Smart Transmission Grid: Vision and Framework

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Abstract—A modern power grid needs to become smarter in order to provide an affordable, reliable, and sustainable supply of electricity. For these reasons, considerable activity has been carried out in the United States and Europe to formulate and promote a vision for the development of future smart power grids. However, the majority of these activities emphasized only the distribution grid and demand side leaving the big picture of the transmission grid in the context of smart grids unclear. This paper presents a unique vision for the future of smart transmission grids in which their major features are 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 network, smart transmission system.

I. INTRODUCTION

THE ELECTRIC power transmission grid has been progressively developed for over a century [1], from the initial design of local dc networks in low-voltage levels to three-phase high voltage ac networks, and finally to modern bulk interconnected networks with various voltage levels and multiple complex electrical components. The development of human society and economic needs was the catalyst that drove the revolution of transmission grids stage-by-stage with the aid of innovative technologies. As the backbone used to deliver electricity from points of generation to the consumers, the transmission grid revolution needs to recognize and deal with more diversified challenges than ever before. It should be noted that in this paper the word "grid" refers not only to the physical network but also to the controls and devices supporting the function of the physical network, such that this work is aligned with the ongoing smart grid initiative.

In this paper, we summarize the challenges and needs for future smart transmission grids into four aspects.

a) *Environmental challenges*. Traditional electric power production, as the largest man-created CO_2 emission source, must be changed to mitigate the climate change [2]. Also, a shortage of fossil energy resources has been foreseen in the next few decades. Natural catastrophes, such as hurricanes, earthquakes, and tornados can destroy the transmission grids easily. Finally, the available and suitable space for the future expansion of transmission grids has decreased dramatically.

b) *Market/customer needs*. Full-fledged system operation technologies and power market policies need to be developed to sustain the transparency and liberty of the competitive market. Customer satisfaction with electricity consumption should be improved by providing high quality/price ratio electricity and customers' freedom to interact with the grid.

c) *Infrastructure challenges*. The existing infrastructure for electricity transmission has quickly aging components and insufficient investments for improvements. With the pressure of the 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 needed to improve the reliability of the networks.

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

Whereas the innovation of the transmission grid was driven by technology in the past, the current power industry is being modernized and tends to deal with the challenges more proactively by using state-of-the-art technological advances in the areas of sensing, communications, control, computing, and information technology [3]–[7]. The shift in the development of transmission grids to be more intelligent has been summarized as "smart grid," as well as several other terminologies such as IntelliGrid, GridWise, FutureGrid, etc.

The IntelliGrid program, initiated by the Electric Power Research Institution (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 service [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. The interoperability is expected to be enabled between advanced technologies and the power system.

The SmartGrids program, formed by the European Technology Platform (ETP) in 2005, created a joint vision for the European networks of 2020 and beyond [10], [11]. Its 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 the 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 a 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 the reliability, efficiency, and security of the nation's electric grid, but also contribute to the strategic goal of reducing carbon emissions.

Remarkable research and development activities are also ongoing in both 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 an interesting and promising concept of energy internet. 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 evidenced by the wide range of emerging technologies 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 future smart transmission grids by identifying the major smart characteristics and performance features to handle new challenges. The proposed vision regards the power transmission grid as an integrated system that functionally consists of three interactive parts: control centers, transmission networks, and substations. It takes into account each fundamental component of the smart grid.

The remainder of this paper is organized as follows. Section II presents the general framework and major characteristics of the proposed smart transmission grid. The features and enabling technologies of the three functional components, smart control centers, smart transmission networks, and smart substations, will be discussed in detail in Sections III through V. Further discussions and conclusions are provided 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 under significant pressure from the diversified challenges and needs of the environment, customers, and the market, as well as existing infrastructure issues. These challenges and needs are more important and urgent than ever before and will drive the present transmission grid to expand and enhance its functions towards smarter features with the leverage of rapidly developing technologies. As a roadmap for research and development, the smart features of the transmission grid are envisaged and summarized in this paper as digitalization, flexibility, intelligence, resilience, sustainability, and customization. With these smart features, the future transmission grid is expected to deal with the challenges in all four identified areas.

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 that will facilitate the realization of the other smart features. This platform is featured with user-friendly visualization for sensitive situation awareness and a high tolerance for 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 geographical locations and climates; 3) multiple control strategies for the coordination of decentralized control schemes among substations and control centers; and 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 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 analysis such as voltage/angular stability and security analysis. Self-healing will be achieved to enhance the security of transmission grid via coordinated protection and control schemes.

D. Resiliency

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

E. Sustainability

The sustainability of the smart transmission grid is featured as sufficiency, efficiency, and environment-friendly. The growth
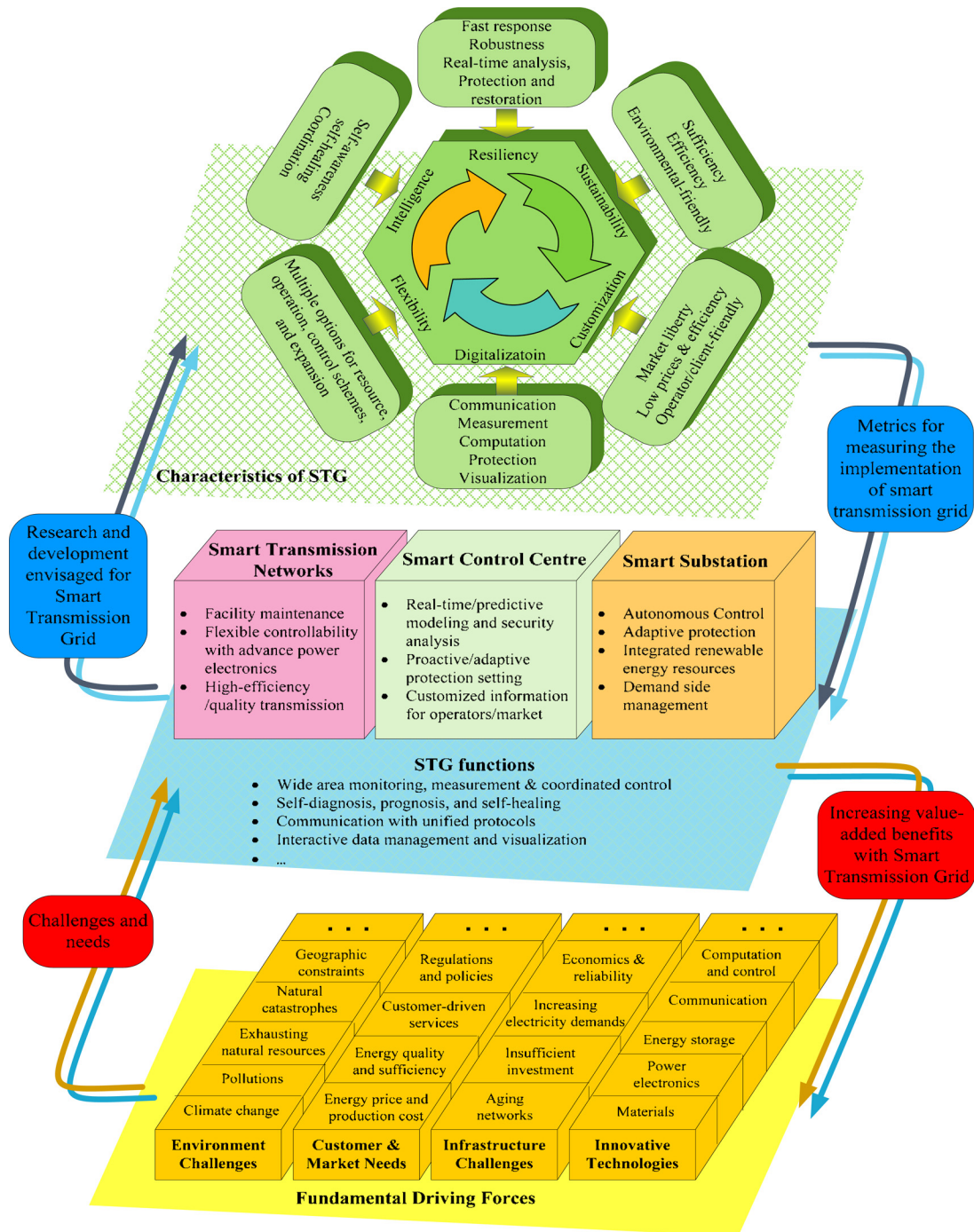
Fig. 1.   Vision of a smart transmission grid.

of electricity demand should be satisfied with the implementation of affordable alternative energy resources, increased energy savings via 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 decarbonize with consideration to the environment and climate changes.

F. Customization

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

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

1) *New materials and alternative clean energy resources*. The 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. The 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 the 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 to operate on a unique platform. Real-time control based on a fast and accurate information exchange in different platforms will improve the system resilience by the enhancement of system reliability and security, and optimization of the 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 operations 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 a smarter transmission grid.

The application of the technologies will be discussed in detail in concert with smart control centers, smart transmission networks, and smart substations in Sections III to V.

III. Smart Control Centers

The vision of the future smart control centers is built on the existing control centers, originally developed approximately a half-century ago. The expected new functions, such as monitoring/visualization, analytical capability, and controllability of the future control centers, are discussed in this section. Also discussed is the interaction with electricity market, although this work excludes the market operation from the control centers' functions.

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 provide the state variables, in particular, voltage angles. As a comparison, the present state estimation demands additional running time and is less robust,

since the data collected from the RTUs is not synchronized and significant effort must be made 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 broad scope and prevent inappropriate operations when a neighboring system is not fully known.

Since the future visualization and monitoring technology will cover a much broader scope, an increased information exchange is needed. The present technology for interarea communications includes a mix of obsolete and current technologies, such as telephone lines, wireless, microwave, and fiber optics [23]. In the future, the communication channels are expected to be more dedicated such as employing a fiber optic network for communications with quality 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 desirable 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 becomes a recurring threat, not merely depends on voltage magnitudes alone, 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 the use of possible frequency wave technology [54]. Once these new monitoring technologies are implemented with the 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. This will greatly assist the operators in identifying potential problems in the real-time operation.

Another noteworthy technology can be the alarming system. The present technology typically presents alarming signals without priority. The future control centers should be able to provide the root cause of possible problems to enable the operators to provide closer monitoring.

B. Analytical Capability

The present online analytic tool in control centers typically performs steady-state contingency analysis. Each credible contingency event is analyzed using contingency power flow studies allowing line flow violations to 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 predefined 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 security analysis for the next operational time interval, such as every 5 min. This does not address the possible short- to midterm (within 1 h) variation of system conditions. In the future, online analysis is expected to have look-ahead simulation capability so that future system conditions will be considered. Then, possible short- to midterm 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, credible N-x or cascading failures should be considered with a probabilistic approach for security risk analysis.

C. Controllability

In the present control centers, the ultimate control action, such as 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 to 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 sufficient coordination of protection and control systems [23], [28]. Each component takes actions based on its own decision. This uncoordinated control could lead to an overreaction under the present contingency plan. The future control centers shall have the capability to coordinate multiple control devices distributed in the system such that optimal coordination can be achieved simultaneously for better controllability.

D. Interactions With Electricity Market

The electricity market is highly intertwined with the future 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 to adapt to the dynamic transition during the market's development. The control center associated with a market actively interacts with other control centers, existing market participants, and new entrants. Thus, modern control centers should 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' ability to monitor and mitigate market power. Furthermore, given the increasing interest in utilizing renewable energy and

controllable load to meet future demand, the smart control center should be flexible to include such energy resources into the unit dispatch. The market 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 them with help from the wide-area GIS systems.

IV. SMART TRANSMISSION NETWORKS

This vision of the smart transmission networks is built on the existing electric transmission infrastructure. However, the emergence of new technologies, including advanced materials, power electronics, sensing, communication, signal processing, and computing 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., 6- or 12-phase transmission line configurations, allow 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), high-voltage dc (HVDC) devices, and other power electronics-based devices.

FACTS devices (including traditional large-scale FACTS 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 full 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. Power electronics-based fault current limiters or current limiting conductors [31], [34] may achieve maximum utilization of line and system capacity, increased reliability, and improved system operation under contingencies. 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.

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 the reliability and security of the transmission system.

D. Advanced Transmission Facility Maintenance

In the smart transmission networks, live-line maintenance can be used to clean and deice 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. 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 and 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 is built on the existing comprehensive automation technologies of substations. It should enable more reliable and efficient monitoring, operation, control, protection, and maintenance of the equipment and apparatus installed in the substations. From the operation viewpoint, a smart substation must rapidly respond and provide increased operator safety. To achieve these goals, the major characteristics of a smart substation shall include the following.

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 find it 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 high accuracy by using a global positioning

system (GPS) signal. The RTU function will be replaced by a PMU in the future. The traditional electromechanical current transformer (CT) and potential transformer (PT) will be replaced by an 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 measurement units and local applications together. Each smart substation also has a server that connects to the higher level communication network via 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, [42] proposed a prototype platform of smart substations that provides a 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 intelligent electronic devices (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 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 the 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 data in the substation and communicate with other communication units such as the control centers and other substations by just publishing the data to the communication network with the publisher–subscriber infrastructure [44]. All the data from the PMU units, relays, fault recorders, power quality monitors, and equipment monitors should be efficiently managed and displayed. Real-time data visualization provides the operators with a clear picture of the current operation status of the local substation as well as the grid through distributed intelligence [55].

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 is gathered in a substation, a more intelligent alarm management and processing system, such as an expert system, should be developed to find the root cause of the fault. 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 these faults could cause more catastrophic failures to occur [50].

F. Diagnosis and Prognosis

Fast diagnosis and prognosis are necessary in a smart substation, and several technologies have been produced to achieve this. Online 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 on a large scale at the subtransmission level. By incorporating microgrids, the substation can deliver quality power to 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 the capability to operate in the islanding mode taking into account the transmission capacity, load demand, and stability limit, and provide mechanisms for seamlessly transitioning 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 produce 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 the substation level will estimate the substation states to provide a more reliable and full view of the substation. Previous work focusing on the distributed state estimation has already provided the idea of building the substation-level state estimator and related filter
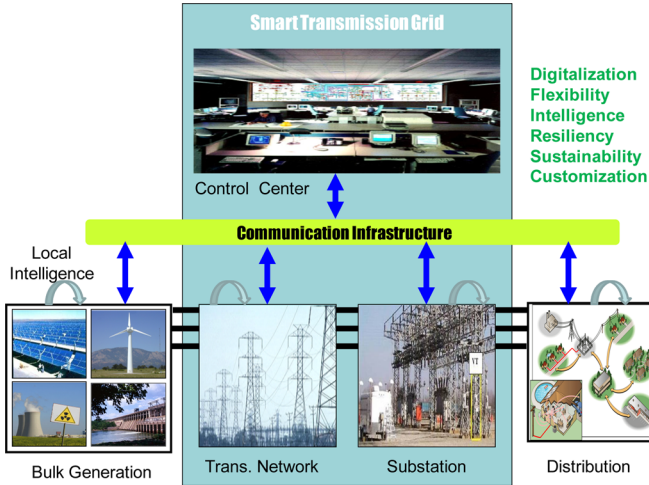
Fig. 2. Interaction among smart transmission grid, generation, and distribution.

technology. An example is the SuperCalibrator [53], where intelligent analysis for bad data processing can be completed at the substation level.

Whenever changes happen in the power system, such as a change in the substation topology or the 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 conditions to significantly improve the operating resilience of control centers against physical and cyber attacks, as well as natural disasters.

VI. INTEGRATION FRAMEWORK

The integration framework of the above three components as well as the future generation and distribution can be briefly illustrated in Fig. 2.

Under the general framework of the smart transmission grid with the advanced communication infrastructure, the backbone of the integration is the distributed intelligence at the smart transmission networks and substations, which can assist with making decisions based on local information to reduce the work load of the control center. Meanwhile, the control center oversees the entire system and sends the system-level decisions, such as various control actions, to remote devices or substations. Also, the intelligent agents at transmission network devices or substations may interact with neighbor agents to achieve broader information in order to make improved decisions without extensive communication back to the control center. In short, the actual control action will be a combination of local decisions from the distributed intelligent agents, central decisions from the smart control center, and the "regional" decision based on the information exchange among peer substations and network devices. Each type of action shall have a different response time and is most efficient for a particular type of work. The actual control process may require a few iterations among the three types of actions.

Fig. 2 also shows the generation and distribution systems that will be equipped with distributed intelligent agents for local decisions as well as interactions with peer agents and the control

center through the communication infrastructure. Under a disturbance in the generation or distribution system, local decisions may be made for a fast response and central decisions are necessary for global control, especially for severe disturbance. Meanwhile, the interactions with other peer agents at various sites in generation, transmission network devices, substations, and distribution are highly desired for a regionally optimal decision. Details of this interactive, decentralized architecture shall be the subject of possible future research.

Development and implementation of the proposed integration framework demands a concerted effort to apply and extend the existing technologies through initiatives in the near future, while promoting forward-looking research and development to solve underlying critical issues in the long term to ensure economic prosperity and environmental health. To achieve this goal, government agencies, 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.

VII. CONCLUDING REMARKS

This paper has presented a unique vision of the next-generation smart transmission grids. It aims to promote 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. This paper presents the major features and functions of the smart transmission grids in detail through three interactive, smart components: smart control centers, smart transmission networks, and smart substations. Since this initial work cannot address everything within the proposed framework and vision, more research and development efforts are needed to fully implement the proposed framework through a joint effort of various entities.

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Smart Transmission Grid: Vision and Framework

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Abstract—**A modern power grid needs to become smarter in order to provide an affordable, reliable, and sustainable supply of electricity. For these reasons, considerable activity has been carried out in the United States and Europe to formulate and promote a vision for the development of future smart power grids. However, the majority of these activities emphasized only the distribution grid and demand side leaving the big picture of the transmission grid in the context of smart grids unclear. This paper presents a unique vision for the future of smart transmission grids in which their major features are 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 network, smart transmission system.**

I. INTRODUCTION

THE ELECTRIC power transmission grid has been progressively developed for over a century [1], from the initial design of local dc networks in low-voltage levels to three-phase high voltage ac networks, and finally to modern bulk interconnected networks with various voltage levels and multiple complex electrical components. The development of human society and economic needs was the catalyst that drove the revolution of transmission grids stage-by-stage with the aid of innovative technologies. As the backbone used to deliver electricity from points of generation to the consumers, the transmission grid revolution needs to recognize and deal with more diversified challenges than ever before. It should be noted that in this

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paper the word "grid" refers not only to the physical network but also to the controls and devices supporting the function of the physical network, such that this work is aligned with the ongoing smart grid initiative.

In this paper, we summarize the challenges and needs for future smart transmission grids into four aspects.

a) *Environmental challenges*. Traditional electric power production, as the largest man-created CO_2 emission source, must be changed to mitigate the climate change [2]. Also, a shortage of fossil energy resources has been foreseen in the next few decades. Natural catastrophes, such as hurricanes, earthquakes, and tornados can destroy the transmission grids easily. Finally, the available and suitable space for the future expansion of transmission grids has decreased dramatically.

b) *Market/customer needs*. Full-fledged system operation technologies and power market policies need to be developed to sustain the transparency and liberty of the competitive market. Customer satisfaction with electricity consumption should be improved by providing high quality/price ratio electricity and customers' freedom to interact with the grid.

c) *Infrastructure challenges*. The existing infrastructure for electricity transmission has quickly aging components and insufficient investments for improvements. With the pressure of the 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 needed to improve the reliability of the networks.

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

Whereas the innovation of the transmission grid was driven by technology in the past, the current power industry is being modernized and tends to deal with the challenges more proactively by using state-of-the-art technological advances in the areas of sensing, communications, control, computing, and information technology [3]–[7]. The shift in the development of transmission grids to be more intelligent has been summarized as "smart grid," as well as several other terminologies such as IntelliGrid, GridWise, FutureGrid, etc.

The IntelliGrid program, initiated by the Electric Power Research Institution (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 service [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. The interoperability is expected to be enabled between advanced technologies and the power system.

The SmartGrids program, formed by the European Technology Platform (ETP) in 2005, created a joint vision for the European networks of 2020 and beyond [10], [11]. Its 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 the 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 a 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 the reliability, efficiency, and security of the nation's electric grid, but also contribute to the strategic goal of reducing carbon emissions.

Remarkable research and development activities are also ongoing in both 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 an interesting and promising concept of energy internet. 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 evidenced by the wide range of emerging technologies 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 future smart transmission grids by identifying the major smart characteristics and performance features to handle new challenges. The proposed vision regards the power transmission grid as an integrated system that functionally consists of three interactive parts: control centers, transmission networks, and substations. It takes into account each fundamental component of the smart grid.

The remainder of this paper is organized as follows. Section II presents the general framework and major characteristics of the proposed smart transmission grid. The features and enabling technologies of the three functional components, smart control centers, smart transmission networks, and smart substations, will be discussed in detail in Sections III through V. Further discussions and conclusions are provided 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 under significant pressure from the diversified challenges and needs of the environment, customers, and the market, as well as existing infrastructure issues. These challenges and needs are more important and urgent than ever before and will drive the present transmission grid to expand and enhance its functions towards smarter features with the leverage of rapidly developing technologies. As a roadmap for research and development, the smart features of the transmission grid are envisaged and summarized in this paper as digitalization, flexibility, intelligence, resilience, sustainability, and customization. With these smart features, the future transmission grid is expected to deal with the challenges in all four identified areas.

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 that will facilitate the realization of the other smart features. This platform is featured with user-friendly visualization for sensitive situation awareness and a high tolerance for 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 geographical locations and climates; 3) multiple control strategies for the coordination of decentralized control schemes among substations and control centers; and 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 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 analysis such as voltage/angular stability and security analysis. Self-healing will be achieved to enhance the security of transmission grid via coordinated protection and control schemes.

D. Resiliency

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

E. Sustainability

The sustainability of the smart transmission grid is featured as sufficiency, efficiency, and environment-friendly. The growth
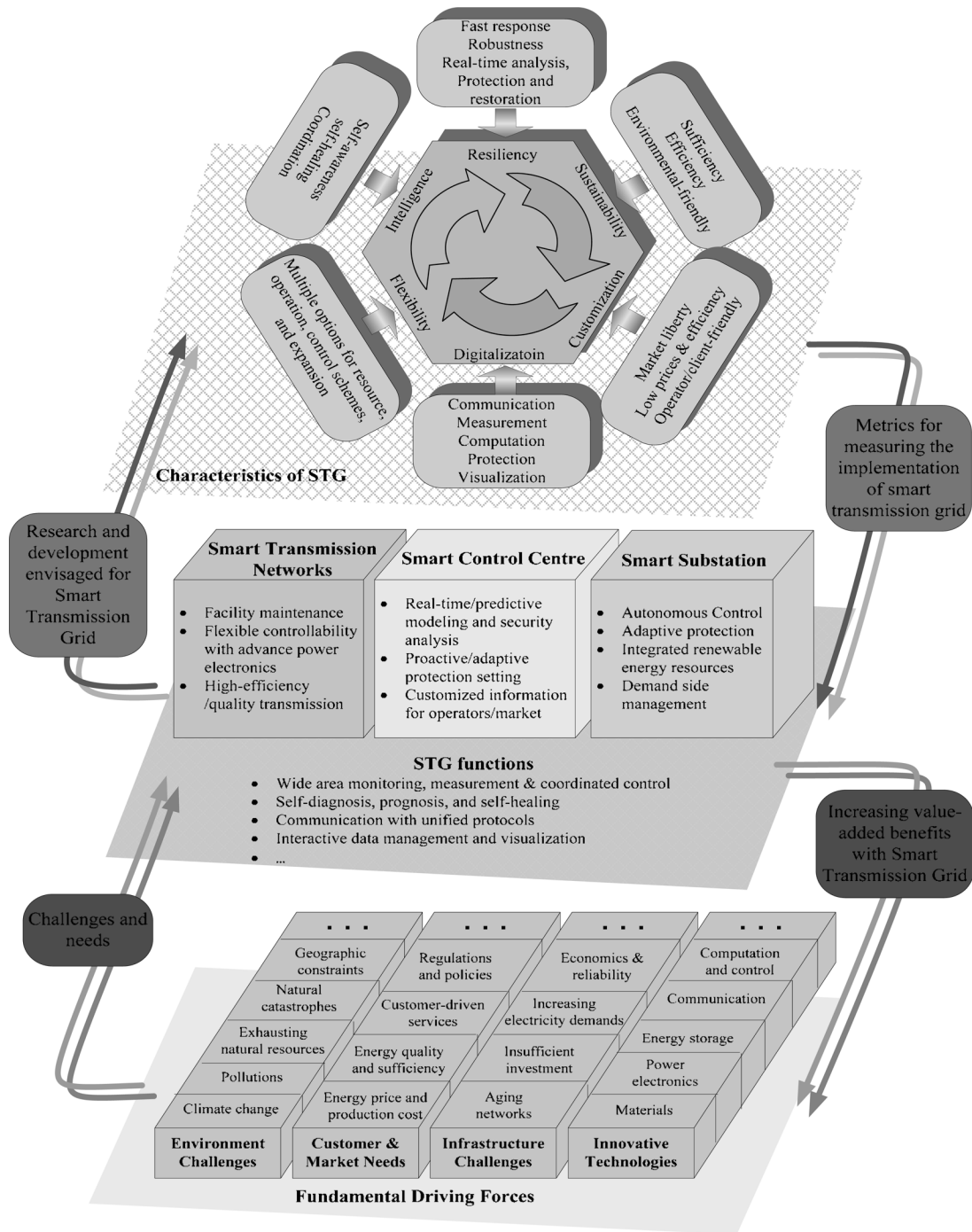
Fig. 1. Vision of a smart transmission grid.

of electricity demand should be satisfied with the implementation of affordable alternative energy resources, increased energy savings via 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 decarbonize with consideration to the environment and climate changes.

F. Customization

The design of the smart transmission grid will be client-tailored for the operators' convenience without the loss of its functions and interoperability. It will also cater to customers with more energy consumption options for a high quality/price

ratio. The smart transmission grid will further liberate the power market by increasing transparency and improving competition for market participants.

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

1) *New materials and alternative clean energy resources*. The 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. The 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 the 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 to operate on a unique platform. Real-time control based on a fast and accurate information exchange in different platforms will improve the system resilience by the enhancement of system reliability and security, and optimization of the 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 operations 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 a smarter transmission grid.

The application of the technologies will be discussed in detail in concert with smart control centers, smart transmission networks, and smart substations in Sections III to V.

III. Smart Control Centers

The vision of the future smart control centers is built on the existing control centers, originally developed approximately a half-century ago. The expected new functions, such as monitoring/visualization, analytical capability, and controllability of the future control centers, are discussed in this section. Also discussed is the interaction with electricity market, although this work excludes the market operation from the control centers' functions.

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 provide the state variables, in particular, voltage angles. As a comparison, the present state estimation demands additional running time and is less robust,

since the data collected from the RTUs is not synchronized and significant effort must be made 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 broad scope and prevent inappropriate operations when a neighboring system is not fully known.

Since the future visualization and monitoring technology will cover a much broader scope, an increased information exchange is needed. The present technology for interarea communications includes a mix of obsolete and current technologies, such as telephone lines, wireless, microwave, and fiber optics [23]. In the future, the communication channels are expected to be more dedicated such as employing a fiber optic network for communications with quality 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 desirable 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 becomes a recurring threat, not merely depends on voltage magnitudes alone, 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 the use of possible frequency wave technology [54]. Once these new monitoring technologies are implemented with the 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. This will greatly assist the operators in identifying potential problems in the real-time operation.

Another noteworthy technology can be the alarming system. The present technology typically presents alarming signals without priority. The future control centers should be able to provide the root cause of possible problems to enable the operators to provide closer monitoring.

B. Analytical Capability

The present online analytic tool in control centers typically performs steady-state contingency analysis. Each credible contingency event is analyzed using contingency power flow studies allowing line flow violations to 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 predefined 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 security analysis for the next operational time interval, such as every 5 min. This does not address the possible short- to midterm (within 1 h) variation of system conditions. In the future, online analysis is expected to have look-ahead simulation capability so that future system conditions will be considered. Then, possible short- to midterm 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, credible N-x or cascading failures should be considered with a probabilistic approach for security risk analysis.

C. Controllability

In the present control centers, the ultimate control action, such as 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 to 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 sufficient coordination of protection and control systems [23], [28]. Each component takes actions based on its own decision. This uncoordinated control could lead to an overreaction under the present contingency plan. The future control centers shall have the capability to coordinate multiple control devices distributed in the system such that optimal coordination can be achieved simultaneously for better controllability.

D. Interactions With Electricity Market

The electricity market is highly intertwined with the future 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 to adapt to the dynamic transition during the market's development. The control center associated with a market actively interacts with other control centers, existing market participants, and new entrants. Thus, modern control centers should 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' ability to monitor and mitigate market power. Furthermore, given the increasing interest in utilizing renewable energy and

controllable load to meet future demand, the smart control center should be flexible to include such energy resources into the unit dispatch. The market 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 them with help from the wide-area GIS systems.

IV. SMART TRANSMISSION NETWORKS

This vision of the smart transmission networks is built on the existing electric transmission infrastructure. However, the emergence of new technologies, including advanced materials, power electronics, sensing, communication, signal processing, and computing 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., 6- or 12-phase transmission line configurations, allow 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), high-voltage dc (HVDC) devices, and other power electronics-based devices.

FACTS devices (including traditional large-scale FACTS 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 full 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. Power electronics-based fault current limiters or current limiting conductors [31], [34] may achieve maximum utilization of line and system capacity, increased reliability, and improved system operation under contingencies. 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.

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 the reliability and security of the transmission system.

D. Advanced Transmission Facility Maintenance

In the smart transmission networks, live-line maintenance can be used to clean and deice 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. 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 and 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 is built on the existing comprehensive automation technologies of substations. It should enable more reliable and efficient monitoring, operation, control, protection, and maintenance of the equipment and apparatus installed in the substations. From the operation viewpoint, a smart substation must rapidly respond and provide increased operator safety. To achieve these goals, the major characteristics of a smart substation shall include the following.

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 find it 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 high accuracy by using a global positioning

system (GPS) signal. The RTU function will be replaced by a PMU in the future. The traditional electromechanical current transformer (CT) and potential transformer (PT) will be replaced by an 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 measurement units and local applications together. Each smart substation also has a server that connects to the higher level communication network via 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, [42] proposed a prototype platform of smart substations that provides a 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 intelligent electronic devices (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 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 the 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 data in the substation and communicate with other communication units such as the

control centers and other substations by just publishing the data to the communication network with the publisher–subscriber infrastructure [44]. All the data from the PMU units, relays, fault recorders, power quality monitors, and equipment monitors should be efficiently managed and displayed. Real-time data visualization provides the operators with a clear picture of the current operation status of the local substation as well as the grid through distributed intelligence [55].

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 is gathered in a substation, a more intelligent alarm management and processing system, such as an expert system, should be developed to find the root cause of the fault. 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 these faults could cause more catastrophic failures to occur [50].

F. Diagnosis and Prognosis

Fast diagnosis and prognosis are necessary in a smart substation, and several technologies have been produced to achieve this. Online 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 on a large scale at the subtransmission level. By incorporating microgrids, the substation can deliver quality power to 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 the capability to operate in the islanding mode taking into account the transmission capacity, load demand, and stability limit, and provide mechanisms for seamlessly transitioning 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 produce 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 the substation level will estimate the substation states to provide a more reliable and full view of the substation. Previous work focusing on the distributed state estimation has already provided the idea of building the substation-level state estimator and related filter
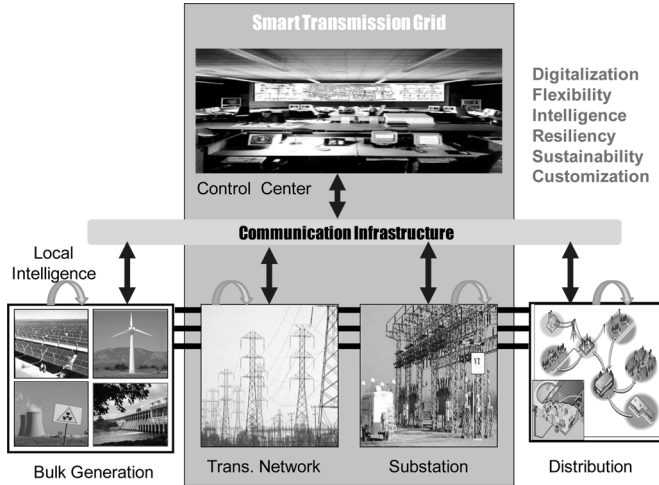
Fig. 2. Interaction among smart transmission grid, generation, and distribution.

technology. An example is the SuperCalibrator [53], where intelligent analysis for bad data processing can be completed at the substation level.

Whenever changes happen in the power system, such as a change in the substation topology or the 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 conditions to significantly improve the operating resilience of control centers against physical and cyber attacks, as well as natural disasters.

VI. INTEGRATION FRAMEWORK

The integration framework of the above three components as well as the future generation and distribution can be briefly illustrated in Fig. 2.

Under the general framework of the smart transmission grid with the advanced communication infrastructure, the backbone of the integration is the distributed intelligence at the smart transmission networks and substations, which can assist with making decisions based on local information to reduce the work load of the control center. Meanwhile, the control center oversees the entire system and sends the system-level decisions, such as various control actions, to remote devices or substations. Also, the intelligent agents at transmission network devices or substations may interact with neighbor agents to achieve broader information in order to make improved decisions without extensive communication back to the control center. In short, the actual control action will be a combination of local decisions from the distributed intelligent agents, central decisions from the smart control center, and the "regional" decision based on the information exchange among peer substations and network devices. Each type of action shall have a different response time and is most efficient for a particular type of work. The actual control process may require a few iterations among the three types of actions.

Fig. 2 also shows the generation and distribution systems that will be equipped with distributed intelligent agents for local decisions as well as interactions with peer agents and the control

center through the communication infrastructure. Under a disturbance in the generation or distribution system, local decisions may be made for a fast response and central decisions are necessary for global control, especially for severe disturbance. Meanwhile, the interactions with other peer agents at various sites in generation, transmission network devices, substations, and distribution are highly desired for a regionally optimal decision. Details of this interactive, decentralized architecture shall be the subject of possible future research.

Development and implementation of the proposed integration framework demands a concerted effort to apply and extend the existing technologies through initiatives in the near future, while promoting forward-looking research and development to solve underlying critical issues in the long term to ensure economic prosperity and environmental health. To achieve this goal, government agencies, 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.

VII. CONCLUDING REMARKS

This paper has presented a unique vision of the next-generation smart transmission grids. It aims to promote 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. This paper presents the major features and functions of the smart transmission grids in detail through three interactive, smart components: smart control centers, smart transmission networks, and smart substations. Since this initial work cannot address everything within the proposed framework and vision, more research and development efforts are needed to fully implement the proposed framework through a joint effort of various entities.

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