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A COMPREHENSIVE STUDY ON FUTURE SMART GRIDS: DEFINITIONS, STRATEGIES AND RECOMMENDATIONS

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Abstract: Nowadays, focusing on some critical points such as decreasing global warming and ambient pollution, better utilization of renewable energy resources, energy management and improvement of power systems operation becomes the field of attention for many modern societies. Although a large number of these aspects have been studied carefully and valuable results have been achieved, rarely can be found an article that makes a comprehensive review on different aspects of smart grids and their issues, therefore a working definition is presented that will help to put in context the framework for discussing and designing the Smart Grid. On the other hand, implementation of Smart Grids as the future of power Networks is strongly dependent on successive layers of functionality and capability using existing equipment and systems. Renewable energies (wind, solar), distributed automation and energy management gateways are some key elements of Smart Grids that will be covered discussed as well.

Key Words: distributed generation; renewable energy; smart grid; storage devices.

INTRODUCTION

The conventional power grids and their assets that span large areas of the Earth are huge interconnected meshes. They are massively complex and are inextricably linked to other parts of societies and have a close relationship with social and economic activities (ETPS 2006). One of the main disadvantages of such networks are their reliance on large centralized power generation units connected to H.V transmission systems supplying power to M.V and L.V distribution systems locally. Besides, existing transmission and distribution systems in many parts of the world use technologies and strategies that are many decades old. They make limited use of digital communication and control technologies. To update this aging infrastructure and to create a power system that meets the growing and changing needs of customers, developed societies try to create intelligent means which use advanced sensing, communication, and control technologies to distribute electricity more effectively, economically, and securely. Furthermore, there are some important side benefits for the consumers such as potential lower cost, higher service reliability, better power quality, increased energy efficiency and energy independence that are all reasons for an increased interest in distributed energy resources (DERs) focusing on what are called "Smart Grids," as the future of power systems (Bayod-Rújula 2009; SAIC 2006) Although the term "Smart Grid" is frequently used today, there is no agreement on its definition. In other words the concept of intelligence in Smart Grid design and how it will be measured is unclear and, a working definition is presented that will help put in context the framework for discussing and designing the Smart Grid. The U.S. Department of Energy (DOE) mentioned in one of its recent issues that "a Smart Grid uses digital technology to improve reliability, security and efficiency of the electric system from large generation, through the delivery systems to electricity consumers and a growing number of distributed-generation and storage resources." (Slootweg 2009). Later, in June 2008, a meeting of industry leaders was held at the U.S. Department of Energy and seven different characteristics were declared for the smart grid concept (U.S. DOE 2008):

1) Better utilization of conventional assets, optimization and efficient operation,
2) Accommodation of all generation and storage options in power grids,
3) Supply of Power quality as a great need of today's industry,
4) Prediction of events and fast response to system disturbances in a self-healing manner,
5) Robust operation against attacks and natural disasters,
6) Active participation of consumers,
7) Introduction of new services, products and markets.

The Smart Grid technology is sometimes applied to smart meters and energy distribution infrastructures which provide a better and more effective approach for reducing the wasteful use of energy for households and business owners. However, this concept may be called the "Super Grid" because it essentially has two components. First, it includes a low-loss transmission system utilizing long-distance from areas with a small number of people but a large number of renewable resources to the places where it can be used. Second, it involves embedded subsystems using data processing and very powerful and effective information technologies allowing customers to use less and receive more, including the ability to sell electricity back into the grid if they have means of distributed generations.

Energy management systems and power system optimizers accompanied by integration of new generation resources which form a whole Smart Grid vision, have the capability of serving as a basic tool to reach energy independence and climate change objectives. Regardless of what managerial framework emerges and how it works or which regulatory system plays the role, the size and the complexity of the bulk power grids joined with the electrification of the local and main sectors (e.g., transportation sector) will necessitate adaptability and flexibility, which are both inherent to future Smart power Grids. What is not clearly defined in related articles, but is important as well, is that a highly developed smart grid outline carries more meaning than smart meters. It includes technologies not only at the transmission level but also at the sub transmission and distribution level covering both hardware and software, such as supervisory control and monitoring systems, as well as primary tools like power transformers and protective relays (Abbasi et al. 2010; ABB 2009). A better list of smart grid criteria which is mentioned below covers much of the same concepts as DOE's, but focuses on broad characteristics rather than specific functions. Under this model, the smart grid is:

- Flexible, adaptive and versatile, with minimal dependence on operators, particularly in response to rapid conditional changes,
- Highly Secured from faults, attacks and naturally occurring disruptions.
- Prognostic, in the case of applying operational data for maintenance practices of devices and equipment and even determining potential failures or outages before they occur.
- Integrated, in terms of real-time two-way communications and control functions.
- Interactive between customers and markets.
- Optimized to enhance availability, efficiency, reliability and economic performance.

While details about the definition of a smart grid vary greatly, a general definition can be made as follow:

A smart grid is an intelligent, auto-balancing, self-healing power grid that accepts any source of fuel as its input and transforms it into a consumer's end use with minimal human intervention. It is a course of action that will result in better utilization of renewable energy resources and reduce environmental vestiges as much as possible. It has a sense of detection to understand where it is loaded beyond capacity and the ability to reroute power to lessen overload and impede potential outages. It is a base that provides real-time communication between consumers and the utility in order to optimize energy harvesting based on environmental benefits or cost preferences (X. Energy 2007). However, it should be noted that deployment of smart grid technologies will occur over a long period of time, adding successive layers of functionality and capability onto existing equipment and systems. Although technology is the focal point, it is only a way to achieve the goal, and the smart grid should be defined by more extensive characteristics. How the smart grid differs from conventional grids we know today is illustrated in Table 1.

The last expression in the table, "system topology," refers to what is perhaps the most essential movement that a fully realized smart grid will require. Conventional networks are designed to support large power units that serve faraway consumers via one-way transmission and distribution grids (Fig. 1), but the future grids will necessarily be two-way real time systems where power is generated not only by a large number of small and distributed energy resources but also by large power plants. Power flow across the network is based on a mesh grid structure rather than a hierarchical one (Fig. 2).

SMART GRID TECHNOLOGIES IN USE TODAY

Several categories are proposed for the Smart-Grid concept which includes: developing information technology (IT) and Integrated communications across the grid, SCADA/DMS (distribution management systems), Designing advanced control methods, advanced sensing, metering and measurement devices and technologies, Real-time situational awareness and analysis of the distribution system, Substation automation (SA) and Designing main and local supervisory control units along with suitable human interfaces. Of course, this is not an exhaustive list but generally speaking, five key technology areas for smart grids can be mentioned (Momoh 2009):

- *Interconnected Communications*

Integrated communications allow each part of the network to be both "talk" and "listen." i.e., this exchange of information connects different components to an open architecture for real-time optimization and control.

- *Advanced Sensing and Measurement*

Table 1. Current grid vs. Future smart grid.

Features	Current Grid	Smart Grid
Grid Communication	*Non or one-way; typically not real time*	*Two-way; real time*
Interaction between Customers	*Limited*	*Comprehensive and Extensive*
Type of Metering	*Electromechanical*	*Digital(enabling real time pricing and net metering)*
Operation & Maintenance	*Manual equipment checks, maintenance*	*Remote monitoring, protective; time-based maintenance*
Power Generation	*Centralized*	*Centralized, Distributed*
Energy control	*Limited*	*Comprehensive, automated*
Reliability & Dependability	*Vulnerable to downfalls, failures and cascading outages; essentially reactive*	*Automatic, pro-active protection; outages prevented before starting*
Restoring procedure following disturbance	*Manual*	*Self-healing*
System topology	*Radial, generally one-way power flow*	*Network, multiple power flow pathways*

These advanced technologies provide more rapid and true responses, such as remote control and monitoring, time-of-use pricing and demand-side management.

- *Advanced Components*

Latest innovations and research in IT, superconductivity, power electronics, fault tolerance, renewable energies, storage options and diagnostics introduce advanced components of smart grids.

- *Advanced Control Methods*

Advanced control methods supervise essential elements, allowing rapid diagnosis and exact solutions appropriate to any event.

- *Improved Interfaces and Decision Support*

This technology enables decision-making which transforms grid operators and managers into knowledgeable workers.

BUILDING A SMARTER SMART GRID

A smarter energy ecosystem will enable improved consumer choices via different commodities and standards but in order to achieve such an intelligent structure some rules and agreements must be met appropriately. Reliability in power grids at any level of voltage is essential to assure adequate penetration of renewable energies (wind, solar, etc.) and to enable new services and products for consumers. As a matter of fact there is a need to develop new Smart Grid business models for continued investment beyond the current stimulus. Grid reliability requirements must be well defined through real-time metrical methods and wide area situational awareness to address the future challenges properly. However there may be a need to distinguish the available reliability of different grids based on consumer needs (Battaglini et al. 2009). It should be also noted that there must be an uninterrupted effort to use existing standards and to develop new ones, but this should not impede our progress in deploying the new ecosystem. In other words, we must build on what we already have – focus on existing solutions including grid reliability solutions (energy and distribution management systems, situation awareness systems), advanced forecasting solutions, interoperability and standards, energy efficiency and smart devices (Venayagamoorthy et al. 2009; Coll-Mayor et al. 2007). Moreover, demand-forecasting methodologies must be improved to optimize new consumer needs (demand response, electric vehicles, etc.). Cyber-security issues must be addressed to ensure that consumers and their data are protected, but we must not impede data transparency, which is key for consumer decision process and participation. Additionally, asset management systems must be deployed to better utilize existing grid assets for real-time operations and condition-based monitoring for optimal asset performance. An aging engineer workforce must be addressed through investment in universities' engineering programs, further research, progressive methodologies and facilities. Another option includes modern knowledge-based solutions to capture existing situational data and plan for future generations. Also keep in mind that energy storage technology is essential to Smart Grid development and will enable further penetration of renewable and distributed generation. As important is the vital role of consumers for the success of Smart Grid (Thompson et al. 2009). It must be ensured that tariffs and electricity prices do not increase aberrantly and do not impede the deployment of a Smarter Grid in any direction. Consumers must be educated (through scenario planning activities) on potential price increases in electricity due to load growth, fuel and generation scarcity situations. Consumers must be provided with incentives and data (electric price prediction, renewable energy generation patterns, etc.) to participate in energy conservation and improved electricity usage, as well.

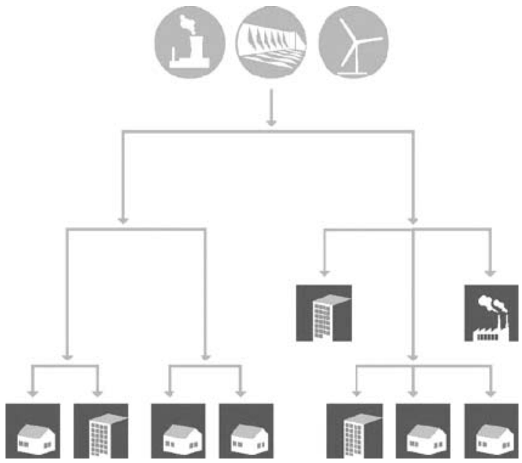

FIG. 1. Conventional power system.

FIG. 2. Future power system (smart grid).

SMART GRID CYBER SECURITY STRATEGIES AND RISK MANAGEMENT

While developing an efficient and reliable strategy to ensure interoperability of solutions across different parts of an intelligent infrastructure, there will be a need for an overall cyber security strategy including both domain-specific and common requirements. From the other point of view, implementation of such security plans for the Smart Grid architecture requires the development of a comprehensive cyber security risk management framework which is based on existing risk management approaches developed by both private and public sectors. This risk management framework provides a means for a combination of different information on impacts, susceptibilities, vulnerabilities and threats to produce an estimation of risk for the Smart Grid, its domains and sub-domains, such as homes, industrial companies and businesses. The desired goal toward building a smarter grid is to reach a comprehensive assessment of its systems and components, so a smart grid includes a variety of systems and components from the integrated communications, advanced sensing and measurement devices to the improved interfaces, decision support mediums, and the risk management framework as needed to be applied on an asset, system, and network basis, as applicable. The next step is to select and accommodate the security requirements. All in all, in a typical risk management process: assets, systems and networks are identified; risks, including vulnerabilities, impacts and threats are assessed; security requirements are specified; and security controls are selected, implemented, assessed for effectiveness, authorized, and then monitored over the lifecycle of the system. When the security requirements are specified, the risk assessment process for the Smart Grid will be completed. These requirements will be selected on the basis of a risk assessment and will not be allocated to specific systems, components, or functions of the Smart Grid. When a system comes to an operational phase, the implementation, assessment and monitoring of security controls are applicable. In other words, anything considered as the output of the Smart Grid risk management process should be used in these steps. In addition, when new systems are implemented or existing systems are modified the full risk management process should be applied as well. Recently, several documents have been published in developing the risk management approach for the Smart Grid:

- North American Electric Reliability Corporation (NERC), *Security Guidelines for the Electricity Sector: Vulnerability and Risk Assessment*, 2002;
- FIPS 199, *Standards for Security Categorization of Federal Information and Information Systems*, February 2004;
- Federal Information Processing Standard (FIPS) 200, *Minimum Security Requirements for Federal Information and Information Systems*, March 2006;
- ANSI/ISA-99, *Manufacturing and Control Systems Security*, Part 1: *Concepts, Models and Terminology*, 2007 and Part 2: *Establishing a Manufacturing and Control Systems Security Program*, 2009;
- National Institute of Standards and Technology (NIST) Special Publication (SP), 800-39, DRAFT, *Managing Risk from Information Systems: An Organizational Perspective*, April 2008;
- *The Advanced Metering Infrastructure (AMI) System Security Requirements*, 2008.
- *The National Infrastructure Protection Plan*, 2009;

Although there are many documents and standards that may be applicable to the operation of the Smart Grid, at this time there are only two authenticated standards which are obligatory for a specific domain of the Smart Grid: the North American Electric Reliability Corporation (NERC) and Critical Infrastructure Protection (CIPs). The following standards are directly relevant to a Smart Grid (NISTIR 2009):

- NERC CIP 002, 003-009
- IEEE 1686–2007, *IEEE Standard for Substation Intelligent Electronic Devices (IEDs) Cyber Security Capabilities*
- AMI System Security Requirements, 2008
- *Utility AMI Home Area Network System Requirements Specification*, 2008
- IEC 62351 1–8, *Power System Control and Associated Communications* – Data and Communication Security

The risk assessment, including identifying vulnerabilities, impacts and threats will be achieved through different ways, among them the top-down and bottom-up approaches are more rampant. The top-down approach concentrates upon the entire Smart Grid functionality while the bottom-up approach emphasizes perceptible problems that need to be addressed well, such as authenticating and authorizing users in system architectures, protocols, Intelligent Electronic Devices (IEDs), key management for meters and intrusion detection for power equipment. Moreover, reciprocity among Smart Grid domains will be taken into account while evaluating the consequences of a cyber or physical security incident because an incident in one or more infrastructures can result in failures in other domains or systems.

RENEWABLE ENERGIES AND STORAGE OPTIONS IN SMART GRID

As was said beforehand, the ability to better integrate renewable energy is one of the driving factors in some smart grid installations. With low incorporation of renewable energies the total effect on grid operations is confined, but as the penetration of such resources increases, their mutual effects increase too. Nevertheless, exploitation of renewable energy sources (RESs), even when there is a good potential resource, may be problematic due to their variable and intermittent nature (Hammons 2006). Earlier studies have indicated that energy storage can compensate for the stochastic nature and sudden deficiencies of RESs for short periods without suffering loss of load events, and without the need to start more generating plants (Kaldellis et al. 2007; Koeppel et al. 2008; Divya et al. 2009). Using storage options small peak load problems, improves electrical stability and eliminates power quality disturbances. Furthermore, energy storage systems in combination with power electronics are expected to be key elements for the growth and integration of distributed generation (DG) and renewable energy sources (RES) into the eclectic system to build future smart grids (Molderink et al. 2009). Thus, the main focus should be on small to medium sized storages which are installed closely to distributed energy resources.

For the actual operation of the smart grid, forecasts of future requirements are essential to be able to prepare the flexible systems to behave in the appropriate manner. Unplanned renewable resources introduce new variables to the decision making procedure and complicate the balancing act. The fact that these types of generations cannot be dispatched in the traditional style can bring about problems for conventional system operation. A smart grid takes advantage of potential improvements that can be made to a conventional operation through the use of communications and information. While renewable energy cannot necessarily be operated in a conventional manner, its behavior can be predicted and the forecast information is exactly the kind of information that a smart grid must use to improve system efficiency. In fact, as renewable energy penetration levels continue to increase, non-scheduled renewable energy may become the single largest source of variability on the power system. This makes the employment of accurate forecasting of renewable energies a key component of a smart grid.

SMART ENERGY MANAGEMENT SYSTEM

Considering a smart grid, decisions are dynamically made based on information about electricity supply and demand. Basically, in the world of renewable energies, it is the forecasted information that feeds the smart grid. Hence, designing a supervisory control unit and a smart energy management system (SEMS), which allows instantaneous optimization of alternative and renewable power sources, is necessary (Hajizadeh et al. 2007; Figueiredo et al. 2010; Lagorse et al. 2010). The function of these control systems is to generate set points for all the sources and storages in such a way that economically optimized power dispatch will be maintained to fulfill certain load demand, i.e., a smart energy management can be viewed as a plan of action that chooses a proper set of generators that can supply certain loads in an efficient and economical manner. During this smart planning, forecasting of both demand and power generation as well as some fast online algorithms are used to define the energy availability and to optimize power dispatch signals to the loads and the grid using advanced components. This energy management system generally consists of several different parts such as a prediction module, optimization module and online control module shaped as a whole set (Fig. 3). The prediction module is usually based on a trained Artificial Neural Network (ANN), a fuzzy algorithm or a combination of these two intelligence methods

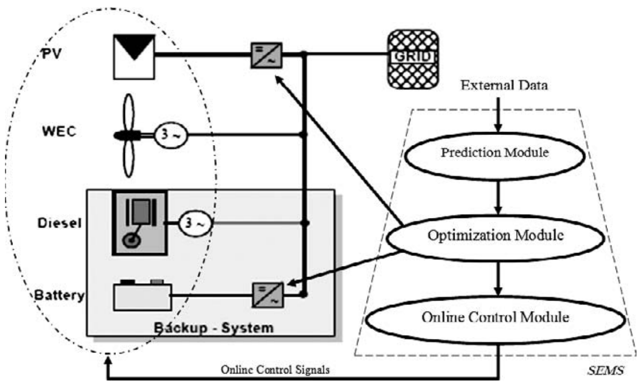

FIG. 3. SEMS in smart grid.

which results in a good and valid prediction of renewable energies or demands at periods of future times (Kalogirou 2000; Soteris et al. 2000–01; Kalogirou 2001; Cinar et al. 2010). Since the aim of an optimization module is to find an optimum way of generation into a demand side at minimum operation cost and maximum profit (if it is possible) this section often utilizes Linear Programming (LP) or such similar techniques which formulate cost function of the system along with its constraints. All optimum planning schemes, e.g., defining a certain rate of charge and discharge relating to storage options, is made in this part as well (Clark et al. 2004). Finally, the online control model which is fed by the latter section, generates set points for all controllers and components while investigating the power balance through the entire network (Chuang et al. 2008).

RECOMMENDATIONS FOR DEVELOPING SMART GRID TECHNOLOGY

Fundamental agreements and key elements will drive solutions within a few years and it should be feasible to achieve meaningful benefits that drive extra intelligent actions on Smart Grid utilization over a longer period of time.

- *Establish open standards and architecture:*

A nationwide platform for Smart Grid technology programs should seek open standards and architecture, i.e., clear security standards, transportability, data accessibility and interoperability should be designed in a way that ensure that all partners and cooperators invest together for a common execution, risk and reward sharing for using Smart Grid technology [similar to the telecommunications industry (NISTIR 2009)].

- *Transparency:*

Recognize that we are creating smarter consumers, so there must be transparency in pricing and operational signals to consumers and operators. Clear data should be generally ready for use in order to facilitate innovation and technology development.

- *Rate-making:*

Address rate-making changes that utilize decoupling, capitalizing efficiencies and demand response. Rate-making must also be transparent.

- *Define essential foundational elements of "Smart Grid":*

The definition must provide the foundation for making choices about what to do first. Seek an industry agreed upon definition of what a Smart Grid encompasses.

- *Workforce improvement:*

Development of expert opinions in some fields of study such as electrical and power engineering, information technology, mechanical engineering and promotion of utility operations and maintenance could be helpful for smart operation of future power grids, i.e., it is required to update our knowledge of engineering, our systematic and routine curriculum and programs along with investing in worker recruiting and retraining programs.

- *Offer external incentives:*

Stimulus patterns or supportive actions must be provided in societies and among engineering communities in order to develop a workforce, create and fill the jobs that will implement new technologies.

CONCLUSION

An intelligent grid can lead to a revolution in power system operation, a revolution that will take place if new ideas and technologies along with very large penetrations of renewable energy are to be incorporated onto the grid. However, in order to efficiently operate and make good decisions, a smart grid must have an information feeding supervisory control unit and Smart Energy Management System (SEMS). This information can be used to create better procedures and capabilities for the smart grid and allow more prudent investments. Moreover the optimal integration of decentralized energy storages will be an extremely important task in the near future for the utilities. On the other hand, to reach a pathway toward intelligent structures, first the barriers must be identified and then research, development and demonstrations of operation must be conducted to overcome these barriers.

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