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Background of the Smart Grid

The world has been rapidly developing higher efficiency in many aspects. As one of these important aspects, power grids in many countries have been evolving from traditional power grids into *smart grids* in recent years. What is a smart grid? In this chapter, we will introduce the background of the smart grid, including its motivations, communication architecture, applications, and requirements.

1.1 Motivations and Objectives of the Smart Grid

The traditional power grid, or just “the grid,” is a network of transmission lines, substations, transformers, and more that delivers electricity from the power plant to consumers (e.g. your home, business, etc.). Our current power grid was built over a century ago. To move forward, we need a new kind of power grid that can automate and manage the increasing need for and complexity of delivering electricity. You may have heard of this new kind of power grid, which is called the *smart grid*. The smart grid is a revolutionary upgrade to the traditional power grid that adds communication capabilities, intelligence, and modern control [1–10]. The US Department of Energy (DoE), Office of Electricity Delivery & Energy Reliability has listed the benefits associated with the smart grid as follows [11]:

- More efficient transmission of electricity.
- Quicker restoration of electricity after power disturbances.
- Reduced operations and management costs for utilities and ultimately lower power costs for consumers.

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- Reduced peak demand, which will also help to reduce electricity rates.
- Increased integration of large-scale renewable energy systems.
- Better integration of customer-owner power generation systems, including renewable energy systems.
- Improved security.

We further summarize the benefits into three major motivations for the smart grid: 1) To better adapt renewable energy resources, 2) to increase the efficiency of grid operations and to reduce losses, and 3) to improve system reliability and security.

1.1.1 Better Renewable Energy Resource Adaption

In the current power grid, the majority of the power generation stations are based on fossil fuels (e.g. coal, natural gas, petroleum, etc.) [12]. While such power stations have supported civilization for over a century, we have come to realize the shortcomings and disadvantages of such power supplies. Since fossil fuel is limited resource, its ever-decreasing supply will ultimately affect the power stations. Moreover, the emission of greenhouse gases from those power stations has gradually contributed to global climate change, especially global warming. Therefore, cleaner energy resources and renewable energy resources have been deployed to the grid in the past few decades. Some examples of existing power stations using cleaner energy resources are hydropower, geothermal, etc.

The smart grid will include both central and distributed generation sources with a mix of dispatchable and nondispatchable resources, as illustrated in Figure 1.1. Despite their obvious benefits, renewable sources other than hydropower provide only about 5% of the electricity supply for our grid. What's holding us back is not the amount of electricity we can generate from those renewable resources but the power grid itself. Due to the remote locations of most renewable resources, extra infrastructure is required to deliver electricity to consumers, who are mostly in urban areas. Moreover, the current power grid has difficulty accommodating renewable sources of power due to their unpredictability. The smart grid will have much better control systems to manage those renewable energy resources to supplement existing fossil-fuel power stations. For example, the smart grid will give grid operators new tools to reduce power demand

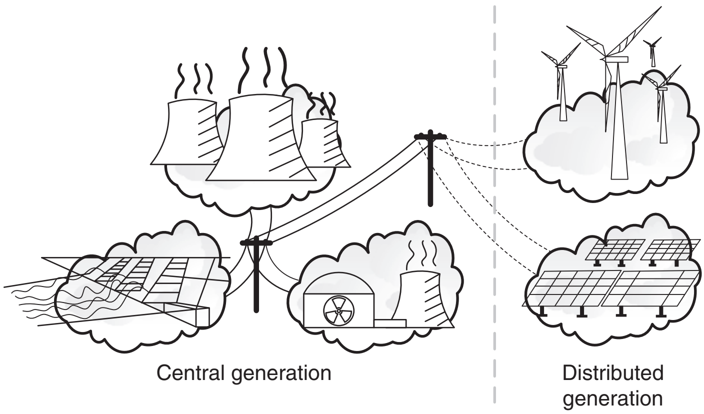

Figure 1.1 Dispatchable renewable resources.

quickly when the level of wind or solar power dips, and it will have more energy storage capabilities to absorb excess wind and solar power when it isn't needed, then to release that energy when the level of wind and solar power dips.

1.1.2 Grid Operation Efficiency Advancement

The smart grid is able to increase the efficiency of the grid operations while reducing losses because of its advanced monitoring and controlling systems. In the current power grid, the pricing of electricity is based on peak and off-peak demand. The price of electricity during peak hours is higher than during off-peak hours. For some consumers, the higher price may be a few times more than the lower one. The uneven pricing of electricity is due to the dynamic cost of power generation, especially in fossil-fuel-based power stations. It is costlier per unit to generate electricity for periods of higher demand. Furthermore, the transition process from high demand to low demand (or vice versa) cannot happen instantly, which results in a large amount of fuel waste in power stations and extra greenhouse gas emission. Even worse, the extra cost due to inefficient grid operation is distributed to consumers. With the advent of electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs), the electricity requirement of the power grid will increase immensely [13, 14]. Peak and off-peak hours may have a more complicated and dynamic pattern in the future.

The solution provided in the smart grid is demand response, which can be applied to balance the supply and demand of electricity. Electricity usage during peak periods can be reduced or shifted in response to time-based rates and other forms of financial incentives. As a result, the power load is smoother in the smart grid, without sudden transitions. Thus the efficiency of the fossil-fuel power stations can be increased dramatically. Moreover, losses caused by energy theft, system failure, and other factors can be reduced in the smart grid because of the accurate and reliable automated monitoring systems [15, 16]. At first glance, such features enabled by the smart grid involve sacrifice on the part of consumers. Fortunately, consumers have opportunities to earn savings on their electricity bills in return. In addition to the pricing difference between peak and off-peak hours, the smart grid will allow utilities to launch more sophisticated programs as incentives. For example, some utilities may offer credits if consumers will allow a central office to control cycling their air conditioners on and off during times of peak power demand.

Consumers will use the grid in different ways. More consumers will become “prosumers”-both consumers and producers of energy [17]. Power will flow both ways, and other ancillary services may also be provided by these new prosumers. Some utilities even purchase back electricity generated by consumers. In theory, some consumers may receive checks from utilities, which could only happen in the smart grid. On top of potential savings, the smart grid offers consumers active control of their energy bills, allowing them to opt in and out of the demand response program; thus customer experience could be enhanced from just one-way communication.

1.1.3 Grid Reliability and Security Improvement

The current power grid has been improved quite a lot decade by decade in terms of reliability and security; however, blackouts still occur once or twice each year. The notorious blackout on Aug. 14, 2003 in parts of America and Canada affected 45 million people in the United States and 10 million people in Canada. The blackout was triggered by a relatively insignificant but overheated power line. In the smart grid, many intelligent sensors and actuators are deployed to monitor and control the grid’s transmission system in real time [18–21]. New technologies in the smart grid, such as phasor measurement units (PMU), sample voltage and current many times per second, as opposed to once every few seconds in the current power grid. On systems equipped with smart grid communications technologies, system failure and hazardous situations can be reported to control centers promptly for fast reaction. As a result, distribution outages will be reduced in the smart grid. It would have been easier to detect the types of oscillations that led to the 2003 blackout in the smart grid. Moreover, advanced and comprehensive cybersecurity is provided in the smart grid communication infrastructures. Therefore, system reliability and security in the smart grid are greatly improved compared to the traditional power grid. However, the system will be even more complex.

With all of the new entities and energy resources, managing and optimizing the system will become increasingly challenging. Based on the aforementioned motivations, research and practical deployment in the smart grid need to achieve the objectives shown in the following list:

1) The smart grid needs to be adaptive to changing situations and able to self-heal when some system failures occur.
2) Customers are actively involved in the smart grid, based on dynamic pricing and other incentive programs.
3) The smart grid needs to increase the efficiency of grid operations while reducing losses.
4) The smart grid needs to be able to handle the integration of a large variety of generation options.

In order to achieve those objectives, it is necessary to develop and deploy communication infrastructures and advanced monitoring and control systems with cutting-edge technologies in the smart grid.

1.2 Smart Grid Communications Architecture

Its special publication *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0* [22], the National Institute of Standards and Technology (NIST) has defined that the smart grid is a complex cyber-physical system that must support 1) devices and systems developed independently by many different solution providers; 2) different utilities; 3) millions of industrial, business, and residential customers; and 4) different regulatory environments.

1.2.1 Conceptual Domain Model

A conceptual domain model was published in the NIST special publication to support planning, requirements development, documentation, and organization of the increasingly diverse collection of interconnected networks and equipment that will compose the smart grid, as illustrated in Figure 1.2. The NIST divides the smart grid into seven domains. Their roles and services in the smart grid conceptual model are described as follows:

1) **Customers**: the end users of electricity. May also generate, store, and manage the use of energy. Traditionally, three customer types are discussed, each with its own domain: residential, commercial, and industrial.
2) **Markets**: the operators of and participants in electricity markets.
3) **Service providers**: The organizations providing services to customers and to utilities.
4) **Operations**: the managers of the movement of electricity.
5) **Generation**: the generators of electricity. May also store energy for later distribution. This domain includes traditional sources (traditionally referred to as generation) and distributed energy resources (DER). At a logical level, "generation" includes coal, nuclear, and large-scale hydro generation systems that are usually

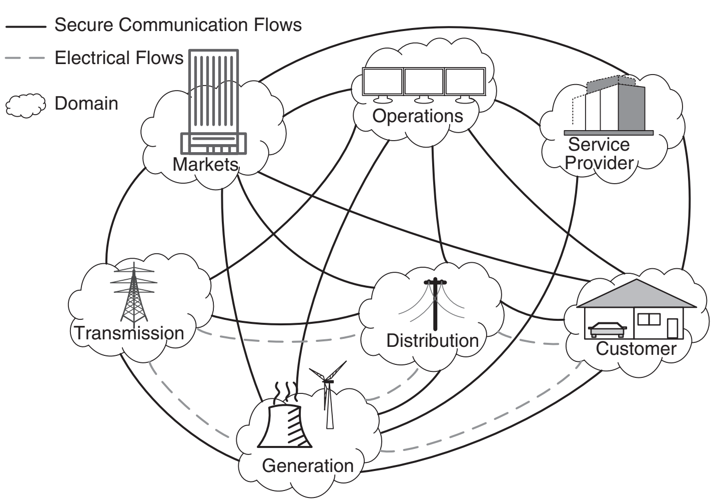

Figure 1.2 NIST conceptual domain model for the smart grid.

attached to transmission. Generation is associated with customer and distribution-domain-provided generation and storage and with service-provider-aggregated energy resources.
6) **Transmission**: the carriers of bulk electricity over long distances. May also store and generate electricity.
7) **Distribution**: the distributors of electricity to and from customers. May also store and generate electricity.

Each of the seven domains is a high-level grouping of physical entities that rely on or participate in similar types of services. In general, roles in the same domain have similar objectives. However, communications within the same domain may have different characteristics and may have to meet different requirements to achieve interoperability. The roles in a particular domain interact with roles in other domains to achieve interoperability.

1.2.2 Two-Way Communications Network

The interoperability that can be achieved in the NIST conceptual model for the smart grid is achieved by the secure communication flows that interconnect all seven domains. Generally speaking, it is a two-way communications network between utilities and customers. A high-level illustration of the smart grid communications network is shown in Figure 1.3. As it shows, the communications network in the smart grid consists of different types of networks and communication technologies that can be categorized into home-area networks (HAN), neighborhood-area networks (NAN), and wide-area networks (WAN).

- **Home-Area Networks in the Smart Grid**
  A HAN enables secure communication flows within a household. A gateway (usually a smart meter and a data aggregate unit) bridges a HAN to a NAN. Readers may have heard of the smart home that

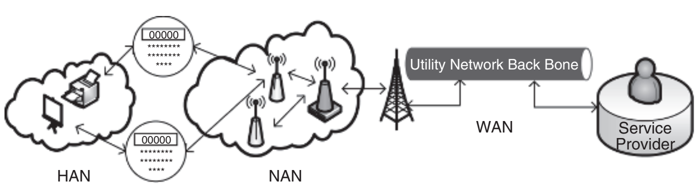

Figure 1.3 High-level illustration of the smart grid communication architecture.

can be achieved with intelligent and remote control. Note that a HAN in the smart grid communications network serves a different purpose than a smart home network. A smart grid HAN is part of the utilities' infrastructure that may or may not have Internet access. Even customers in the household may not have direct access to the network. The network that enables a smart home is owned by the customers and usually has Internet access; for example, a home Wi-Fi system. We are not ruling out the possibility that a smart grid HAN may merge with a smart home network in the future, especially when the Internet of Things and public Internet access will gain the support of utilities.

- **Neighborhood-Area Networks**
  A NAN is also referred to as the *last-mile* network to the customer side. It enables the secure flow of communication between households and the utilities' backbone network. Some existing NANs are composed of smart meters only, while others may utilize dedicated data aggregate units for relay. In either case, a smart meter is the gateway of a HAN that monitors and controls electricity consumption within that household. Through NANs and HANs, the smart grid achieves direct communications between customers and utilities. The communications are not only for metering and billing, but they also carry critical information for demand response, which actively controls the power load of some customers.
- **Wide-Area Networks**
  Utilities have their backbone network infrastructure that connects all major components, such as substations, power stations, and operation centers. This backbone network infrastructure is upgraded and reused as the WAN in the smart grid. The current power grid has applied power line carriers (PLC) for data communications for many years, especially in remote areas. Although the technology theoretically achieves wide area coverage, other communication technologies, such as fiber optics and cellular networks, are deployed to the smart grid to improve the WAN.

The three types of networks are named after their coverage. Nonetheless, their roles and services are vastly different; thus the communication technologies applied to each of the three types of network are based on their specific requirements. For example, a WAN is required to be high-speed, reliable, and secure while covering long-distance communications. Utilities have already deployed high-speed backhaul networks (also known as communication core networks) alongside most of their power transmission lines. The backhaul networks consist of optical fiber and Ethernet. PLCs [23, 24] are also applied in some areas to provide wide area communications. Most of PLC-based WANs are deployed for monitoring purposes instead of large data communications [23, 24]. Cellular communication technologies are also deployed as WANs for similar purposes. NANs and HANs are last-mile connections to customers [25, 26]. They are required to be low profile, low cost, reliable, and secure while providing enough bandwidth to meet latency requirements. In NANs and HANs, wireless communication technologies are preferred due to their flexibility and low-cost deployment. Wireless technologies for longer distance transmission, such as GPRS, WiMAX, and LTE, are promoted for communications between NANs and concentrators that connect to the backhaul network. Several wireless technologies for local-area networks, including Wi-Fi, Zigbee, and Bluetooth, are promoted for HANs and intracommuncations in NANs.

1.3 Applications and Requirements

In order to achieve the objectives of the smart grid, several important applications must be added to or upgraded in the current power grid. The most important applications and requirements include demand response, advanced metering infrastructure, wide-area situational awareness and wide-area monitoring systems, and communication networks and cybersecurity.

1.3.1 Demand Response

Demand response (DR) has been mentioned in earlier sections. It is the key component applied to the smart grid that can smooth the power load of the grid [27–30]. A smoother load may not necessarily reduce power consumption. It aims to decrease the gap between peak and off-peak grid loads and ease the transition process between high and low power demand, as shown in Figure 1.4. Maintaining a relatively steady power load would increase operational efficiency of renewable resources, as utilities worry only about a total demand that is given in advance. Fewer transition processes with less fluctuation would greatly reduce fossil-fuel waste and greenhouse gas emission from those types of power stations.

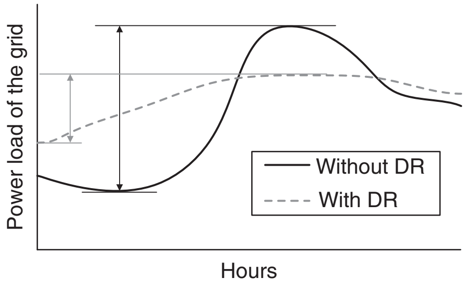

Figure 1.4 Smoother power load achieved by DR.

There are generally two ways to apply DR. One is direct load control from utilities, while the other is to actively involve customers by utilizing mechanisms and incentives. Both approaches have the goal of shifting some of the power demand from peak hours to off-peak hours. Direct load control can be implemented if consumers such as large business, government buildings, and some factories are willing to participate. Residential customers, on the other hand, may not be willing to give away their own control. Dynamic pricing motivates those types of customers in the smart grid. Generally speaking, electricity pricing is higher during peak hours. Customers adaptively control their appliances so that they can lower their bills. The incentive mechanisms are more complex than just a load shift in the smart grid. For example, in the past, the hours of 11 a.m. and 6 p.m. were set as off-peak hours in California with lower tariffs. However, the peak hours have shifted and extended over the years. Incentive mechanisms for DR in the smart grid need to accommodate these dynamic changes in a timely fashion.

1.3.2 Advanced Metering Infrastructure

Utilities and grid operators in the smart grid need to predict conditions in close to real time with sophisticated modeling and state estimation capabilities. Doing this will allow for more efficient dispatch and system balancing. This capability relies on advanced metering infrastructure (AMI) that carries near real-time data in the smart grid. Defined by the US DoE, AMI is an integrated system of smart meters, communications networks, and data management systems that enables two-way communication between utilities and customers, as shown in Figure 1.5. Customer systems include in-home displays, home-area networks, energy management systems,

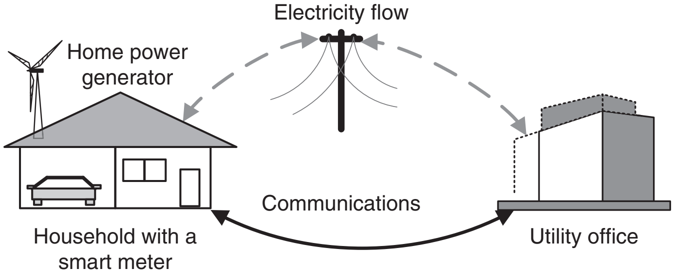

Figure 1.5 High-level illustration of AMI.

and other customer-side-of-the-meter equipment that enable smart grid functions in residential, commercial, and industrial facilities.

AMI is an ideal application of machine-to-machine (M2M) communications [31, 32] that achieves two-way communication between customers (through smart meters) and utilities [10, 33–36]. AMI equips each customer with a smart meter, whose basic function is to gather the energy consumption status and upload the information to the control center (also known as the power distributor or service provider). A smart meter is also capable of receiving control information (e.g. electricity pricing/tariff) from the control center. Such a two-way information exchange is near real-time. The information and control needed to implement residential demand response relies significantly on the development of AMI. AMI deployment in the smart grid will benefit both system operation and customer service.

1.3.3 Wide-Area Situational Awareness and Wide-Area Monitoring Systems

Wide-area situational awareness (WASA) and wide area monitoring systems (WAMS) in the smart grid monitor the status of power-system components over large geographic areas in near real time. The advanced monitoring system improves visibility and understanding of stresses in the power system and detects transient behavior that is not detected with traditional supervisory control and data acquisition (SCADA) systems.

As shown in Fig. 1.6, many types of intelligent electronic devices (IEDs) are deployed in the monitoring and control system, such as synchronized phasor measurement units (PMUs), phasor data concentrators (PDCs), circuit break monitors, solar flare detectors, etc. [37–42].

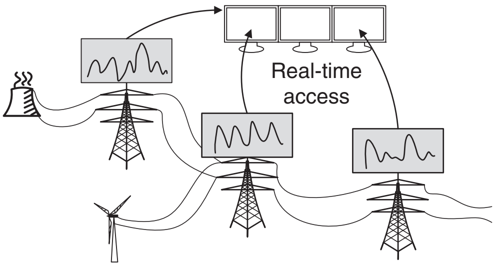

Figure 1.6 High-level illustration of the monitoring system.

Management of power-network components can be better achieved with the monitoring and control system. A system failure or a blackout can be ultimately anticipated, prevented, or quickly recovered from. While being considered a stand-alone system, the monitoring system is a composite of SCADA, AMI, energy management systems (EMS), and other systems in the smart grid that provides near real-time monitoring and control of the grid.

1.3.4 Communication Networks and Cybersecurity

The smart grid has a complicated and advanced communication infrastructure that may involve both private and public networks. In order to achieve interoperability between different domains, various types of communication technologies, including both wired and wireless technologies, are needed to support the infrastructure.

As mentioned earlier, the utility backbone network is mostly a private network deployed by utilities and grid operators, using fiber optics and Ethernet to meet the requirement of fast and reliable data delivery. Other parts of the communication infrastructure may not have fiber optics support, due to high cost of its development, implementation, and maintenance. For example, the "last mile" in AMI can be deployed with wireless technologies. A HAN may be supported by ZigBee, Wi-Fi, and other local area wireless technologies. A NAN may be supported by WiMAX, multihop Wi-Fi, etc. Communications in the smart grid monitoring system may be achieved by cellular networks or PLC. The exchange of information between the transmission and distribution systems will be automated and optimized by the development of standard data structures. Techniques from big data analytics and cloud computing will play a critical role in leveraging exponential growth in data.

With all those types of communication technologies and data involved, cybersecurity and control of access to the communication networks are critical issues to the smart grid [4, 43, 44]. Cybersecurity needs to be designed into the new systems that support the smart grid without impacting operations. In addition to the protection of information from traditional cyberattacks, smart grid cybersecurity must expand it focus to address the combination of information technology, industrial control systems, communication systems, and their integration with physical equipment and resources to maintain the security of the grid and to protect the privacy of consumers.

1.4 The Rest of the Book

In the rest of this book, we will explore some of the major topics in smart grid communication infrastructures and provide our solutions and suggestions. Some of the highlights are as follows:

- The overall communication infrastructures in the smart grid are studied.
- A complete information and communication technologies framework for the smart grid is proposed.
- The communication networks of the advanced metering infrastructure are studied.
  - A self-sustaining neighborhood-area network design is proposed.
  - An efficient power control scheme for the proposed network design is proposed.
- Demand response is studied, based on the communication infrastructures.
- Big data analytics and cloud computing are introduced into the smart grid communications to enhance grid operations and control.
- Network security is studied for smart grid communications.
  - Security schemes are proposed for communications in the advanced metering infrastructure.
  - ID-based security schemes are proposed for transmission over the Internet in the smart grid.