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Excerpt
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Part I

Communication architectures and models for smart grid

1 Communication networks in smart grid: an architectural view

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1.1 Introduction

The existing electrical grid needs to be smarter in order to provide an economical, reliable, and sustainable supply of electricity [1]. Although the current electrical grid has served well in providing the necessary power supply of electricity, the growing demand, fast depletion of primary energy resources, unreliability, and impact on the environment must be responded to in a vision of the future [2]. This vision is being realized using *smart grid*, which is a user-centric system that will elevate the conventional electrical grid system to one that functions more cooperatively, responsively, economically, and organically [1].

One of the most important features of smart grid technology that makes it smart or smarter than the current grid is the integration of bi-directional flow of information along with electricity, which can be used to provide effective and controlled power generation and consumption [3]. This two-way flow of information in turn enables active participation of consumers, thus empowering them to control and manage their own electricity usage by providing near real-time information on their electric consumption and associated cost. Due to this overlaid communication infrastructure, smart grid will incorporate into the grid the benefits of distributed computing and communications, which would provide the necessary intelligence to instantaneously balance the supply and demand at the device level. Clearly, modern communication and information technology will play an important role in managing, controlling, and optimizing different functional and smart devices and systems in a smart grid. A flexible framework is required to ensure the collection of timely and accurate information from various aspects of generation, transmission, distribution, and user networks to provide continuous and reliable operation [4]. Therefore, the existing and future data communications protocols will have to evolve with the developing smart grid taking into consideration the characteristics of the electrical systems.

The transition to smart grid will require considering and modifying many components and technologies of the current electrical grid. A proper vision could be to understand the specific requirements and characteristics of this future grid. This vision will not only help to identify different inefficiencies in the current electrical grid, but also help to set the required foundation for the transition. The main characteristics and benefits of smart grid are summarized in Table 1.1 [5].

Table 1.1. Smart grid characteristics and benefits

Characteristic	Benefits
1. Self-healing	Capability to rapidly detect, analyse, respond, and restore from fault and failures
2. Consumer friendly	Ability to involve a consumer in the decision process of electrical power grid
3. High reliability and power quality	Ability to supply continuous power to satisfy consumer needs
4. Resistance to cyber attacks	Ability to be immune and to protect the system from any cyber and physical attacks
5. Accommodates all generation and storage options	Ability to adapt to a large number of diverse distributed generation (e.g., wind energy and renewable energy) and storage devices deployed to complement the large power generating plants
6. Optimization of asset and operation	Ability to monitor and optimize the capital assets by minimizing operation and maintenance expenses
7. Enables markets	Offering new consumer choices such as green power products and new generations of electric vehicles, which lead to reduction in transmission congestion

With smart grid, a number of technical and procedural challenges emerge [6]. On the technical side, for example, communication systems must be secured and reliable enough to handle different and new media technologies as they emerge. In addition, smart equipment (e.g., computer-based or microprocessor-based) and data-management techniques must be robust and scalable to handle any existing and future applications. Finally, the new smart grid technologies must be interoperable with the existing electrical grid. On the procedural side, efforts to establish the interoperability framework must consider a broad set of smart grid stakeholders, as every person and business will be affected by this technology. Thus, the shift towards smart grid will be an evolutionary process such that it will follow incremental development. Action plans should be developed to align all the stakeholders of smart grid, from researcher to industry to government, in a direction that ensures an orderly transition to visionary smart grid [7].

In this chapter, we provide a comprehensive study on the importance of communication infrastructure and networking in smart grid. Section 1.2 reviews the conceptual model for smart grid. Section 1.3 describes the importance of communication infrastructure in an attempt to provide better understanding of smart grid hierarchical landscape and its association with the conceptual model. Section 1.4 describes the interoperability issues in smart grid, the GridWise interoperability context-setting framework, and its association with the Open Systems Interconnection (OSI) 7-layer communication model. Section 1.5 outlines the role of communication infrastructure in various stages of smart grid, and provides an overview of the existing communication technologies. The importance of security and privacy is summarized in Section 1.6. Section 1.7 highlights some of the critical issues that still need further investigation. Section 1.8 concludes the chapter.

1.2 Smart grid conceptual model

This chapter considers the smart grid conceptual model adopted by the National Institute of Standards and Technology (NIST) [3], which is followed by many standards such as the Electrical Power Research Institute (EPRI) [8], European Commission Research (ECR) [2], and International Electrotechnical Commission (IEC) [9] as the basis for describing, discussing, and developing the final architecture of the smart grid. The conceptual model not only identifies different smart grid stakeholders, but also provides various electrical and communication interfaces required to understand various interoperability frameworks. For this purpose, NIST has divided the smart grid into seven domains, as shown in Figure 1.1 and described in Table 1.2.

Each domain is comprised of a group of *actors* and *applications*, as shown in Figure 1.1. The actors are typically devices, systems, or programs that make decisions and exchange information through a variety of interfaces in order to perform applications and processes [3]. The applications are various tasks performed by an actor or actors within a certain domain. The domains are able to communicate with one another via communication interfaces, as shown in Figure 1.1 and Table 1.2. This communication

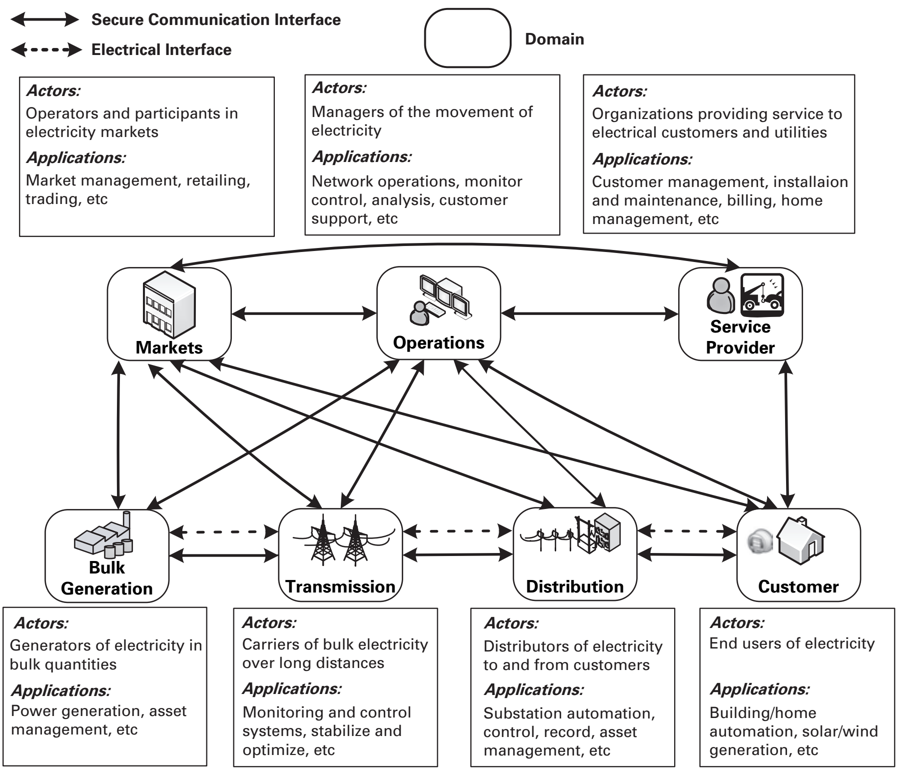

Figure 1.1 Smart grid conceptual model showing interactions among different smart grid domains through secure communication and electrical interfaces.

Table 1.2. Smart grid domains and the associated communication and electrical interfaces with typical applications

Domain	Communication interface	Electrical interface
Customer	Distribution, markets, operations, service provider	Distribution
Distribution	Customer, transmission, market, operations	Customer and transmission
Transmission	Distribution, bulk generation, markets, operators	Bulk generation and distribution
Bulk generation	Transmission, markets, operations	Transmission
Markets	Customer, distribution, transmission, bulk generation, operations, service providers	None
Operations	Customer, distribution, transmission, markets, service providers	None
Service providers	Customer, markets, operations	None

is critical to the overall interoperability of the smart grid, allowing it to collectively generate and distribute electricity efficiently based on the input from all domains.

1.3 Smart grid communication infrastructures

A smart grid can be considered as a network of many systems and subsystems which are interconnected intelligently to provide cost-effective and reliable energy supply for increasing demand response [3]. Moreover, smart grid will be achieved by overlaying the communication infrastructure with an electrical system infrastructure. The application of advanced communication techniques is expected to greatly improve the reliability, security, interoperability, and efficiency of the electrical grid, while reducing environmental impacts and promoting economic growth [3]. Furthermore, in order to achieve enhanced connectivity and interoperability, smart grid will require open-system architecture as an integration platform, and commonly shared technical standards and protocols for communications, and information systems to operate seamlessly among the vast number of smart devices and systems. This makes it hard to realize a single and composite architecture. In fact, smart grid can contain many system architectures developed independently or in association with other systems.

Figure 1.2 shows a hierarchical overview of the smart grid landscape, its relation to NIST domains, and associated examples of components and technologies. Ideally, each of the domains, members, and technologies would interact with each other to provide any of the smart grid's business, technological, and societal goals [10].

This interaction is made possible using *advanced metering infrastructure* (AMI), which will act as the gateway for access, enabling the bi-directional flow of information and power in support of distributed energy resource (DER) management or distributed generation (DG) and consumer participation [1]. There is no standard document defining

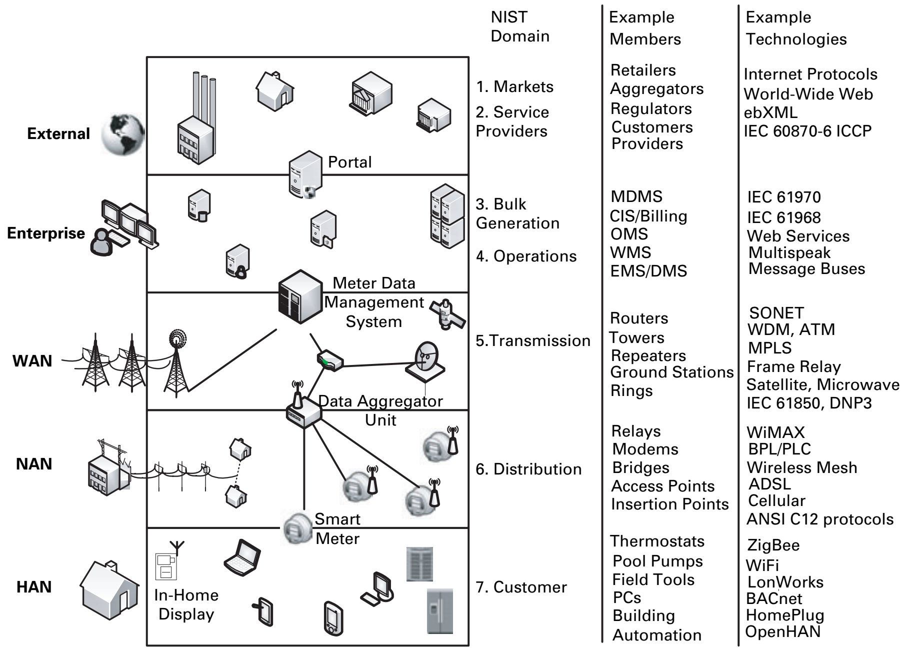

Figure 1.2 Hierarchical overview of smart grid communication infrastructure.

AMI, and it is still open to new development and implementation. Some efforts have been made on behalf of the New York State Electric and Gas Company (NYSEG) [11] to define the system. Following the NYSEG architecture, an AMI consists of several different components such as smart meter, hierarchical networks, and other subsystems shown in Figure 1.2.

The most important requirement of AMI is to provide near real-time metering data including fault and outage to the utility control centre. For this, smart meter will be an integral part of AMI which will support efficient outage management, dynamic rate structures, customer billing, and also demand response for load control [11]. Further, AMI will include a hierarchical network or a multi-tier architecture with star and mesh topologies and a variety of communications technologies such as power-line communication (e.g., broadband over power line (BPL)), cellular network (e.g., GSM and CDMA), other wireless technologies (e.g., Wi-Fi, ZigBee, and worldwide interoperability for microwave access (WiMAX)), and Internet Protocol (IP)-based networks. AMI will comprise local data aggregator units (DAUs) to collect and relay the information from the smart meter to the meter data-management system (MDMS). MDMS will provide storage, management, and processing of meter data for proper usage by other power system applications and services. Also, many systems and subsystems such as wide-area measurement systems (WAMSs), sensor and actuator networks (SANETs) will be grouped under a hierarchical structure based on home-area networks (HANs), neighbourhood-area networks (NANs), and wide-area networks (WANs).

1.3.1 Home-area networks (HANs)

A HAN (sometimes referred to as a premise-area network (PAN) or a building-area network (BAN)) is an important and the smallest subsystem in the hierarchical chain of smart grid as shown in Figure 1.2 [12]. HAN provides a dedicated demand-side management (DSM), including energy efficiency management and demand response by proactive involvement of power users and consumers [3]. HAN consists of smart devices with sensors and actuators, in-home display, smart meter, and home energy-management system (HEMS). HEMS helps to manage the energy consumption in the household.

The HAN communicates with different smart devices using wireline technologies including power-line communication (PLC), or BACnet protocol [13], and wireless technologies (e.g., Wi-Fi and ZigBee [14]). Wireless technology such as ZigBee is becoming a popular choice in contrast to wireline technology due to its low installation cost and better control and flexibility. ZigBee is an open-standard low-power wireless protocol and by far the most popular IEEE 802.15.4 networking standard that meets most of the criteria defined in the OpenHAN system requirement specification (SRS) [15]. The OpenHAN SRS is formed by the OpenAMI task force under the UCA International Users Group (UCAIug) [16] to facilitate interconnection among various appliances in HAN as well as with external networks (e.g., neighbourhood-area network or NAN) using energy service interface (ESI). This ESI acts as a gateway for connecting HAN with other external networks and thus can be referred to as a HAN gateway.

1.3.2 Neighbourhood-area networks (NANs)

A NAN connects multiple HANs and one or more networks between the individual service connections for distribution of electricity and information. As shown in Figure 1.2, all the data from HAN are collected to the data-aggregator unit (DAU). The NAN consists of HAN with smart meters to provide secure and seamless control of different home appliances. DAU consists of a NAN gateway to interface with the HAN and also with the WAN. The DAU communicates with the HAN gateway using network technologies such as PLC, ANSI C12 protocols, WiMAX, or ZigBee. The NAN acts as an access network to forward customer data to the utility local office [15].

1.3.3 Wide-area networks (WANs)

A WAN connects multiple distribution systems together and acts as a bridge between NANs and HANs and the utility network. As shown in Figure 1.2, WAN provides a backhaul for connecting the utility company to the customer premises. In this case, a backhaul can adopt a variety of technologies (e.g., Ethernet, cellular network, or broadband access) to transfer the information extracted from the NAN to the utility local offices [15]. A WAN gateway can use broadband connection (e.g., satellite) or possibly an IP-based network (e.g., MPLS and DNP3) to provide an access for the utility offices to collect the required data. Since information privacy and reliability are the major concerns for the customer, security and fault tolerance of these communication technologies are crucial issues.

1.3.4 Enterprise

Enterprise is the higher-level entity in the smart grid hierarchy which is responsible for processing and analysing all the data collected from various hierarchy levels as shown in Figure 1.2. These distribution systems consist of measurement systems (e.g., supervisory control and data acquisition (SCADA) and wide-area measurement system (WAMS)) to monitor and control the entire electrical grid. WAMS consists of a control centre, phasor measurement units (PMUs), and phasor data collectors (PDCs). The information is acquired synchronously using a global positioning system (GPS)-enabled PMU or synchrophasor which measures the electrical waves on an electrical grid to determine the status of the system. WAMS can be considered as a synchronous version of the conventional SCADA system to collect information about different system components in the power grid. PMU is considered to be one of the most important measuring devices in future power systems [17]. The PDC and PMU are connected in a star network topology, whereas the control centre is connected to the PDC using a wide-area network (e.g., synchronous digital hierarchy (SDH)) [18]. Various applications such as meter data-management system (MDMS), outage-management system (OMS), energy-management system (EMS), distribution-management system (DMS), customer-information system (CIS), and billing are performed at this level.

1.3.5 External

All the retailers, regulators, and providers related to price exchanges, supply and demand support the business process of the electrical system comprising the external level. Communication to and from the external market and service providers should be reliable to match electric production with consumption. Also, various business processes such as billing and customer account management help to enhance customer services, such as the management of energy use and home energy generation. This external level provides new and innovative services and products to meet the new requirements and opportunities provided by the evolving smart grid.

1.4 Interoperability issues

Smart grid will be an interoperable system since it will constitute various communication networks and systems [3]. In this context, interoperability becomes a crucial issue, which allows the information and infrastructure to come together into an interoperable and integrated system for information to flow and be exchanged without user intervention. The most important objective of interoperability is to provide plug-and-play capability, where the component/system automatically configures itself and begins to operate by simply plugging into the main system. Although the concept is simple, achieving plug-and-play capability is not easy and in many situations becomes complex and rather impractical to specify a standard interface between two different systems. For example, consider specifying a customer interface to HEMS. HEMS may use different software tools and protocols to manage the energy consumption in the household. Conventionally, integrating these software tools and protocols will require some manual changes and upgrades so that the interface agreements can be satisfied. Moreover, the interoperability issue increases as the effort to make and test these changes increases. However, standards or best practices such as using a common semantic model (e.g., XML) that a community of system integrators readily understand can decrease the interoperability problems. Thus, by reaching agreements in a specific area of interoperation, a community can improve system integration and effort to achieve interoperation to some extent.

Improving interoperability not only reduces installation and integration costs, but also provides well-defined points in a system in which this interoperability allows for new automation components to connect to the existing system. This can enable substitutability where one automated component can be substituted by other components with a reasonable amount of effort such that the overall integrity of the system is preserved. This substitutability characteristic will provide necessary scalability to the electrical system such that it can evolve to satisfy changing resources, demands, and more efficient technologies. In order to visualize the necessary interoperability issues, this chapter follows the high-level categorization approach developed by the GridWise Architecture Council (GWAC) [19]. Referred to as the *GWAC stack*, the GridWise interoperability context-setting framework identifies eight interoperability categories that are relevant to integration and interoperation of different systems in smart grid. The *GWAC stack* groups these eight categories into three broad types as follows [19]:

- *Organizational* emphasizes the pragmatic (business and policy) aspects of interoperation, those pertaining to the management of electricity. Three layers, namely economic/regulatory policy, business objectives, and business procedures form this category.
- *Informational* emphasizes the semantic aspects of interoperation, focusing on what information is exchanged and its meaning. Business context and semantic understanding layers form this group.
- *Technical* emphasizes the syntax or format of the information, focusing on how information is represented within a message exchange and on the communication medium. Syntactic interoperability, network interoperability, and basic connectivity layers form this group.

The most important feature of the *GWAC stack* is that each layer defines a specific interoperability issue such that establishing interoperability at one layer can enable flexibility at other layers. This means that each layer depends upon, and is enabled by, the layer below it. This chapter focuses on the technical driver and its associated layers, which define the communication networking and syntax issues of smart grid interoperability. Figure 1.3 shows the association of the GWAC stack technical driver with the layers in the Open Systems Interconnection (OSI) 7-layer communication model [20],