Smart Grid: The Electric Energy System of the Future

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I. INTRODUCTION

Three dominant factors are impacting future electric systems of the world: governmental policies at both federal and state levels, customer efficiency needs, and new intelligent computer software and hardware technologies. In addition, environmental concerns are driving the entire energy system to efficiency, conservation, and renewable sources of electricity. Customers are becoming more proactive and are being empowered to engage in energy consumption decisions affecting their day-to-day lives. At the same time, energy needs are continually expanding. For example, consumer participation will soon include extensive use of electric vehicles (both cars and trucks), remote control of in-home appliances to promote energy conservation, ownership of distributed generation from ever more renewable energy sources, and management of electricity storage to locally match supply to demand. The availability of new technologies such as distributed sensors, two-way secure communication, advanced software for data management, and intelligent and autonomous controllers has opened up new opportunities for changing the energy system. For instance, while networking technologies and systems have been greatly enhanced, the Smart Grid faces challenges in terms of reliability and security in both wired and wireless communication environments. In particular, smart home appliances represent a major part of the Smart Grid vision, which aims at increasing energy efficiency. To achieve this goal, home appliances need to communicate with entities and players in other Smart Grid domains via home area networks. Therefore, the electric system of the future will address all these needs and concerns by using new advanced technologies to create a smarter, more efficient and sustainable grid.

The Smart Grid can be defined as an electric system that uses information, two-way, cyber-secure communication technologies, and computational intelligence in an integrated fashion across the entire spectrum of the energy system from the generation to the end points of consumption of the electricity.

Although many different definitions have been proposed for the Smart Grid, in most cases, the users have chosen narrowly focused definitions related to their specific applications and local needs. The main objective of this special issue is to report on some, if not all, of the technical challenges posed by this conversion. While acknowledging its limited coverage, this special issue offers a range of valuable contributions. For the benefit of readers before beginning your excursion, we first provide a description of the current conventional electric energy system. We then identify the key areas that must change in order to provide the intelligence and control necessary to convert to the safe, secure, and efficient Smart Grid of the future.

II. CONVENTIONAL ELECTRIC ENERGY SYSTEM

A general description of today's conventional electric delivery system can

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be broken into mostly isolated components of generation, transmission, substation, distribution, and the customer. Key characteristics of this conventional system that will be most strongly impacted by the changes required to implement the Smart Grid are the following attributes:

1) centralized sources of power generation;
2) unidirectional flow of energy from the sources to the customers;
3) passive participation by the customers, customer knowledge of electrical energy usage is limited to a monthly bill received, after the fact, at the end of the month;
4) real-time monitoring and control is mainly limited to generation and transmission, and only at some utilities, does it extend to the distribution system;
5) the system is not flexible, so that it is difficult to either inject electricity from alternative sources at any point along the grid, or to efficiently manage new services desired by the users of electricity.

These conventional attributes have adequately served the needs of electric utilities and their customers in the past. However, the new needs of more energy knowledgeable, computer savvy, and environmentally conscious customers, combined with regulatory changes, availability of more intelligent technologies, and ever greater demands for enough energy to drive the global economy, require an electric energy system of the future that will become fundamentally different in all five areas listed above.

III. FUTURE SMART ELECTRIC ENERGY SYSTEM

Some of the key requirements of the Smart Grid are summarized below:

- allow for the integration of renewable energy resources to address global climate change;
- allow for active customer participation to enable far better energy conservation;
- allow for secure communications;
- allow for better utilization of existing assets to address long term sustainability;
- allow for optimized energy flow to reduce losses and lower the cost of energy;
- allow for the integration of electric vehicles to reduce dependence on hydrocarbon fuels;
- allow for the management of distributed generation and energy storage to eliminate or defer system expansion and reduce the overall cost of energy;
- allow for the integration of communication and control across the energy system to promote interoperability and open systems and to increase safety and operational flexibility.

It should be noted that the Smart Grid, as characterized above, does not replace the existing electric system but rather builds on the available infrastructure to increase the utilization of existing assets and to empower the implementation of the new functionality. For example, centralized sources of generation will still play a major role in the Smart Grid, but large-scale wind and solar generation, wherever cost justified, will become major parts of the generation mix. Availability of two-way, cyber-secure, end-to-end communications systems will provide customers with the knowledge of their energy usage necessary to allow them to locally and/or remotely control their smart appliances and temperature settings. Monitoring and control of the electric system components will provide the utility with the real time status of the system. The use of this real time data, combined with integrated system modeling and powerful new diagnostic tools and techniques, will provide the detection of precursors to failure in order to drive preventive maintenance and dynamic work management systems. Distributed generation and storage resources and remotely controlled equipment will also play an important role in the management of the Smart Grid energy system, not only to address contingency needs but also to optimize power flow and minimize system losses. It should be noted that building the Smart Grid, as envisioned here, will be very costly and will require a sustained implementation process that evolves over decades.

A. Smart Grid Definition and Characteristics

The Smart Grid can be defined as an electric system that uses information, two-way, cyber-secure communication technologies, and computational intelligence in an integrated fashion across electricity generation, transmission, substations, distribution and consumption to achieve a system that is clean, safe, secure, reliable, resilient, efficient, and sustainable. This definition covers the entire spectrum of the energy system from the generation to the end points of consumption of the electricity. The ultimate Smart Grid is a vision, and it will require cost justification at every step before implementation, then testing and verification before extensive deployment.

Nonetheless, in order to qualify as a Smart Grid, it is neither necessary nor feasible to incorporate all features at once, but rather incorporation of each new feature can be carried out independently. Each will require cost justification and reasonable pay back on investments. However, interoperability of open systems will allow each addition to "Plug-and-Play" into the Smart Grid once the technologies have been validated. Assuming fully realized, the Smart Grid will have the following characteristics:

- Self healing: automatic repair or removal of potentially faulty equipment from service before it fails, and reconfiguration of the system to reroute supplies of energy to sustain power to all customers.

- Flexible: the rapid and safe interconnection of distributed generation and energy storage at any point on the system at any time.
- Predictive: use of machine learning, weather impact projections, and stochastic analysis to provide predictions of the next most likely events so that appropriate actions are taken to reconfigure the system before next worst events can happen.
- Interactive: appropriate information regarding the status of the system is provided not only to the operators, but also to the customers to allow all key participants in the energy system to play an active role in optimal management of contingencies.
- Optimized: knowing the status of every major component in real or near real time and having control equipment to provide optional routing paths provides the capability for autonomous optimization of the flow of electricity throughout the system.
- Secure: considering the two-way communication capability of the Smart Grid covering the end-to-end system, the need for physical- as well as cyber-security of all critical assets is essential.

As indicated by the above characteristics, the Smart Grid involves installation of much new, intelligent equipment at all critical generation, transmission, distribution, and consumption points. For this equipment to become an effective part of the operations of an integrated Smart Grid, fundamental control technologies for communications, data management, diagnostic analysis, and work management are also required. It is expected that the Smart Grid will change the conventional concept of energy management and operations. This is mainly due to the fact that traditional demand and generation concepts are evolving into distributed resources where demand can change into generation (for example, with electric vehicles) and energy storage can locally complement supply needs.

IV. OVERVIEW OF THE SPECIAL ISSUE

The papers span a number of interdependent themes that include: communication and networking, cyber security and control, microgrid, electric vehicle, and energy storage. As can be gleaned from the breadth of papers in this issue, we realize that there has been a tremendous effort by the National Institute and Technology (NIST) to coordinate standards activities for providing a two-way, secure, end-to-end communications system. Therefore, the first article entitled "Challenges and Opportunities in Smart Grid," by George Arnold, the National Coordinator for Smart Grid Interoperability, overviews the important role of communications technology in the Smart Grid.

Following this introductory article is the paper by Bakken *et al.*, entitled "Smart Generation and Transmission with Coherent, Real-Time Data." This paper deals with issues involving the bulk power system and describes leading-edge power applications for the wide area measurement system. It derives a diverse set of baseline requirements that any data delivery system must meet. The paper then presents implementation guidelines and options for achieving these baseline requirements and analyzes current network and middleware technologies in terms of these requirements.

State estimators (SE) constitute the cornerstone of modern energy management systems, where diverse applications rely on accurate information about the system state. Despite the developments in the past couple of decades, the single-area centralized architecture of existing SEs remains essentially unchanged, compared to that of the nineteen seventies. Based on the anticipated new role of SEs in the context of future smart grids, Gómez-Expósito *et al.*, present a multilevel SE architecture, which can sustain growth in size, complexity of data, and information flow facilitated by better monitoring devices including synchronized phasors. This is accomplished by reformulating existing geographically distributed bilevel schemes, through a unified theoretical framework that constitutes the basis of the resulting hierarchical paradigm. In addition, the authors provide an overview of recent advances in information communications technology, such as phasor measurement units (PNUs) and intelligent electronic devise (IED) communication protocols. The next paper by M. Kezunovic is mainly concerned with converting data to knowledge in order to facilitate control actions in the Smart Grid. The paper is entitled "Translational Knowledge: From Collecting Data to Making Decisions in a Smart Grid," and provides a new data processing solution, which is illustrated through several applications such as fault locating, alarm processing, and protective relaying.

It is well recognized that the Smart Grid will employ a variety of wired and wireless networking technologies. The next two papers in this special issue are dedicated to these *technologies*. The first paper by Galli *et al.* addresses the role of power line communications (PLC) in the Smart Grid. The paper presents a comprehensive review of what PLC can offer as a Smart Grid communications technology from the transmission side to the distribution side, as well as within the home. In reviewing the entire application scenario of the PLC within the Smart Grid, the authors also discuss two important aspects of engineering modeling: the first is related to the definition of a statistical PLC channel model, and the second aspect deals with topological studies of the power grid. The wireless networking aspect of smart grid is presented in a paper by Gharavi and Hu. This paper in particular deals with wireless mesh networking aspects of the last mile communications of Smart Grid. It presents a multigate mesh network architecture to handle real-time traffic. The paper describes various techniques such as multigate, multi channel routing as well as a packet scheduling technique to enhance the network performance in terms of reliability, latency, and throughput.

A major component of future Smart Grid systems, however, relies on cyber security and control which is the topic of the next paper entitled "High Assurance Smart Grid: A three-part model for Smart Grid control systems" presented by Overman *et al.* In this paper, the authors suggest that the high assurance Smart Grid is both an architectural approach and an aspirational goal. They present a three-part model that enables the reconsideration of the underlying hierarchical nature of most grid control systems. This hierarchical view evolves to a more hybrid approach which uses distributed control primarily for real-time grid management, and hierarchical control for advanced planning and dispatch.

High penetration levels of distributed photovoltaic (PV) generation on an electrical distribution circuit present several challenges and opportunities for distribution utilities. Rapidly varying irradiance conditions may cause voltage sags and swells that cannot be compensated by slowly responding utility equipment resulting in a degradation of power quality. Fast-reacting, VAR-capable photovoltaic (PV) inverters may provide the necessary reactive power injection or consumption needed to maintain voltage regulation under difficult transient conditions, as described in the paper by Turitsysn *et al.* This paper "Options for Control of Reactive Power by Distributed Photovoltaic Generators," presents several challenges and opportunities for distribution utilities under the high penetration levels of distributed PV generation on an electrical distribution circuit. Various design options for control systems to manage the reactive power generated by these inverters have been compared via simulations. The authors discuss the benefits of choosing different local variables to effectively control the system.

The distribution system provides major opportunities for "Smart Grid" concepts. One way to realize this opportunity is to rethink our distribution system to include the integration of high levels of distributed energy resources (DER). Managing significant levels of DER with their wide ranging dynamics and control points requires sophisticated command and control systems. According to the paper by R. H. Lasseter "Smart Distribution: Coupled Microgrids," an alternative approach would be to build on microgrid concepts. Using microgrids in the distribution system is straightforward and also simplifies the implementation of many "Smart Grid" functions. This includes improved reliability, high penetration of renewable sources, self-healing, active load control, and improved efficiencies.

Advances in technology at all levels of the power system enable the integration of wind energy into the emerging smart grid efficiently and reliably. Onland and offshore wind energy has become a major component of the energy systems across the world. A smart grid will allow connectivity of the wind turbines as intermittent sources of energy, and the advanced wind turbines with power electronics controls and other devices can support a grid with reactive power and protect the equipment during severe grid disturbances. In the paper by Glinkowski, Hou, and Rackliffe, the authors describe interconnection of large wind farms with the power grid using technologies such as high voltage direct current and static VAR compensator with energy storage that can add a new degree of control to the power system, mitigating the intermittency of the wind energy production, and the impact of electrical disturbances.

We are at the point of a historic paradigm shift, with the opportunity to implement new, intelligent methods for producing, distributing, delivering, and using electricity in a much more sustainable manner. Creation of the Smart Grid that will elevate electricity to the efficient and self-healing capabilities comparable to the modern Internet is mainly the theme of the next paper presented by Anderson, Boulanger, Powell, and Scott. This paper entitled "Adaptive Stochastic Control for the Smart Grid," presents an approach that is based on approximate dynamic programming driven adaptive stochastic control. The objective is to provide load and source management for better grid performance by utilities and service providers alike.

Electric vehicles (EVs) present the possibility to amplify the benefits of the smart grid with economic and environmental impacts that reduce the carbon footprint of modern society. A main path to this reduction in the future is the delivery of "green" power to EVs. The paper, authored by Boulanger *et al.*, explores the status of current EV development and the challenges and opportunities for global EV adoption. While global leaders strive for international agreements, the potential of EVs and the smart grid empowers people to effect change. The last paper of this special issue is concerned with the energy storage aspects of the Smart Grid, which can have a major impact on the operations and usage of electricity in the future. In this paper, authored by Roberts and Sandberg, various storage technologies are reviewed and the importance of storage systems in electric grid operation is described.

Finally, we would like to acknowledge Prof. R. Anderson of Columbia University for his insightful views and support in determining the scope of the Special Issue. We would also like to thank all the invited authors for their valuable contributions, as well as

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