, this also demands a unified protocol for better communications among different control areas.

With the state variables obtained from state measurement and GIS data, it is desired to display the system stability measures in real time. The present technology typically displays the voltage magnitude. As the system is more stressed and voltage collapse is a recurring threat, the voltage magnitude is no longer a good indicator of voltage stability. Hence, a true indicator of voltage stability margin is needed for better monitoring. Similarly, the present technology monitors the local frequency. However, if the global frequency and particularly the frequency change can be monitored and traced, it is possible to identify the fault location even in a remote location through possible frequency wave technology. Once these new monitoring technologies are implemented with wide-area GIS data, the voltage stability margin and frequency wave can be displayed on top of the actual wide-area map in real time. It will greatly help the operators identify potential problems in real-time operation.

Other noteworthy technology can be the alarming system. The present technology typically presents alarming signals without priority. The future control center should be able to give root cause of possible problems for the operators to take closer monitoring of these root causes.

B. Analytical Capability

The present on-line analytic tool in control centers typically performs steady-state contingency analysis. Each credible contingency event is analyzed using contingency power flow studies and line flow violations will be identified. In the future control center, it is expected that online time-domain-based analysis such as voltage stability and transient angular stability [24] should be available. In addition, online small-signal stability analysis is expected.

The present analysis is based on a pre-defined generator and transmission models. This does not represent the real-time dynamic characteristics of the system. Therefore, the future online analysis in the control center shall perform dynamic model update and validation. The updated and validated data will be used for the online stability analysis previously mentioned.

The present technology is for the online analysis for the next operational time interval such as every 5 minutes. This does not address the possible short-to-mid term (like within an hour) variation of system conditions. In the future, online analysis is expected to have look-ahead simulation capability such that future system conditions will be considered. Then, possible short-to-mid term strategic actions can be considered.

Several other factors should be addressed. For instance, the present technology generally applies N-1 contingency in a deterministic approach [25]. In the future control centers, N-x or cascading failure should be considered. Also, probabilistic risk analysis should be considered.

C. Controllability

In the present control centers, the ultimate control action like separation is taken based on offline studies. In the future, the system separation will be performed in real-time to better utilize the dynamic system condition. Similarly, the present restoration plan based on offline studies should be replaced with online restorative plans.

Presently, the protection and control settings are configured as fixed values based on offline studies [23], [26]. In the future, these settings should be configured in real-time in a proactive and adaptive approach such that it will better utilize the generation and transmission asset when the system is not stressed and to better protect the system under extremely stressed conditions [27].

The present technology lacks the coordination of protection and control systems [23], [28]. Each component takes actions based on its own decision. Sometime this uncoordinated control may lead to over reaction under contingency. The future control centers shall have the capability to coordinate many control devices distributed in the system such that the optimal coordination can be achieved for better controllability.

D. Interactions with Electricity Market

The electricity market is highly intertwined with smart grid. An efficient electricity market is powered by an advanced grid infrastructure. On the other hand, a smart grid would not be called "smart" without achieving higher market efficiency. The constantly changing electricity market requires the control center adapt to the dynamic transition during the market development. The control centers in a market actively interact with other control centers, existing market participants and new entrants. Thus, modern control centers have to be able to cope with the changing business architecture [29]. More sophisticated tools should be provided by the control centers to facilitate the system operators to monitor and mitigate market power. Furthermore, given the increasing interest in utilizing renewable energy to meet future demand, the smart control centers should be capable of being adjusted flexibly to include such energy resources into the unit dispatch. The central clearing algorithms should be robust enough to accommodate the volatile nature of certain renewables such as wind generators with finer forecasting and scheduling methods. Demand-side participants should have access to the market through certain communications, control and information channels. Congestion management is another important feature of the smart control centers. The control centers should forecast and identify the potential congestions in the network and alleviate it with the help from wide-area GIS systems.

IV. Smart Transmission Networks

This vision of the smart transmission networks builds on the existing electric transmission infrastructure. However, the emergence of new technologies, including advanced materials, power electronics, sensing, communication, signal processing, and computing, etc., will increase the utilization, efficiency, quality, and security of existing systems and enable the development of a new architecture for transmission networks.

A. High-Efficiency and High-Quality Transmission Networks

In the concept of smart transmission networks, ultra-high-voltage, high-capacity transmission corridors can link major regional interconnections. It is thus possible to balance electric supply and demand on a national basis. Within each regional interconnection, long-distance transmission is accomplished by using controllable high-capacity AC and DC facilities. Underground cables are widely used when overhead lines are not practical, mostly in urban and underwater areas. Advanced conductors, including high-temperature composite conductors for overhead transmission and high-temperature superconducting cables, are widely used for electricity transmission. These conductors have the properties of greater current-carrying capacity, lower voltage drops, reduced line losses, lighter weight, and greater controllability. In addition, new transmission line configurations, e.g., six or twelve phase transmission line configurations, allows for greater power transmission in a particular right-of-way with reduced electromagnetic fields due to greater phase cancellation.

B. Flexible Controllability, Improved Transmission Reliability and Asset Utilization through the Use of Advanced Power Electronics

In a smart transmission network, flexible and reliable transmission capabilities can be facilitated by the advanced Flexible AC Transmission Systems (FACTS) and High-voltage DC (HVDC) devices and other power electronics-based devices.

FACTS devices (including traditional large-scale FACTS devices and new distributed FACTS devices [30]-[33]) are optimally placed in the transmission network to provide a flexible control of the transmission network and increase power transfer levels without new transmission lines. These devices also improve the dynamic performance and stability of the transmission network. Through the utilization of FACTS technologies, advanced power flow control, etc., the future smart transmission grids should be able to maximally relieve transmission congestions, and therefore, fully support deregulation and enable competitive power markets. In addition, with the trend of increasing penetration of large-scale renewable/alternative energy resources, the future smart transmission grids should be able to enable fully integration of these resources.

HVDC lines are widely used to provide an economic and controllable alternative to AC lines for long distance and high-capacity power transmission and integration of large wind farms. Maximum utilization of line and system capacity, increased reliability, and improved system operation under contingencies by using of power electronics-based Fault Current Limiters or Current Limiting Conductors [31], [34]. Solid-state transformers are used to replace traditional electromagnetic transformers to provide flexible and efficient transformation between different voltage levels [35]. Solid-state circuit breakers are used to replace traditional mechanical breakers. These solid state devices are free from arcing and switch bounce, and offer correspondingly higher reliability and longer lifetimes as well as much faster switching times [34], [36].

C. Self-Healing and Robust Electricity Transmission

Smart transmission networks will extensively incorporate advanced sensing, signal processing, and communication technologies to monitor operating conditions of transmission lines, transformers, and circuit breakers in real time [37]-[38].

A cost-effective distributed power line condition monitoring system [39], based on a distributed power line wireless sensor net in which each distributed intelligent sensor module incorporates with advanced signal processing and communication functions, is able to continuously measure line parameters and monitor line status in the immediate vicinity of the sensor that are critical for line operation and utilization, including measurement of overhead conductor sags, estimation of conductor temperature profile, estimation of line dynamic thermal capacity, detection of vegetation in proximity to the power line, detection of ice on lines, detection of galloping lines, estimation of mechanical strength of towers, prediction of incipient failure of insulators and towers, identification of the critical span limiting line capacity, and identification of the fault location of the line, etc.

A sophisticated transformer monitoring system is able to monitor health and efficiency, measure dissolved gases-in-oil and load tap changers of transformers in real time. A circuit breaker monitoring system is able to measure the number of operations since last maintenance, oil or gas insulation levels, and breaker mechanism signatures, and monitor the health and operation of circuit breakers in real time.

Based on the parameters and operating conditions of transmission facilities, it can automatically detect, analyze, and respond to emerging problems before they impact service; make protective relaying to be the last line of defense, not the only defense as it is today; quickly restore the faulty, damaged, or compromised sections of the system during an emergency; and therefore, enhance dynamic and static utilization and maintain reliability and security of the transmission system.

D. Advanced Transmission Facility Maintenance

In the smart transmission networks, live-line maintenance can used to clean and de-ice conductors, clean and lubricate moving parts that open and close, replace spacer/dampers, disconnect/connect breakers, tighten or replace bolts and install sensors and measuring devices, etc. Advanced maintenance and power line condition monitoring technologies allow for prioritized equipment ranking, condition based maintenance, prevention programs, smart equipment replacement programs and right-of-way maintenance. This reduces catastrophic failures, reduces maintenance costs, and improves the overall reliability of the transmission system [40].

E. Extreme Event Facility Hardening System

An extreme event facility hardening system is able to identify potential extreme contingencies that are not readily identifiable from a single cause, develop various extreme event scenarios (e.g., floods, extreme weather, etc.), develop modular equipment designs for lines and novel system configuration to manage failures and enable rapid system restoration under catastrophic events [40].

V. Smart Substations

The smart substation concept builds on the existing comprehensive automation technologies of substations, and enables more reliable and efficient monitoring, operation, control, protection and maintenance of the equipment and apparatus installed in the substations. From the operation point of view, a smart substation must be rapidly responsive and provide increased operator safety. To achieve these goals, the major characteristics of a smart substation shall include:

1) Digitalization: The smart substation provides a unique and compatible platform for fast and reliable sensing, measurement, communication, control, protection, and

maintenance of all the equipment and apparatus installed in a variety of substations. All of these tasks can be done in the digital form, which allows for easy connection with control centers and business units.

2) Autonomy: The smart substation is autonomous. The operation of the smart substation does not depend upon the control centers and other substations, but they can communicate with each other to increase the efficiency and stability of power transmission. Within a substation, the operation of individual components and devices is also autonomous to ensure fast and reliable response, especially under emergency conditions.

3) Coordination: The smart substation should be ready and easy to communicate and coordinate with other substations and control centers. Adaption of protection and control schemes should be achieved under coordination of control centers to improve the security of the whole power grid.

4) Self-healing: The smart substation is able to reconfigure itself dynamically to recover from attacks, natural disasters, blackouts, or network component failures.

The main functions of a smart substation are summarized as follows:

A. *Smart Sensing and Measurement*

In a smart substation, all measurement signals will be time stamped with a high accuracy by using a GPS (global positioning system) signal. The RTU (remote terminal unit) function will be replaced by PMU (phasor measurement unit) in the future. Traditional electromechanical CT (current transducer) and PT ((potential transducer) will be replaced by optical or electronic CT and PT whose advantages include wide bandwidth, high accuracy of measurement, and low maintenance costs [41]. Computational intelligence technology will be incorporated in the sensing and measurement circuits to reduce the burden of communications.

B. *Communications*

Each smart substation has its own high-speed local area network (LAN) which ties all the measurement units and local applications together. Each smart substation also has a server that connects to the higher-level communication network through a router. A smart substation should be based on a self-healing communication network to significantly improve the reliability of monitoring and control of substations. Based on intelligent and ubiquitous IT techniques, reference [42] proposed a prototype platform of smart substations that provides compatible connection interface for various wired and wireless communication capabilities, flexible networking for wired and wireless topologies, uninterruptible SCADA network. If existing wired (serial bus) networks have a fault or accident, then the ubiquitous network reconfigures itself to bypass or detour around the fault in the local substation.

The communication protocol of a smart substation should be standardized and open. A good option is the IEC 61850 standard [43], which provides an open interface not only among the IEDs inside a substation but also between substations and between substations and control centers. This improves the interoperability of communication networks significantly. A middleware concept for power grid communications named Gridstat has been proposed in [44].

C. *Autonomous Control and Adaptive Protection*

A smart substation should contain fully intelligent decentralized controllers for auto-restoration, remedial actions, or predictive actions or normal optimization. Traditional automatic voltage/Var controllers based on local measurement information in a substation will be coordinated by control centers. Voltage instability conditions can be assessed much faster based on local PMU measurement information [45]-[46]. Further, the results of voltage stability assessment calculations can be directly incorporated into remedial action schemes to improve the power system security.

In a smart grid, a great improvement is that the settings of protective relays can be remotely modified in real time to adapt to the changes in the grid configuration [47]. A smart substation will serve as an intelligent unit of special protective schemes (SPS) to improve the reliability of power grid [48]. Advanced protective relay algorithms based on travelling waves are under development [49].

D. *Data Management and Visualization*

In a smart substation, widely deployed decentralized applications require a strong distributed database management system, which will manage and share all the data in the substation and communicate with other communication units such as the control centers and other substations by just publishing those data to the communication network with the Publisher-Subscriber infrastructure [44]. All these data from PMU units, relays, fault recorders, power quality monitors, equipment monitors, etc., should be efficiently managed and displayed. Real-time data visualization gives the operators a clear picture of the current operation status of the gird.

E. *Monitoring and Alarming*

Advances in modern communications enable remote operators to be informed immediately of equipment status changes and trips. For example, smart substations can provide immediate alarm warnings to authorized users via cell phones, pagers, and the intranet to improve awareness. While an increasing amount of data about fault conditions are gathered in a substation, a more intelligent alarm management and processing system should be developed to find the root cause of the fault based on artificial intelligent technologies such as expert system. Traditionally, these common devices, such as battery chargers, UPS systems and fire alarm systems, alarm a fault condition locally, but, unless a substation visit is performed, the fault may go undetected for extended periods. Ignoring some of these faults would cause more catastrophic failures to occur [50].

F. Diagnosis and Prognosis

Fast diagnosis and prognosis are necessary in a smart substation, and some technologies have been achieved. On-line asset condition monitoring [51] based on advanced sensor technology provides stable operation and reduces the repair time. Expert system based fault diagnosis technology [52] provides intelligent maintenance and management of devices in a substation.

G. Advanced Interfaces with Distributed Resources

Smart substations should provide advanced power electronics and control interfaces for renewable energy and demand response resources so that they can be integrated into the power grid in a large scale at the sub-transmission level. By incorporating microgrids, the substation can deliver quality power to the customers in a manner that the power supply degrades gracefully after a major commercial outage, as opposed to a catastrophic loss of power, allowing more of the installations to continue operations. Smart substations should have a capability to operate in the islanding mode taking into account the transmission capacity, load demand, and stability limit, and provide mechanisms for a seamlessly transition to islanding operation.

H. Real-Time Modeling

A real-time model of substations should be built for better control inside and outside a smart substation. In order to get a reliable and consistent real-time model for a substation, the substation level topology processor will build the substation topology while the state estimator at substation level will estimate the substation states to provide a more reliable and full view of the substation. Some previous work focusing on distributed state estimation has already provided the idea of building the substation-level state estimator and the related filter technology. An example is the SuperCalibrator [53], where intelligent analysis for bad data processing can be well done in substation level.

Whenever changes happen in the power system, such as the substation topology changes or addition of a new substation into the power grid, the system-wide model can be rebuilt automatically in the control center by merging the substation models. It is easy to build a backup control center model or even rebuild a new control center model under emergency to significantly improve the operating resilience of control centers against physical and cyber attacks and natural disasters.

VI. Conclusion

This paper has presented a unique vision of next-generation smart transmission grids. It aims at promoting technology innovation to achieve an affordable, reliable, and sustainable delivery of electricity. With a common digitalized platform, the smart transmission grids will enable increased flexibility in control, operation, and expansion, allow for embedded intelligence, essentially foster the resilience and sustainability of the grids, and eventually benefit the customers with lower costs, improved services, and increased convenience. The major features and functions of smart transmission grids have been described in detail through three interactive, smart components: smart control centers, smart transmission networks, and smart substations. Implementation of such a vision demands a concerted effort to apply and extend the existing technologies through initiatives in the near term, while promoting forward-looking research and development to solve underlying critical issues in the long term.

To develop and implement the next-generation electric grid ensuring economic prosperity and environmental health, the government officials, utility executives, energy policy makers, and technology providers must agree on a common vision and take action to accelerate the process towards final deployment. Given the scale of the effort required and the enormity of the challenges ahead, collaboration among different sectors is essential and should be developed through various channels in order to ensure and accelerate the success of realizing the smart transmission grid.

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