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SMART GRID ARCHITECTURAL DESIGNS

1.1 INTRODUCTION

Today's electric grid was designed to operate as a vertical structure consisting of generation, transmission, and distribution and supported with controls and devices to maintain reliability, stability, and efficiency. However, system operators are now facing new challenges including the penetration of RER in the legacy system, rapid technological change, and different types of market players and end users. The next iteration, the smart grid, will be equipped with communication support schemes and real-time measurement techniques to enhance resiliency and forecasting as well as to protect against internal and external threats. The design framework of the smart grid is based upon unbundling and restructuring the power sector and optimizing its assets. The new grid will be capable of:

- Handling uncertainties in schedules and power transfers across regions
- Accommodating renewables
- Optimizing the transfer capability of the transmission and distribution networks and meeting the demand for increased quality and reliable supply
- Managing and resolving unpredictable events and uncertainties in operations and planning more aggressively.

Smart Grid: Fundamentals of Design and Analysis, First Edition. James Momoh.

TABLE 1.1. Comparison of Today's Grid vs. Smart Grid [4]

Preferred Characteristics	Today's Grid	Smart Grid
Active Consumer Participation	Consumers are uninformed and do not participate	Informed, involved consumers—demand response and distributed energy resources
Accommodation of all generation and storage options	Dominated by central generation—many obstacles exist for distributed energy resources interconnection	Many distributed energy resources with plug-and-play convenience focus on renewables
New products, services, and markets	Limited, poorly integrated wholesale markets; limited opportunities for consumers	Mature, well-integrated wholesale markets; growth of new electricity markets for consumers
Provision of power quality for the digital economy	Focus on outages—slow response to power quality issues	Power quality a priority with a variety of quality/price options—rapid resolution of issues
Optimization of assets and operates efficiently	Little integration of operational data with asset management—business process silos	Greatly expanded data acquisition of grid parameters; focus on prevention, minimizing impact to consumers
Anticipating responses to system disturbances (self-healing)	Responds to prevent further damage; focus on protecting assets following a fault	Automatically detects and responds to problems; focus on prevention, minimizing impact to consumers
Resiliency against cyber attack and natural disasters	Vulnerable to malicious acts of terror and natural disasters; slow response	Resilient to cyber attack and natural disasters; rapid restoration capabilities

1.2 TODAY'S GRID VERSUS THE SMART GRID

As mentioned, several factors contribute to the inability of today's grid to efficiently meet the demand for reliable power supply. Table 1.1 compares the characteristics of today's grid with the preferred characteristics of the smart grid.

1.3 ENERGY INDEPENDENCE AND SECURITY ACT OF 2007: RATIONALE FOR THE SMART GRID

The Energy Independence and Security Act of 2007 (EISA) signed into law by President George W. Bush vividly depicts a smart grid that can predict, adapt, and reconfigure itself efficiently and reliably. The objective of the modernization of the U.S. grid as outlined in the Act is to maintain a reliable and secure electricity [2] infrastructure that

Figure 1.1. Rationale for the smart grid.

will meet future demand growth. Figure 1.1 illustrates the features needed to facilitate the development of an energy-efficient, reliable system.

The Act established a Smart Grid Task Force, whose mission is "to insure awareness, coordination and integration of the diverse activities of the DoE Office and elsewhere in the Federal Government related to smart-grid technologies and practices" [1]. The task force's activities include research and development; development of widely accepted standards and protocols; the relationship of smart grid technologies and practices to electric utility regulation; the relationship of smart grid technologies and practices to infrastructure development, system reliability, and security; and the relationship of smart grid technologies and practices to other facets of electricity supply, demand, transmission, distribution, and policy. In response to the legislation, the U.S. research and education community is actively engaged in:

1. Smart grid research and development program
2. Development of widely accepted smart grid standards and protection
3. Development of infrastructure to enable smart grid deployment
4. Certainty of system reliability and security
5. Policy and motivation to encourage smart grid technology support for generation, transmission and distribution

As Figure 1.2 shows, there are five key aspects of smart grid development and deployment.

1.4 COMPUTATIONAL INTELLIGENCE

Computational intelligence is the term used to describe the advanced analytical tools needed to optimize the bulk power network. The toolbox will include heuristic, evolution programming, decision support tools, and adaptive optimization techniques.

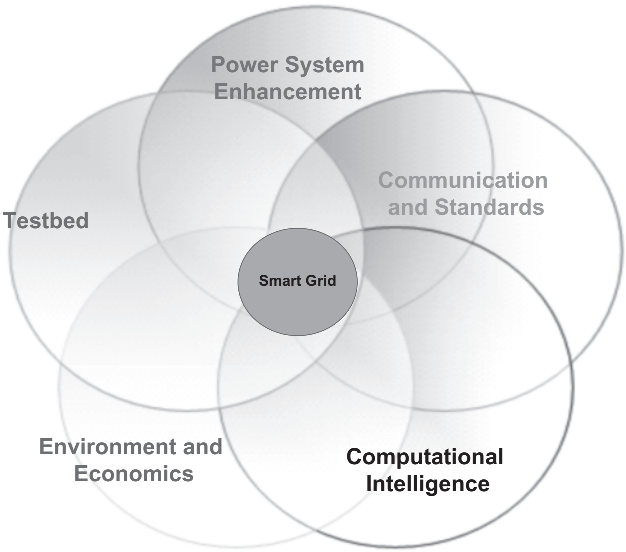

Figure 1.2. Five key aspects of smart grid development.

1.5 POWER SYSTEM ENHANCEMENT

Policy-makers assume that greatly expanded use of renewable energy [4,5] resources in the United States will help to offset the impacts of carbon emissions from thermal and fossil energy, meet demand uncertainty, and to some extent, increase reliability of delivery.

1.6 COMMUNICATION AND STANDARDS

Since planning horizons can be short as an hour ahead, the smart grid's advanced automations will generate vast amounts of operational data in a rapid decision-making environment. New algorithms will help it become adaptive and capable of predicting with foresight. In turn, new rules will be needed for managing, operating, and marketing networks.

1.7 ENVIRONMENT AND ECONOMICS

Based on these desired features, an assessment of the differences in the characteristics of the present power grid and the proposed smart grid is needed to highlight characteristics of the grid and the challenges. When fully developed the smart grid system will allow customer involvement, enhance generation and transmission with tools to allow minimization of system vulnerability, resiliency, reliability, adequacy and power quality. The training tools and capacity development to manage and operate the grids and hence crate new job opportunities is part of the desired goals of the smart grid evolution which will be tested using test-bed. To achieve the rapid deployment of the grids test bed and research centers need to work across disciplines to build the first generation of smart grid.

By focusing on security controls rather than individual vulnerabilities and threats, utility companies and smart-grid technology vendors can remediate the root causes that lead to vulnerabilities. However, security controls are more difficult and sometimes impossible to add to an existing system, and ideally should be integrated from the beginning to minimize implementation issues. The operating effectiveness of the implemented security controls-base will be assessed routinely to protect the smart grid against evolving threats.

1.8 OUTLINE OF THE BOOK

This book is organized into 10 chapters. Following this chapter's introduction, Chapter 2 presents the smart grid concept, fundamentals, working definitions, and system architecture. Chapter 3 describes the tools using load flow concepts, optimal power flows, and contingencies and Chapter 4 describes those using voltage stability, angle stability, and state estimation. Chapter 5 evaluates the computational intelligence approach as a feature of the smart grid. Chapter 6 explains the pathways design of the smart grid using general purpose dynamic stochastic optimization. Chapter 7 reviews renewable supply and the related issues of variability and probability distribution functions, followed by a discussion of storage technologies, capabilities, and configurations. Demand side managemen (DSM) and demand response, climate change, and tax credits are highlighted for the purpose of evaluating the economic and environmental benefit of renewable energy sources. Chapter 8 discusses the importance of developing national standards, followed by a discussion of interoperability such that the new technologies can easily be adapted to the legacy system without violating operational constraints. The chapter also discusses cyber security to protect both RER and communication infrastructure. Chapter 9 explains the significant research and employment training for attaining full performance and economic benefits of the new technology. Chapter 10 discusses case studies on smart grid development and testbeds to aid deployment. The chapter outlines the grand challenges facing researchers and policy-makers before the smart grid can be fully deployed, and calls for investment and multidisciplinary collaboration. Figure 1.3 is a schematic of the chapters.

1.9 GENERAL VIEW OF THE SMART GRID MARKET DRIVERS

To improve efficiency and reliability, several market drivers and new opportunities suggest that the smart grid must:

1. Satisfy the need for increased integration of digital systems for increased efficiency of the power system. In the restructured environment, the deregulated electric utility industry allows a renovation of the market to be based on system constraints and the seasonal and daily fluctuations in demand. Competitive markets increase the shipment of power between regions, which further strains today's aging grid and requires updated, real-time controls.
2. Handle grid congestion, increase customer participation, and reduce uncertainty for investment. This requires the enhancement of the grid's capability to handle demand reliably.
3. Seamlessly integrate renewable energy systems (RES) and distributed generation. The drastic increase in the integration of cost-competitive distributed generation technologies affects the power system.

In addition to system operators and policy-makers, stakeholders are contributing to the development of the smart grid. Their specific contributions and conceptual understanding of the aspects to be undertaken are discussed below.

1.10 STAKEHOLDER ROLES AND FUNCTION

As in the legacy system, critical attention must be paid to the identification of the stakeholders and how they function in the grid's development. Stakeholders range from

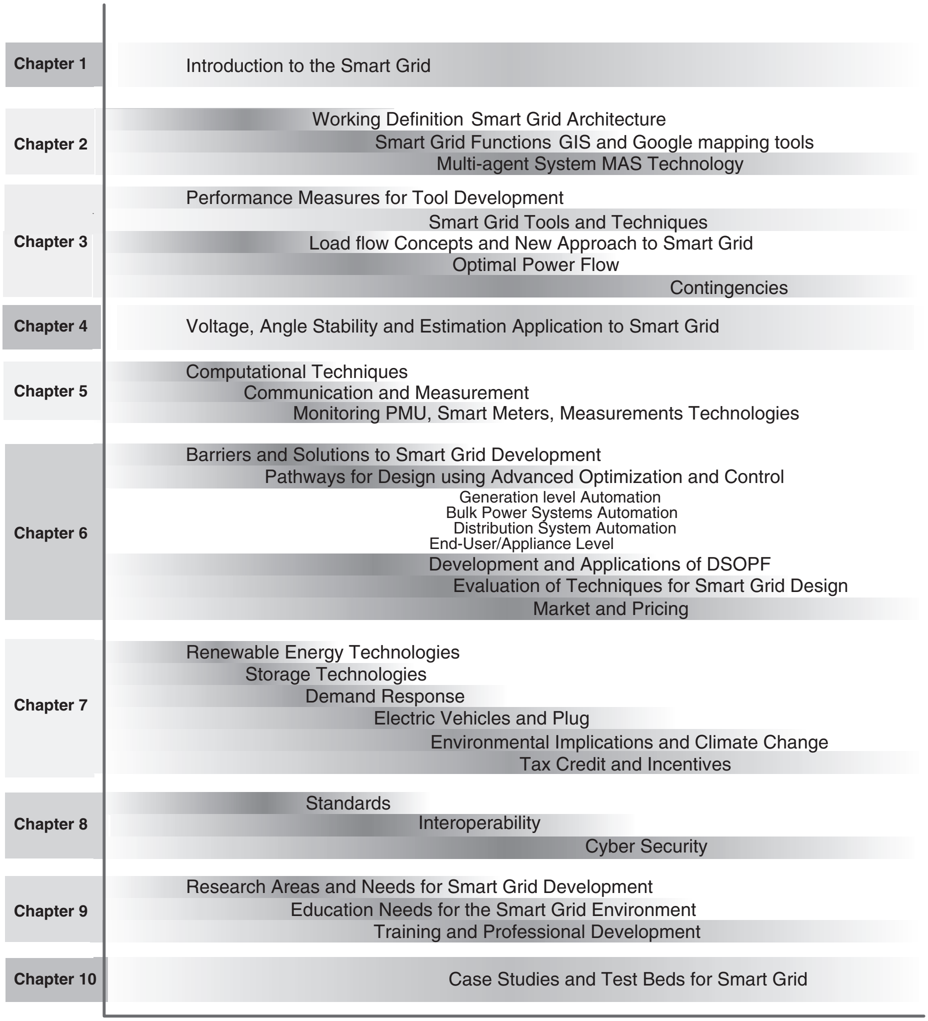

Figure 1.3. Schematic of chapters.

utility and energy producers to consumers, policy-makers, technology providers, and researchers. An important part of the realization of the smart grid is the complete buy-in or involvement of all stakeholders.

Policy-makers are the federal and state regulators responsible for ensuring the cohesiveness of policies for modernization efforts and mediating the needs of all parties. The primary benefit of smart grid development to these stakeholders concerns the mitigation of energy prices, reduced dependence on foreign oil, increased efficiency, and reliability of power supply. Figure 1.4 shows the categories of stakeholders.

Other participants in the development of the smart grid include government agencies, manufacturers, and research institutes. The federal Department of Energy's (DOE)

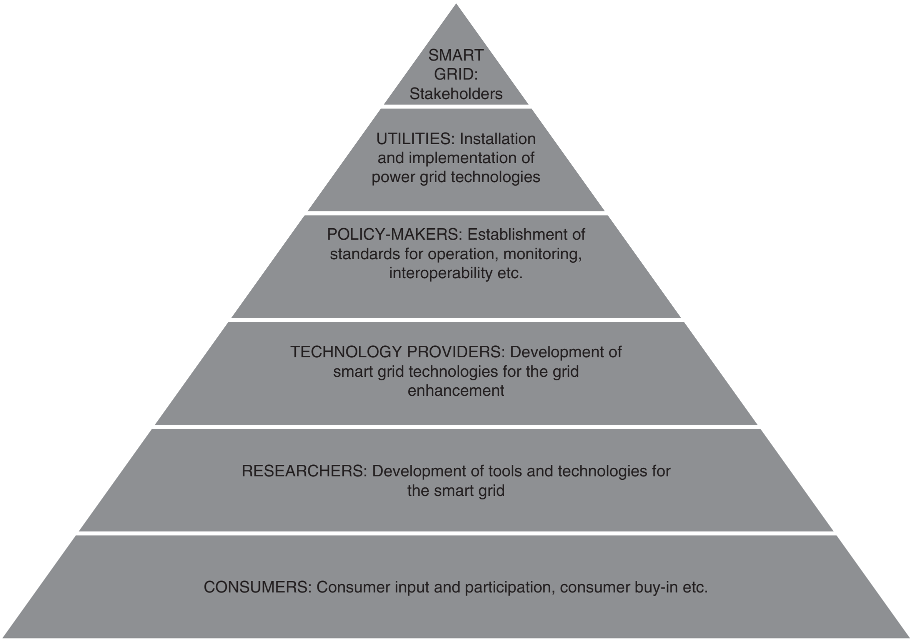

Figure 1.4. Stakeholders and their functions.

National Renewable Energy Laboratory (NREL) and state agencies such as the California Energy Commission and the New York State Energy Research and Development Authority are among the pioneers. In the monograph, "The Smart Grid: An Introduction," the DOE discusses the nature, challenges, opportunities, and necessity for smart grid implementation. It defines the smart grid as technology which "makes this transformation of the electric industry possible by bringing the philosophies, concepts and technologies that enabled the internet to the utility and the electric grid and enables the grid modernization" [1]. The characteristics of the smart grid are two-way digital communication, plug-and-play capabilities, advanced metering infrastructure for integrating customers, facilities for increased customer involvement, interoperability based on standards, and low-cost communication and electronics.

Additional features identified include integration and advancement of grid visualization technology to provide wide-area grid awareness, integrating real-time sensor data, weather information, and grid modeling with geographical information [1].

However, the DOE's definitions in our opinion do not provide measures for addressing uncertainty, predictivity, and foresight. Another federal entity, the Federal Energy Regulatory Commission (FERC), has mandated the development of:

1. **Cyber Security**: require NIST define standard and protocol consistent with the overarching cyber security and reliability requirements of the Energy Independence and Security Act (EISA) and the FERC Reliability Standards.

2. **Intersystem Communications**: Identify standards for common information models for communication among all elements of the bulk power system regional market operators, utilities, demand response aggregators, and customers
3. **Wide-Area Situational Awareness**: Ensure that operators of the nation's bulk power system have the equipment that gives them a complete view of their systems so they can monitor and operate their systems.
4. **Coordination of the bulk power systems with new and emerging technologies:** Identify standards development that help to accommodate the introduction and expansion of renewable resources, demand response, and electricity storage to address several bulk power system challenges. Also identify standards development that help to accommodate another emerging technology, electric transportation.

1.10.1 Utilities

South California Edison (SCE) and other utility companies undertook to reinvent electrical metering. Vendors are migrated to an open standards–based advanced metering infrastructure. These contributions have led to the continual improvement of associated features such as customer service, energy conservation, and economic efficiency.

PEPCO Holdings has been working on an Advanced Metering Infrastructure (AMI). The technology is an integral component of the smart grid [5]. The features proposed include investment in and implementation of innovative, customer-focused technologies and initiatives for efficient energy management, increased pricing options and demand response, reduction of total energy cost and consumption, and reduction of the environmental impacts of electric power consumption.

1.10.2 Government Laboratory Demonstration Activities

Much of the fundamental thinking behind the smart grid concept arose from the DOE's Pacific Northwest National Laboratory (PNNL) more than 20 years ago. In the middle 1980s researchers at PNNL were already designing first-generation data collection systems that were installed in more than 1000 buildings to monitor near real time electricity consumption for every appliance. PNNL developed a broad suite of analytical tools and technologies that resulted in better sensors, improved diagnostics, and enhanced equipment design and operation, from phasor measurement and control at the transmission level to grid-friendly appliances [2]. In January 2006, four years after its first presentation, PNNL unveiled the GridWise Initiative whose objective was the testing of new electric grid technologies [3]. This demonstration project involved 300 homeowners in Washington and Oregon.

The GridWise Alliance manages the GridWise Program in the DOE's Office of Electricity and Energy Assurance. Members include Areva, GE, IBM, Schneider Electric; American Electric Power, Bonneville Power Administration, ConEd, the PJM Interconnection; Battelle, RDS, SAIC, Nexgen, and RockPort Capital Partners [2]. The GridWise Architecture Council [4], a primary advocate for the smart grid, promotes the benefits of improving interoperability between the automation systems needed to enable smart grid applications.

1.10.3 Power Systems Engineering Research Center (PSERC)

The Power Systems Engineering Research Center (PSERC) [6] consists of 13 universities and industrial collaborators involved in research aimed at solving grid problems using state-of-the-art technologies. The direction of PSERC is the development of new strategies, technologies, analytical capabilities, and computational tools for operating and planning practices that will support an adaptive, reliable, and stable power grid.

1.10.4 Research Institutes

The Electric Power Research Institute (EPRI) and university consortium groups have developed software architecture for smart grid development. These tools focus on the development of the grid's technical framework through the integration of electricity systems, communications, and computer controls. The Intelligrid software from EPRI, an open-standard, requirements-based approach for integrating data networks and equipment, enables interoperability between products and systems. It provides methodology, tools, and recommendations for standards and technologies for utility use in planning, specifying, and procuring IT-based systems.

1.10.5 Technology Companies, Vendors, and Manufacturers

IBM is a major player in the provision of information technology (IT) equipment for the smart grid on a global level. In 2008, IBM was chosen to spearhead IT support and services for smart-grid energy-efficiency programs by American Electric Power, Michigan Gas and Electric, and Consumers Energy. IBM serves as the systems integrator for its GridSmart program that displays energy usage and participate in energy-efficiency program. Its Intelligent Power Grid is characterized by increased grid observability with modern data integration and analytics to support advanced grid operation and control, power delivery chain integration, and high-level utility strategic planning functions [7]. Some key characteristics of the Intelligent Power Grid are:

- Grid equipment and assets contain or are monitored by intelligent IP-enabled devices (digital processors).
- Digital communication networks permit the intelligent devices to communicate securely with the utility enterprise and possibly with each other.
- Data from the intelligent devices and many other sources are consolidated to support the transformation of raw data into useful information through advanced analytics.
- Business intelligence and optimization tools provide advanced decision support at both the automatic and human supervisory level.

The data base and architecture consist of five major components: data sources, data transport, data integration, analytics, and optimization. In addition there are means for data distribution which includes publish-and-subscribe middleware, portals, and Web-based services [8].

CISCO has also contributed with its IP architecture. CISCO describes the smart grid as a data communication network integrated with the electrical grid that collects and analyzes data captured in near-real time about power transmission, distribution, and consumption. Predictive information and recommendations to stakeholders are developed based on the data for power management. Integration of the generation, transmission, distribution, and end user components is a critical feature.

There is no one acceptable or universal definition for the smart grid; rather it is function-selected. Below we give a working definition to encompass the key issues of stakeholders and developers.

1.11 WORKING DEFINITION OF THE SMART GRID BASED ON PERFORMANCE MEASURES

A working definition should include the following attributes:

- Assess grid health in real time
- Predict behavior, anticipate
- Adapt to new environments like distributed resources and renewable energy resources
- Handle stochastic demand and respond to smart appliances
- Provide self-correction, reconfiguration, and restoration
- Handle randomness of loads and market participants in real time
- Create more complex interactive behavior with intelligent devices, communication protocols, and standard and smart algorithms to improve smart communication and transportation systems.

In this environment, smart control strategies will handle congestion, instability, or reliability problems. The smart grid will be cyber-secure, resilient, and able to manage shock to ensure durability and reliability. Additional features include facilities for the integration of renewable and distribution resources, and obtaining information to and from renewable resources and plug-in hybrid vehicles. New interface technologies will make data flow patterns and information available to investors and entrepreneurs interested in creating goods and services.

Thus, the working definition becomes:

> *The smart grid is an advanced digital two-way power flow power system capable of self-healing, and adaptive, resilient, and sustainable, with foresight for prediction under different uncertainties. It is equipped for interoperability with present and future standards of components, devices, and systems that are cyber-secured against malicious attack.*

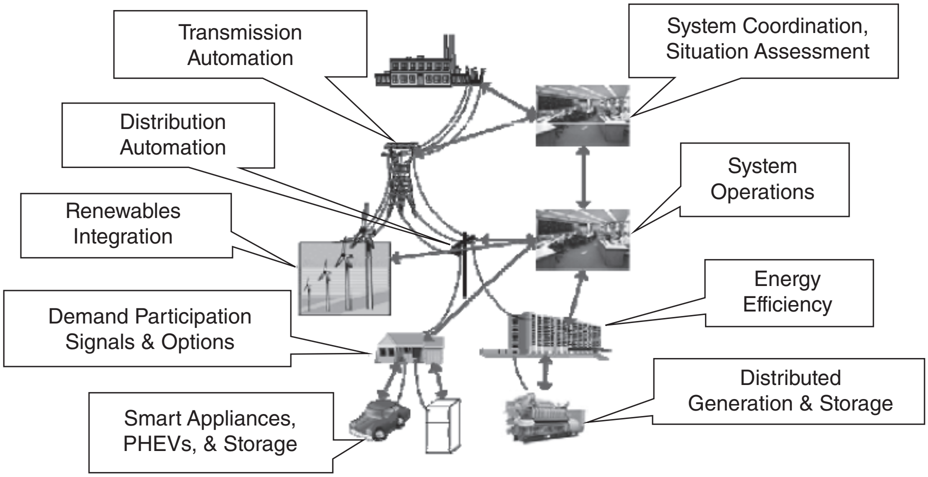

Figure 1.5. DOE representative architecture of the smart grid design (architecture 1).

It is enabled to perform with robust and affordable real-time measurements and enhanced communication technology for data/information transmission. It allows smart appliances and facilitates the deployment of advanced storage technologies including plug-in electric and hybrid vehicles and control options, and supports DSM and demand response schemes.

1.12 REPRESENTATIVE ARCHITECTURE

Several types of architecture have been proposed by the various bodies involved in smart grid development. We present two: one from the DOE and one illustrated by Figure 1.5, which shows how the DOE's proposed smart grid divides into nine areas: transmission automation, system coordination situation assessment, system operations, distribution automation, renewable integration, energy efficiency, distributed generation and storage, demand participation signals and options, and smart appliances, PHEVs, and storage.

Figure 1.6 shows how the second architectural framework is partitioned into subsystems with layers of intelligence and technology and new tools and innovations. It involves bulk power generation, transmission, distribution, and end user level of the electric power system. The function of each component is explained in the next section.

1.13 FUNCTIONS OF SMART GRID COMPONENTS

For the generation level of the power system, smart enhancements will extend from the technologies used to improve the stability and reliability of the generation to intelligent controls and the generation mix consisting of renewable resources.

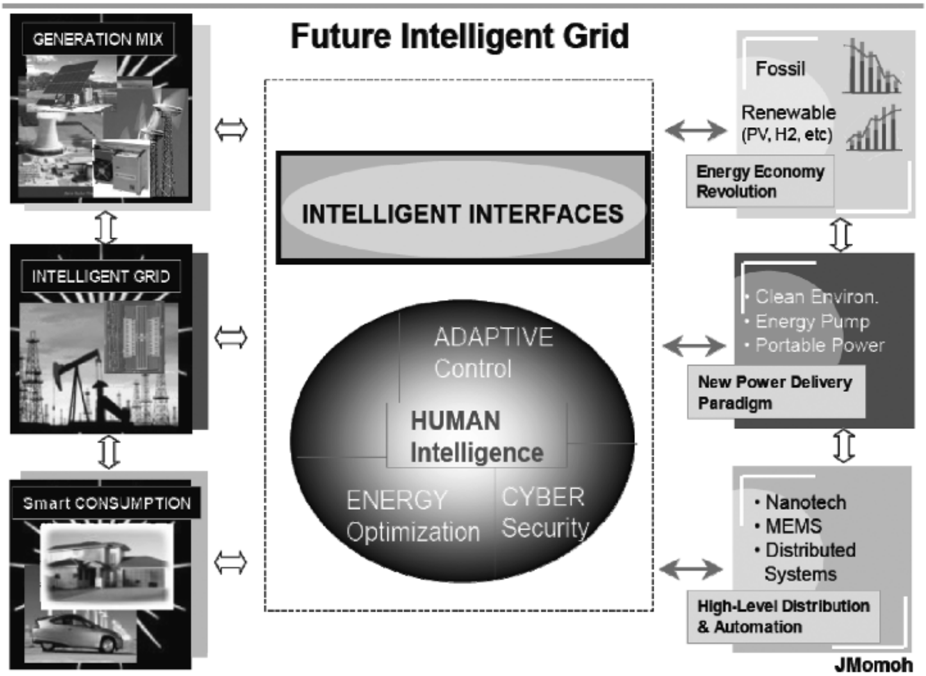

Figure 1.6. The intelligent grid (architecture 2).

1.13.1 Smart Devices Interface Component

Smart devices for monitoring and control form part of the generation components' real time information processes. These resources need to be seamlessly integrated in the operation of both centrally distributed and district energy systems.

1.13.2 Storage Component

Due to the variability of renewable energy and the disjoint between peak availability and peak consumption, it is important to find ways to store the generated energy for later use. Options for energy storage technologies include pumped hydro, advance batteries, flow batteries, compressed air, super-conducting magnetic energy storage, super-capacitors, and flywheels. Associated market mechanisms for handling renewable energy resources, distributed generation, environmental impact and pollution are other components necessary at the generation level.

Associated market mechanism for handling renewable energy resources, distributed generation, environmental impact and pollution has to be introduced in the design of smart grid component at the generation level.

1.13.3 Transmission Subsystem Component

The transmission system that interconnects all major substation and load centers is the backbone of an integrated power system. Efficiency and reliability at an affordable cost continue to be the ultimate aims of transmission planners and operators. Transmission lines must tolerate dynamic changes in load and contingency without service disruptions. To ensure performance, reliability and quality of supply standards are preferred following contingency. Strategies to achieve smart grid performance at the transmission level include the design of analytical tools and advanced technology with intelligence for performance analysis such as dynamic optimal power flow, robust state estimation, real-time stability assessment, and reliability and market simulation tools. Real-time monitoring based on PMU, state estimators sensors, and communication technologies are the transmission subsystem's intelligent enabling tools for developing smart transmission functionality.

1.13.4 Monitoring and Control Technology Component

Intelligent transmission systems/assets include a smart intelligent network, self-monitoring and self-healing, and the adaptability and predictability of generation and demand robust enough to handle congestion, instability, and reliability issues. This new resilient grid has to withstand shock (durability and reliability), and be reliable to provide real-time changes in its use.

1.13.5 Intelligent Grid Distribution Subsystem Component

The distribution system is the final stage in the transmission of power to end users. Primary feeders at this voltage level supply small industrial customers and secondary distribution feeders supply residential and commercial customers. At the distribution level, intelligent support schemes will have monitoring capabilities for automation using smart meters, communication links between consumers and utility control, energy management components, and AMI. The automation function will be equipped with self-learning capability, including modules for fault detection, voltage optimization and load transfer, automatic billing, restoration and feeder reconfiguration, and real-time pricing.

1.13.6 Demand Side Management Component

Demand side management options and energy efficiency options developed for effective means of modifying the consumer demand to cut operating expenses from expensive generators and defer capacity addition.

DSM options provide reduced emissions in fuel production, lower costs, and contribute to reliability of generation. These options have an overall impact on the utility load curve. A standard protocol for customer delivery with two-way information highway technologies as the enabler is needed. Plug-and-play, smart energy buildings and smart homes, demand-side meters, clean air requirements, and customer interfaces for better energy efficiency will be in place.

1.14 SUMMARY

This chapter has discussed the progress made by different stakeholders in the design and development of the smart grid. A working definition of the smart grid was given. Two design architectures and the specific aspects of prospective smart grid function were provided. The next chapters discuss the tools and techniques needed for smart grid analysis and development.

REFERENCES

[1] "The Smart Grid: An Introduction and Smart Grid System Report." Litos Strategic Communication, U.S. Department of Energy, 2009.

[2] L.D. Kinter-Meyer, M.C. Chassin, D.P. Kannberg, et al. "GridWiseTM: The Benefits of a Transformed Energy System." Pacific Northwest National Laboratory, PNNL-14396, 2003.

[3] "Overview of the Smart Grid: Policies, Initiatives and Needs." ISO New England, 2009.

[4] "The Modern Grid Initiative." GridWise Architecture Council, Pacific Northwest National Laboratory, 2008.

[5] "Our Blueprint for the Future." PEPCO Holdings, 2009.

[6] "PSERC Overview, 2008." PSERC, 2008.

[7] J. Taft. "The Intelligent Power Grid." *IBM Global Services*, 2006.

[8] "A National Vision for Electricity's Second 100 Years." Office of Electric Transmission and Distribution, U.S. Department of Energy, 2003.

SUGGESTED READINGS

American Recovery and Reinvestment Act of 2009. Public Law No. 111-5, 2009.

P. Van Doren and J. Taylor. "Rethinking Electricity Restructuring." *Policy Analysis* 2004, 530, 1–8.

EPRI Intelligrid. Electric Power Research Institute, 2001–2010.

"Smart Grid System Report." U.S. Department of Energy, 2009.

The Energy Independence and Security Act of 2007. S. 1419, 90d Congress, 2007.

"The Smart Grid: An Introduction and Smart Grid System Report." U.S. Department of Energy, 2009.