Part One

Electric Power Systems: The Main Component

1

Introduction to Power Systems Before Smart Grid

> This ‘telephone’ has too many shortcomings to be seriously considered as a means of communication. The device is inherently of no value to us.
>
> —Western Union internal memo, 1876

> Those who say it cannot be done should not interfere with those of us who are doing it.
>
> —S. Hickman

1.1 Overview

Power systems and communications are close cousins. This may not be apparent at first, but that is how we will generally view these twin subtopics of electrical engineering. Communications and power systems are the same field with a different emphasis. Both transmit power. Communications seek to minimize power and maximize information content. Power systems seek to maximize power and minimize information content. It is particularly interesting to see what happens when these fields physically come together in technologies such as a power line carrier and wireless power transmission. In a power line carrier, communication attempts to become physically similar to power, following the same conductive path. In wireless power transmission, power seeks to become physically similar to wireless communication, propagating through space similar to wireless communication. It is at these intersections of communication and power systems that the differences between the two fields comes into sharpest contrast. The initial hyperbole regarding the fundamental shift in power systems toward what is being labeled as the “smart grid” will have died down or disappeared altogether by the time the reader has this book in hand. However, the technological change that initiated the smart grid established a platform that will enable revolutionary enhancements in intelligence for power systems. Our goal is to explore both the theoretical and technological underpinnings of this shift in power systems, focusing upon the incorporation of communications and networking technology. There are those who suggest that the integration of communications into the power

Smart Grid: Communication-Enabled Intelligence for the Electric Power Grid, First Edition. Stephen F. Bush.

grid will enable a revolution in electric power distribution, perhaps thinking of the analogy with the explosive growth of the Internet in the 1990s. The simple act of providing data interconnections (for example, via the Internet, cell phone, and other portable computing devices) has spawned new applications, ideas, and solutions that no one could have predicted. Communications in the power grid may indeed enable new and unforeseen applications in power systems. At the same time, we should temper our enthusiasm by noting that communications have already been part of the power grid for over a century, as we will see later.

As a motivation for smart grids, it has often been stated that power systems have evolved slowly while communication and networking have advanced much more rapidly: Alexander Graham Bell would not recognize the phone system of today, whereas Thomas Edison would still recognize much of today's electric power grid. However, this is, of course, not quite true. In fact, power systems has been evolving, and it is difficult to precisely define when and where the so-called smart grid began; much of the technology enabling the smart grid has existed for some time. Part One of this book covers power systems fundamentals; these are fundamentals that existed long before the smart grid and will exist long after, so they are well worth the time and effort to understand, although, as just mentioned, drawing the line between the pre- and post-smart grid is somewhat arbitrary and perhaps still ongoing, as we will see. Part Two defines what we mean by the term "smart grid" and focuses upon communications. Part Three goes on to explore what communications has enabled and could enable, including synchrophasor applications and machine intelligence.

Each new scientific discovery or advance in engineering and technology does not deplete the set of new ideas; on the contrary, it exponentially increases the number of new possibilities to be explored. This book will provide you, the student, academic or industry professional, or casual reader, with the basic building blocks of the smart grid; however, it will be you who will supply the creativity and innovation to combine these building blocks in new ways that may not yet have been considered. Please continue with the thought in mind that these are building blocks for new ideas, innovations, or even products, not as an end in themselves. One of the exciting things about the smart grid is that it is a highly dynamic and evolving system, one that you will be able to participate in, whether as a researcher, designer, developer, or consumer.

This part, Part One, consisting of Chapters 1–5, introduces the electric power grid and fundamental concepts of power systems. The goals for this part are to provide prerequisite material for understanding the power grid, to provide historical perspective on the evolution of the power grid, and to provide motivation for the concept of the smart grid.

This chapter, Chapter 1, provides a general overview of the electric power grid, including the fundamentals necessary to understand the rest of the material that will be covered. The remaining chapters in this part focus upon the topics introduced in this chapter in more detail. Because this part of the book is focused on the historical or legacy power grid, it is divided into standard electric power grid components: Chapter 2 focuses upon generation, Chapter 3 on transmission, Chapter 4 on distribution, and Chapter 5 on the consumption of electric power.

This chapter begins with an overview of the physics of electricity as it relates primarily to power systems, but also as it relates to communications as well. Then we discuss the electric power grid as it has evolved over the last century until the dawn of the smart grid; this provides us with a brief historical perspective. Then we look at the equipment in the legacy power grid; much of the equipment, or at least its functionality, will be the same or similar in the smart grid. It will be this equipment that will be monitored and interconnected via communications within the smart grid. Next, we return to basic power analysis that applies to the legacy power system, and because the fundamental physics does not change, will apply to the smart grid as well. This analysis provides insight into the operation of the power grid as well as provides our first hints at the communication and computational requirements within the smart grid. Simulation and modeling tools are introduced in the appendix; while the reader may be curious as to what tools currently exist, this information will likely become rapidly outdated and is thus not incorporated in the main text. This information may be relatively quickly outdated, but it provides a look at some of the modeling challenges for the smart grid. Next, we briefly consider blackouts in the legacy power grid. This provides us with a sobering look at what we would hope the smart grid would improve. The goals for the smart grid involve extending the capability of the power grid in many different ways, however, if the smart grid cannot reduce the likelihood of a blackout, then all of its other features are pointless. Sections 1.5 and 1.6 discuss the drivers and goals of the smart grid. Finally, we take an excursion back to fundamental theory in Section 1.8 to discuss energy and information. The goal is to intuitively motivate the reader to consider that incorporating communication and computation with the power grid may benefit from a fundamental understanding of the relationship between energy and information. The chapter ends with a summary of the important points. Finally, the exercises at the end of the chapter are available to help solidify understanding of the material.

The term “smart grid” has been used numerous times in this text already and, since it is the main topic of this book, will be used frequently throughout the remainder of the book. Before continuing further, a definition of this term is in order. Let us begin with a simple, broad, intuitive definition and refine it as we progress. The smart grid is an electric power grid that attempts to intelligently respond to all the components with which it is interconnected, including suppliers and consumers, in order to deliver electric power services efficiently, reliably, economically, and sustainably. The details of the definition and the means by which these goals are accomplished vary from one region to another throughout the world. This is in part due to the fact that different regions of the world have different infrastructures, different needs, and different expectations, as well as different regulatory systems. However, even without these differences, the power grid is a very broad system comprised of many different components and technologies. Researchers focusing on a narrow aspect, such as developing smart meters or developing new types of demand-response (DR) mechanisms, sometimes inadvertently equate their areas with the sum total of the smart grid, as illustrated in Figure 1.1. Each blind man equates the elephant with the part he can feel. The areas shown are

- advanced metering infrastructure (AMI) – systems that measure, collect, and analyze energy usage;
- distribution automation (DA) – the extension of intelligent control over electrical power grid functions to the distribution level and beyond;
- distributed generation (DG) – generating electricity from many smaller energy sources and microgrids;
- substation automation (SA) – automating electric power distribution and transmission substations;
- flexible alternating current transmission system (FACTS) – a power electronics-based system to enhance controllability and increase power transfer capability of the network; and
- DR – systems that manage customer consumption of electricity in response to supply conditions.

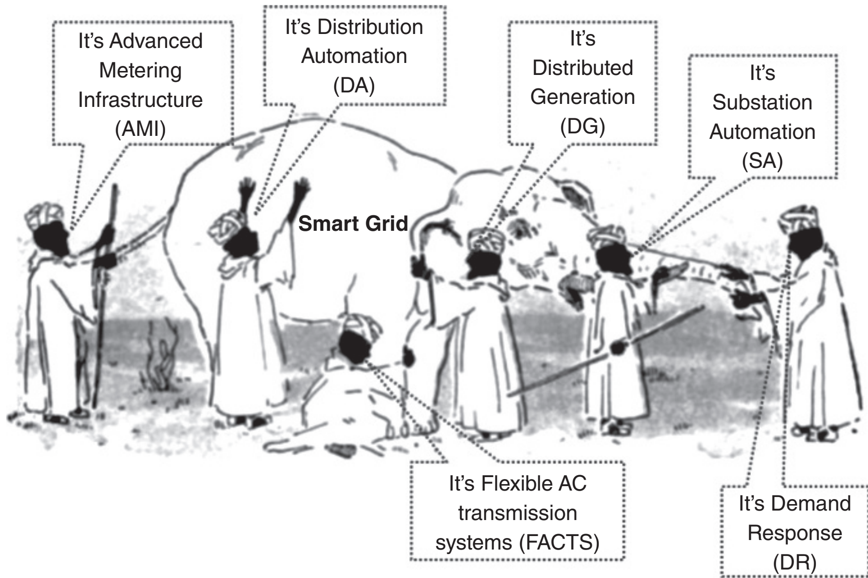

Figure 1.1 What is the smart grid? There is a risk of perceiving the smart grid as only one of many different emerging systems. It is critical for the development of smart-grid communications to understand the complete view of a smart grid. Source: Stebbins C. M. and Coolidge M. H. (1909), Golden Treasury Readers: Primer, American Book Co., New York, NY, p. 89, via Wikimedia Commons.

While these topic areas provide a feel for the smart-grid goals and we will cover these topics in detail in this book, no single subset of these areas defines the smart grid. In fact, these individual components should be viewed as only a subset of the possible components of the smart grid. Some of these components may reach maturity as planned, others may not survive, and many new ones will certainly be created as innovation continues. It is important, then, to understand the fundamentals of both power systems and communications in order to make intelligent decisions regarding how these components will progress and to identify the potential for new ones.

Smart grid is about the evolution of the power grid. In that respect, we discuss where the grid came from, its current state, and its transition into a power grid comprised of DG and microgrids. However, this book should also be of lasting value in terms of a longer term vision for the power grid; that is, how it could evolve further in the coming decades. At this point, it would be instructive to take a risk and predict how the grid could look far into the future. It is a common trend for any technology to evolve from a monolithic structure to become more dynamic, flexible, and eventually merge with its environment. The ultimate advancement is to evolve into a physical field, such as an electric or magnetic field. Figure 1.2 depicts a series of progressively more sophisticated uses of wireless power: from centralized generation and wireless transmission to hard-to-reach places today, to offshore microgrids tomorrow, and to harvesting power from literal nanogrids and stray electromagnetic radiation. Nanogrid has multiple meanings; since power systems tends to deal with power grids that extend over large regions of the earth, nanogrid can colloquially refer to a relatively small power grid such as that inside a laptop. However, here we mean power grids that are literally on the order of nanometers in volume. The concept in this vision is that any power source, including large numbers of nanoscale power generation sources, can connect to the grid and provide power that

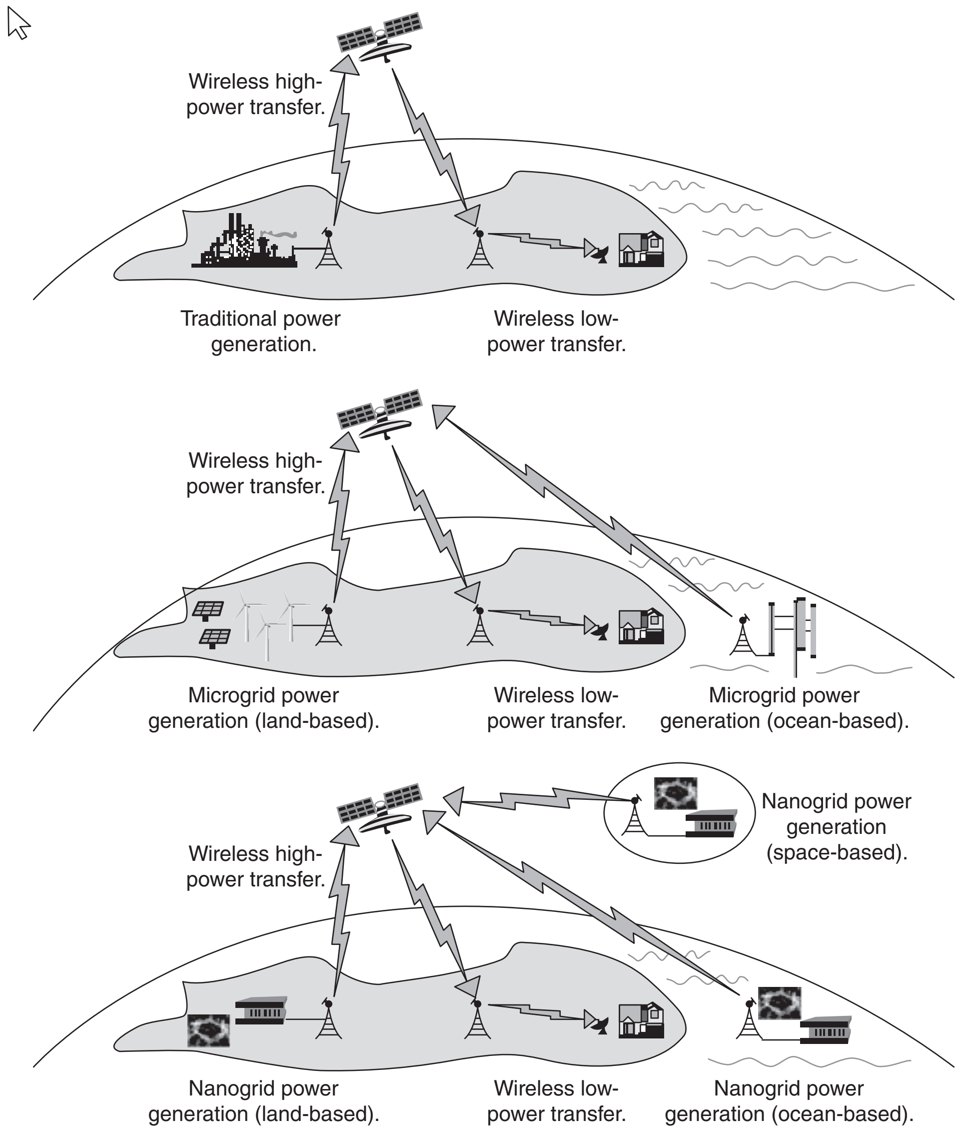

Figure 1.2 The power grid of the future may contain centralized generation with wireless power transfer, micrograms with wireless power transmission, nanogrids and electromagnetic energy harvesting among many other innovations. Smart-grid communication should anticipate how power grid technologies will be evolving so that it can remain viable for the future. Source: Bush, 2013. Reproduced with permission of IEEE.

is then appropriately aggregated into a higher power delivery system. Note that the delivery system is entirely wireless in nature; power is beamed in a wireless manner to consumers. Of course, at the time this is being written this is in the realm of science fiction for power utilities. However, individual components to accomplish this on a small scale exist today and will be discussed in later chapters of the book. The reason for including this futuristic vision up front is to keep the reader's mind open to the possibility of very different requirements for communication that may be required from those that are foreseen today.

1.2 Yesterday's Grid

The classic view of the power grid is shown in Figure 1.3. It is comprised of a relatively few, but very large power generation stations, bulk transport across relatively long distances over the transmission system to areas of denser consumer populations, a distribution substation in which power fans out through feeders to the distribution system, and, finally, delivery through the distribution system to individual power consumers. Power flows primarily in one direction, from large centralized generators to the consumer. As will be explained later, even in this pre-smart-grid architecture, there are aspects of power flow that are not strictly one way; namely, reactive power flow, which oscillates within the power grid, and circulating currents between generators. However, ignore these complicating factors until they are explained in detail later.

From an operational standpoint, the power grid is divided into what are known as "synchronous zones," or "interconnects" in North America. Synchronous zones are areas in which the power grid is highly interconnected and operating at the same frequency. As an example, the interconnects of North America are shown in Figure 1.4. The power grid (remember we are talking about the pre-smart-grid power grid) is one of the most complex machines ever created by man. The National Academy of Engineering ranks the electrification of North America as *the* greatest single achievement of the twentieth century. So how did this complex achievement come about?

The Edison Electric Illuminating Company of New York constructed the first generating station in 1881. This generation station had 250-hp steam boilers, each delivering 110 V direct current via an underground distribution network. As we will see, the means and benefits of

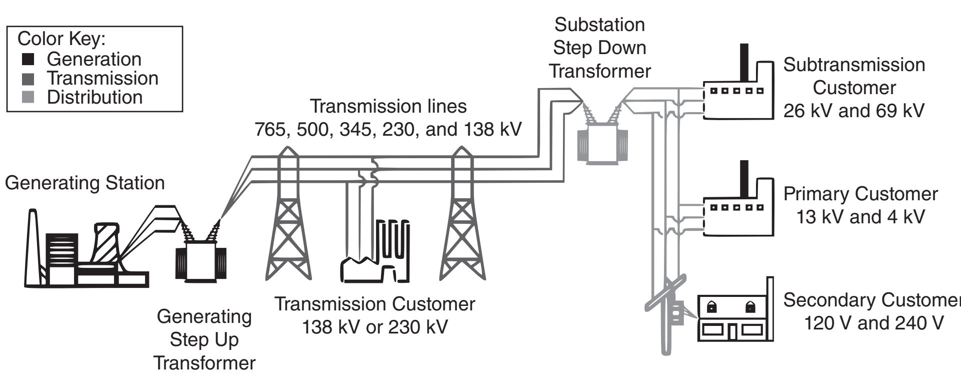

Figure 1.3 The classic view of the power grid has typically been a one-way flow of electric power from generation through transmission, distribution, to consumption. Source: U.S. Canada Power System Outage Task Force, Final Report on the August 14, 2003. Blackout in the United States and Canada: Causes and Recommendations, April 2004.

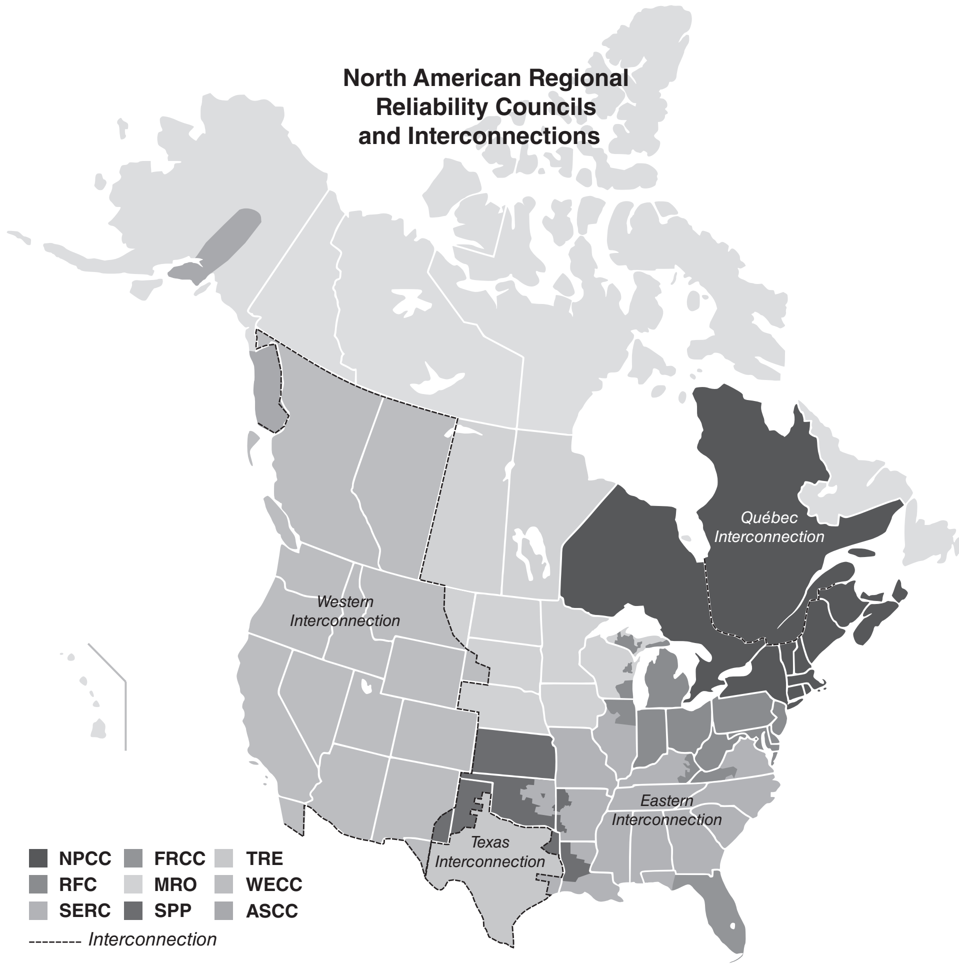

Figure 1.4 Interconnects, or synchronous zones, are areas of relatively dense power interconnectivity where the alternating current cycle is in phase. Source: By Bouchecl (Own work) [CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons.

using alternating current had not yet been discovered. Because voltage is required to move current and the early generating stations could not transmit or distribute their power very far, many stations appeared primarily throughout urban areas to serve only local demand for power. They were, in a sense, the first primitive microgrids. The power grid grew rapidly; electric power grew by over 400 times from the early 1900s to the 1970s. This is significant if you compare it with all other forms of energy, which only grew by 50 times over the same period.

The need for communication to support the power grid was recognized almost immediately. Communication over telegraph lines for automated meter reading was utilized in the late 1800s and patents on power line carrier for meter reading were issued in Britain in 1898 and the USA in 1905 (Schwartz, 2009).

The invention of the transformer allowed high-voltage alternating current power to be efficiently and safely distributed via 1000 V power lines. The first alternating current generation system was developed by Westinghouse in 1866. Nikola Tesla invented the induction motor in 1888, which uses alternating current and helped spread the demand for alternating current power as opposed to direct current power. By 1893, the first three-phase system was developed by the Southern California Edison Company. The result of this early progress was a large number of relatively small electric companies. For example, in 1895, Philadelphia alone had 20 electric companies operating with two-wire direct current lines at 100 V and 500 V, 220 V three-wire direct current lines, single-, two-, and three-phase alternating current at frequencies of 60, 66, 125, and 133 cycles per second and with feeders at 1000–1200 V and 2000–2400 V. The point of this historical interlude is that there was efficiency to be gained by reducing diversity and seeking an economy of scale.

Economy of scale is reflected in the 1973 Cumberland Station of the Tennessee Valley Authority, which inaugurated generating units of up to 1300 MW, a long way from the initial generation stations measured in hundreds of horse power. As generator size increased and the demand grew, the need to transmit and distribute power required higher voltages to both move power efficiently over larger distances to reach consumers and move large amounts of power between power producers. Today's distribution voltages commonly range in classes of 5, 15, 25, 35, and 69 kV.

It is interesting to note that, in a sense, the smart grid is returning to larger numbers of smaller generators via encouraging DG and is also attempting to conserve power by reducing distribution voltages. This is because part of the smart-grid concept is to enable the ability to figuratively "reach out" with many smaller generators to extract energy from the environment; specifically, the sun and wind in many cases. However, in theory, there is no need to stop there; we could continue the trend toward smaller generators reaching deeper into the environment down to the molecular scale. More will be said about this when we discuss the smart grid and future directions.

The ability to move large amounts of power between producers enables power to be generated by the most economical generators and also allows power to be shared so that peak demand can be satisfied when and where it occurs. Peak demand is a problem that occurs today due to the cost and inefficiency of powering up large generators that run for short periods of time. A large amount of consideration has gone into flattening the demand; this is incorporated as a component of the smart grid. An efficient means of sharing power over long distance and between synchronous zones is the use of high-voltage direct-current (HVDC) lines. In 1954, the first HVDC power line went into operation in the Baltic. It is 60 miles long and operates at 100 kV. High voltage provides the same power with less current, and thus less power loss. The fact that power is converted to direct current before transmission and then converted back to alternating current upon reception allows the sending and receiving synchronous zones to be out of phase with each other without causing stability problems. This will be discussed in much more detail later; the point of this subsection is simply to understand the historical development of the technology.

1.2.1 Early Communication Networking in the Power Grid

As mentioned in the brief historical vignette above, communication has been vital to the power grid from the beginning. The telegraph was used for meter reading, soon followed by power line carrier at the beginning of the twentieth century. Power line communication was used for voice communication in 1918 (Schwartz, 2009). However, there are at least two key characteristics of the power grid that worked against the rapid and widespread deployment of modern communication throughout the power grid. They are economies of scale and safety. Economy of scale implies huge investment in large systems; systems that will produce large amounts of relatively low-cost power. But once constructed, they are designed to remain in operation for decades without change. Thus, they are not amenable to removing and reinstalling large amounts of equipment simply to keep pace with every incremental technological advance. These advances accumulated rapidly for communications. Also, safety and reliability in high-power electrical equipment are paramount; any perceived vulnerabilities must be mitigated or avoided. Thus, except where absolutely necessary, power grid control was designed to be accomplished locally, without the need for communication (Tomsovic *et al.*, 2005). In fact, power system engineers have, perhaps unwittingly, become experts at extracting communication signals directly from the power grid's operation and developing a self-organizing system. This statement will become more apparent as the book progresses.

We will go into great detail on the power grid technology and fundamentals soon, but for now consider a high-level discussion of the relation between communication and control in the classical power grid. By classical power grid we are referring to the power grid before the term smart grid was coined. We can consider control divided into high-level areas of protection, generation, voltage, power flow, and stability. Points to consider while reading this book are (1) how well all of these can be accomplished without communication, (2) how well they would be improved with communication, (3) what the requirements of the communication system are in terms of qualities such as cost, latency, bandwidth, and availability among others, and (4) what new features that might be added are given communication capability.

Power system protection is one of the most critical control systems because it involves personal safety. The goal of protection is to isolate faults, such as broken power lines, while keeping power flowing safely to as many consumers as possible. Protection control must be quick and accurate. The common approach is as simple as detecting excessive current flow. However, protection can be applied when needed based upon other characteristics, such as excessive frequency deviation, excessive voltage deviation, or excessive instability. Through careful design and placement, known as protection coordination, it is possible to ensure that the proper relay will open at the proper time by having each relay controlled by locally detected information. However, configuring and managing such a system is a manual process requiring manual effort to adjust every time there is a change. Differential protection relays monitor current on each end of a line and compare the current input to the line with current output from the line; any excessive difference indicates a potential fault. In this case, some form of feedback is required in order to determine whether there is a difference in input and output current (Voloh and Johnson, 2005).

Generator governor control simply refers to keeping the generator producing the required amount of power. The mechanical power applied to the shaft is adjusted to keep the rotor moving at the correct operating speed. Again, this has been done locally.

Voltage control can be accomplished by a variety of mechanisms; for example, by increasing or decreasing the current through the generator rotor coils, known as the exciter, or by changing line tap transformers, which effectively change the winding ratios, and capacitors/reactors (inductors). The exciter can be controlled locally by sensing the generator output voltage and maintaining a given constant voltage. Line tap transformer and capacitor/reactor changes are relatively slow and often predetermined by the load profile and time of day.

Power flow control involves controlling the amount of power flowing over particular power lines in the grid. The classical technique is to use a phase-shifting transformer (Verboomen *et al.*, 2005). However, similar to a line tap changing transformer, this is a relatively slow and predetermined process. A FACTS is a more advanced form of control using power electronics. However, again, it is possible to operate the system with manually configured power flow control.

Stability control is required when multiple interconnected generators lose synchronization with one another. Simply put, their electrical interconnection with each other acts to keep the generators moving together; however, the connection behaves in an elastic manner. Generators can begin swinging out of synchronization with each other to the point that they will not settle back into alignment with each other but instead swing wildly out of control. Thus, it is important to implement mechanisms to dampen such oscillations. One approach is to utilize power system stabilizers located at the generator that attempt to monitor and compensate for such oscillation by adjusting the exciter (Yang *et al.*, 2010).

As previously mentioned, communication has always been part of the power grid for relatively impromptu, specific purposes, typically to implement automated meter reading in some locations and special protection mechanisms. With the advent of the so-called smart grid, communication takes on a much larger role within the power grid. A simple example that comes initially to every layman's mind is demand response, which requires two-way communication between every consumer power meter and the utility. This application alone is a huge undertaking. However, more sophisticated uses of communication are being developed as well. The local control mechanisms mentioned previously may now be improved by expanding to wide-area control. The remainder of the book goes into detail on each of these wide-area applications after providing the necessary background required to understand them.

1.2.1.1 Why the History of Communication in the Power Grid is Important

Keep in mind that while this may seem like potentially interesting but useless ancient history, this is far from the case. First, as befits the saying "Those who cannot remember the past are condemned to repeat it," many of the so-called smart grid implementations are, in effect, a return to the way things were done in the past. This is not necessarily bad, but it would be good to avoid repeating the mistakes of the past. Second, the terminology used in today's power grid derives from terms established long ago. By understanding where terms originated, their meaning will become clearer. Finally, we know that technology follows certain patterns, and the better we know the past, the better we can project into the future. Digital communication first reached the power grid via electric power grid control centers and then substations following the introduction of digital computing in those respective components of the power grid. Both the control center and the substation are spatially relatively small areas; initial digital communication was, of course, wired. However, the inertia behind analog wired communication has been very slow to overcome; remnants of wired thinking appear even within today's terminology and standards.

1.2.1.2 Early Analog Computers

Communication exists to serve a purpose, to gather power system data for computation and then to propagate the results, either to an operator in a power grid control center or for control purposes in substations and in the field. Communication technology has been driven by computational hardware requirements and interfaces. Computation in the power grid was done in an analog manner for a significant portion of early power grid history. Before thinking to yourself how primitive this must have been, consider that analog processing techniques are superior to digital processing in terms of computational speed (Deese, 2008) and work continues on applications of analog computing to power grid analysis (Nwankpa *et al.*, 2006). Of course, industry is overwhelmingly digital in both computation and communication products; however, analog computing would likely work best with simpler, cheaper analog communication. Analog computing can be traced at least as far back as ancient Greece, from around 150 BC, when the Antikythera mechanism was estimated to have been constructed (Freeth *et al.*, 2006). The Antikythera mechanism has been a puzzle to researchers because it demonstrates astounding craftsmanship and engineering at such an early date. It is a geared mechanical computer used to compute astronomical positions. Similar technology did not reappear until the 14th century. Moving from linear mechanical to electrical components is actually straightforward since the electrical equations follow those of mechanical components such as springs and dampers.

1.2.1.3 Analog Computers and Analog Communication in the Power Grid

In 1929, General Electric and Massachusetts Institute of Technology built the first analog-computer-based alternating current transient network analyzer. In the mid 1940s, General Electric's Gabriel Kron developed an analog computer alternating current network analyzer for the power grid that he also employed to solve the Schrödinger wave equation, nuclear power problems, and the early analysis of radio communications (Kron, 1945; Tympas and Dalouka, 2008). Thus, the analog computer was utilized in the real-time operation of the power grid. Originally, the control center grew out of the control operators office (Wu *et al.*, 2005), (Dy-Liacco, 2002). The control operator was known as the "dispatcher" and that term remains in use in a variety of power systems terminology, such as "economic dispatch." Economic dispatch is the process of allocating a set of generator outputs such that the power grid is fully served at the cheapest cost.

1.2.1.4 Early Supervisory Control and Data Acquisition in Substations

By the mid-1950s, analog computers and analog communication were in use to implement automatic grid control (AGC). Load frequency control utilized the alternating current frequency as an estimate of the power balance between generator supply and demand, and this could be done locally. Details on this will be explained later in the book. In fact, early AGC was simply a flywheel to maintain constant generator speed, followed later by input from an amount proportional to the alternating current frequency deviation plus its integral. Then, penalty factors were added for transmission line power losses. Earlier forms of supervisory control and data acquisition (SCADA) existed using analog telephone lines as early as the

1930s. Thus, here we see the first use of communications for digital computers and the birth of SCADA. This replaced having humans at a substation who had to be manually called to collect information or issue control commands.

1.2.1.5 The Introduction of Digital Computers and Digital Communications

Digital computers appeared in the 1960s; remote terminal units (RTUs) were used to collect real-time measurements comprised of voltage, real and reactive power, and the status of breakers at transmission substations through dedicated transmission channels to a central computer. A blackout in the north-eastern USA in 1965 accelerated the use of digital computers to enable more real-time control of the power grid. By the late 1960s and early 1970s, smaller digital computers began to be introduced into substations. The notion of power systems security drove the need for more computational power in the 1970s. Security in power systems essentially involves answering a set of "what-if" questions regarding potential failures and estimating the ability of the system to withstand a given set of failures or contingencies. Thus, computers began by being introduced into the control center and eventually spread from there out into substations.

1.2.1.6 Intelligent Electronic Devices

Each advance in computer technology and new application within the power grid required a corresponding advance in communication technology. However, use of computer processors and communications was slow to develop for use in the power grid because extremely high reliability was required. High reliability was required both for safety and because the mindset for power systems equipment is that it should last decades before being updated. By the late 1970s and early 1980s, microprocessors became integrated into power system devices, yielding the term "intelligent electronic device." Also, by the 1980s, minicomputers were replaced by Unix and personal computers became dominant and ran on local-area networks (LANs) in the substation. Thus, we can see the tentacles of computation spreading from the control center, to the substation, and now embedded within individual devices. This spread of computational power into an increasingly distributed system opens the potential for more communication to support computational interoperability.

1.2.1.7 Impact of Deregulation on Communications

Another impact on computation and communication occurred in the second half of the 1990s when the power market became deregulated. Vertical, regulated power monopolies – that is, utilities that controlled all aspects of power generation, transmission, and distribution – turned into competitive markets where, ideally, generation, transmission, and distribution were designed to be run by different, competing, companies. Now many different competing organizations need to work closely together and share enough information to keep the system running smoothly, but not so much information that they lose competitive advantages. The goal is that the invisible hand of the free market will encourage all provider companies and the consumer to maximize their profit and create a more efficient system where the equilibrium price is closest to the true cost of power. More detail on all these topics will be provided later;

here, we are focus on the historical impact upon communication. The impact on communication is that, after deregulation:

1. The monolithic utility system became split into separate autonomous entities: independent system operators (ISOs) and regional transmission organizations (RTOs), generating companies (GenCos), transmission companies, and load serving entities (LSEs) that operate distribution systems, where each of the entities now needs to share information and related impact.
2. Business and market operation are becoming more closely integrated with communication and control of power.

1.2.1.8 Evolution into Distinct Management Systems

We can see that computation within the control center continued to become more sophisticated, involving state estimation and near-real-time solution of the power flow equation in order to more accurately combine power system stability with economic dispatch. This became known as the energy management system (EMS). Meanwhile, the substation computational sophistication was also increasing and became known as the distribution management system (DMS). Market deregulation motivated the need for business management systems in the power grid. Let us end this discussion on the historical background of power system communications by examining the current state of substation communications.

1.2.1.9 Today's SCADA System in more Detail: DNP-3 Example

This section summarizes the current state of SCADA systems using distributed network protocol 3 (DNP3) as an example. Of course, SCADA is a general term that refers generally to a wide variety of industrial control systems, such as those used in manufacturing, refining, and systems on board ships, buildings, and vehicles, as well as power systems. There are a variety of SCADA communication protocols; DNP3 is only one among many. SCADA is another example of a historical term that may be on its way to becoming obsolete. This is because SCADA and distributed control systems are evolving toward performing the same task: real-time control. Historically, before communication was fast and reliable, the term "supervisory" in supervisory control and data acquisition defined the limits of what the system could do. SCADA systems were not able to perform real-time control, but rather served as a supervisory system. SCADA systems allowed operators to see and manage what was taking place, but communication was not fast or reliable enough to enable real-time control. However, as communication performance improves, SCADA systems are becoming capable of performing real-time control; they are becoming instances of distributed real-time control systems.

Readers who are already familiar with communication will readily understand SCADA protocols by calling to mind the simple network management protocol (SNMP). SCADA protocols have some striking similarities with SNMP. This should not be a surprise, as SNMP is, in a sense, the closest de facto SCADA system for communication networks. SCADA protocols and SNMP are designed to provide quick, lightweight, communication of control and status information to a management system and a system operator. They are both concerned with an object-oriented mapping of control points and handle both query and exception-based reporting for critical control decisions.

DNP3 is a SCADA protocol that interconnects client control stations, RTUs, and other intelligent electronic devices (IEDs) (Mohagheghi *et al.*, 2009). The protocol was developed by General Electric to serve the need for a SCADA protocol while the IEC 60870-5 protocol was under development; DNP3 was released to the public through the DNP Users Group. DNP3 is a small, simple, lightweight protocol comprised of only three layers: a link layer, a transmission layer, and an application layer. It is designed to transmit relatively small messages while being quick and reliable. As we will see in communications and networking, there is always a trade-off between being fast (that is, having low latency) and reliable. Message data may be of any length, including a length of zero for commands. Message data is divided into 2048-byte packets at the application layer, creating an application protocol data unit (APDU). The APDUs are broken down into transport protocol data units (TPDUs) of 250 bytes. At the link layer, the link protocol data unit (LPDU) is created by appending cyclic redundancy checksum (CRC) sequences to the LPDU. The LPDU is transmitted by the physical layer, eight bits at a time, with an additional bit to indicate the beginning and end of a data sequence. The physical layer was originally a simple wired connection such as RS-232 for one-way communication over short distances, RS-422 for two-way communication over longer distances, or RS-485, which allowed multipoint communication. As the Internet became more widespread, the DNP3 protocol was implemented, just as described, over the internet protocol (IP) transport layer, either as a transmission control protocol (TCP) or a user datagram protocol (UDP), which enabled much longer distance, wide-area communication.

As mentioned, DNP3 is only one of a myriad of SCADA and power system-related protocols. The goal in discussing DNP3 at this point is only to provide an illustration of a representative SCADA communication protocol that is widely used. Our goal is not to attempt to exhaustively list every SCADA protocol; more protocol standards are likely to be in development as you read this, and any such list would be quickly out of date. Instead, the goal is to focus on the fundamentals as they regard communications and power systems. For example, many power system communication standards appear to be communication protocols, yet they reside upon existing communication protocols, really acting more like applications to a network engineer. The demarcation between network protocol and application standard has been blurring in the power systems field. For example, there is an inter-control center communications protocol (ICCP) that defines wide-area communication among control centers. However, ICCP resides upon the manufacturing message specification (MMS) which can, and often does, reside upon TCP/IP. MMS addresses the issue of a standardized approach to modeling physical devices as logical devices. The goal of MMS is to enable ease of implementation and code reuse by hiding the vendor-specific device behavior within a consistent, standardized, logical device. Thus, MMS creates a virtual manufacturing device with a simple, well-known interface with which many applications can easily interoperate. However, MMS typically reaches down only as far as the top of the network protocol stack (namely, the presentation and session layer) by standardizing on abstract syntax notation 1 (ASN.1) for the encoding of the machine objects and specifying issues related to opening and closing of the communication connection. Thus, ICCP is really not defining anything new below the transport layer, but rather defining how objects and services are represented. ICCP and MMS are addressing communication in a broad sense, but it is only tangential to network engineering because it is not creating or modifying existing communication network protocols. Another, more recent example of the blurring of the boundary between network and application is IEC 61850. IEC 61850 focuses primarily upon a paradigm for specifying, representing, and configuring power system information, but also resides above a set of alternative existing network protocols that actually provide communication. There are many such standards addressing power system object representation and configuration. Some of these standards are completely independent of the network protocol, while others specify in more detail how the power system objects are mapped onto existing network protocols and precisely how the network protocols are to behave. The fundamental, overarching design question, regardless of the particular protocol, involves the age-old engineering decision regarding ease of use with increased complexity versus the simplicity-and-performance curve, which will be called the functionality–complexity curve for short. DNP3 and IEC 61850 are examples on opposite ends of this curve because DNP3 is an example of a relatively simple protocol with good performance while IEC 61850 attempts to do much more self-configuration with a corresponding increase in complexity. One way IEC 61850 attempts to address the functionality–complexity curve is by providing an alternative set of network protocols, from direct encoding over an Ethernet frame intended for time-critical applications with low-latency requirements to a complete client–server architecture over MMS and TCP/IP. The functionality–complexity trade-off can be seen, for example, in the direct mapping over an Ethernet frame because, while relatively lightweight, basic functionality of the IP, such as routing and efficient handling of error over less reliable links such as wireless links, is unavailable, often requiring complex nonstandard approaches to resolve the issues.

What we learn from this is that, from a networking perspective, when you wish to understand new smart-grid communication protocols, one of the first things to consider is whether the protocol really defines a new set of lower layer network protocols or whether it is really acting as an application that utilizes existing network protocols and, if so, how it utilizes them. This book is focused on the network engineering view of communication and less on the design of power system object models (of which there are many to choose from already), although there is certainly an impact of one upon the other. Now that we have discussed the historical context of power systems and communication in some detail, Section 1.2.2 views power systems and communications from a higher level, seeking to learn through comparing and contrasting the two technologies. Following that, we will go into detail on power system fundamentals necessary to better understand the need and requirements for communications.

1.2.2 An Analogy between the Power Grid and Communication Network

In order to gain deeper insight into power systems and communications, consider a rather loose analogy between the two. The idea is to be able to use knowledge of one field to gain insight into the other. Specifically, in Table 1.1 there are three columns: (1) a general network characteristic column, (2) a power grid network column, and (3) a communication network column. We will examine the communication network as an analog to the power grid, using characteristics between the power grid network and a communication network to construct the analogy.

Let us begin with the product being transferred in each network. The content being transported through the power grid is clearly power over some time duration, which results in energy. For the communication network, the content being transported is information. Note that we do not indicate "data" here because information is more general than data. For example, executable code could be transported such that, when run, it generates the intended information. The medium over which energy is transported will be identified as electric power. Note

Table 1.1 Many analogies can be drawn between the power grid network and communication network.

Network characteristic	Power grid network	Communication network
Content	Energy	Information
Medium	Power	Power
Form	Active power	Modulation
Transmission models	Broadcast, multicast, P2P	Broadcast, multicast, P2P
Routing	Switched	Store-and-forward
QoS	Power quality	QoS
Format	Kilowatt-hours	Packets
Error correction	Capacitor banks	Channel coding
Compression	More power over same lines	Source coding
Buffering	Energy storage and DR	Memory for playback delay
Channel utilization	Reactive power	Bandwidth-delay product
Traffic shaping	DR	Leaky bucket
Network management	Power flow, state estimation	SNMP polling
…	…	…

that there is a temptation to think of the medium as a power line or some form of conductive material; however, this is not an accurate analog because power can be transferred without the need for wire. In communications, information is transferred by transmitting a signal that also involves the flow of power. The form in which the content is transferred in the power grid is active power. Active power will be explained in detail later; however, it will suffice here to understand active power as power that a consumer actually consumes. The analog in a communication network is a form of modulation; the receiver must sense a form of modulation in order to interpret a signal.

Regarding transmission models, the power grid can be thought of as broadcast (from a generator to everyone connected), multicast (from a generator to everyone connected in parallel; only those with devices turned on receive power), or point to point (from one point to another over a power line). Similarly, communication networks allow for broadcast, multicast, or point-to-point transmission. The power grid is primarily a broadcast network, with power branching out from large centralized generation sources to millions of users through the transmission and distribution network, while power lines are point-to-point links. A primary difference in contrast with communication networks is that information can be copied whereas power cannot. Thus, within a communication network, a single multicast packet can be sent toward its destination and then duplicated along its path for each branch leading to a receiver, creating more packets than originally input. Unfortunately, this is impossible for electric power – each new user increases the load on the generator.

With regard to routing through networks, electric power is circuit-switched; it generally requires switching: a circuit is modified in order to connect or disconnect power sources from destinations. Note that power flow can be adjusted using more subtle approaches, such as a FACTS, which are explained in detail later; however, we will ignore this consideration for now. Within communication networks, packets reach their destinations via a store-and-forward mechanism. In other words, packets are sent to intermediate nodes in the network that are hopefully closer to their intended destination. The packets are then sent from the intermediate nodes to other nodes along their route to the destination. Such an approach may someday be used for energy as well, utilizing wireless power transmission from one node to another until the final consumer is reached.

The notion of quality of service (QoS) exists in both power systems and communications. Ideally, the consumer should see a perfectly smooth sinusoidal waveform for both current and voltage, although this is rarely the case. In communication networks, QoS can have many different specific meanings, but they are all related to the ability of the receiver to perceive precisely what was transmitted, particularly with respect to reflecting the order and timing of the packets received. In the power grid, the format of the final product is energy, typically received and measured by the consumer in kilowatt-hours. In communications, the “consumer” receives packets; there is an effective data rate (analog of power) and a total amount of data received (analog of energy).

Both the power grid and communication networks have the notion of error correction. Error occurs in the power grid because inductive loads cause the current to lag behind the voltage, causing a change in the power factor, as we will discuss in detail later. Capacitor banks are used to correct the power factor. Analogously, in communications, bit errors occur in packets, and error correction techniques can be applied to detect and correct the erroneous bits.

Compression is involved conceptually in the power grid, and more literally in communication networks. One of the goals of the smart grid, as will be discussed later, is more efficient utilization of the existing power grid; in other words, delivering more usable power to the consumer over the same-capacity power lines. In effect, this can be somewhat vaguely viewed as “compressing” power such that more power flows over the same power lines; for example, by improving monitoring, power factor, and stability, thus allowing the system to operate closer to its physical limits. In communication, compression, also known as source coding, is often employed to send more usable information over the same-capacity communication channel. As is well known, such systems become more brittle (Bush *et al.*, 1999).

Buffering takes place in both the power grid and communication networks. It is often said that electric power supply and demand must always be perfectly balanced; while this is true on a large scale, it is not true on small scales, as we will see. There is always some “residual” power stored within inductive components of the grid, which, thankfully, allow for decisions to be made within seconds rather than instantaneously. On a larger scale, the development of energy storage within the power grid attempts to act as a large buffer, obviating the need for expensive peak generation to come online. Buffering clearly exists within communication networks; multimedia content is often buffered in order to remove jitter, allowing for a smooth, pleasant user experience.

Channel utilization is an important aspect in both the power grid and communication networks. As previously mentioned, extracting more power from the existing power grid is a significant goal for the smart grid. By utilizing power flow analysis, explained later in this chapter, power generation can be controlled in order to manage the flow of active and reactive power throughout the power grid network. Recall that the consumer only actually consumes active power; reactive power oscillates between the consumer’s devices and the generator. Thus, efficiently utilizing the power line’s “channel” is a key goal of the smart grid. Channel utilization in communication networks is also a common goal. Both consumers and communication providers want to make as efficient use as possible of expensive communication equipment. Traffic shaping takes place in both the power grid and communication networks. One of the well-known components that seems to have become strongly associated with the smart grid is the mechanism of DR, even though the concept was around long before the term smart grid was coined. This is the idea of enforcing the balance between supply and demand via free-market mechanisms. Ideally, consumers would set their demand–price curves and generators would set their price–generation curves and the balance occurs where these curves intersect. In this sense, the power generation rate undergoes traffic shaping. In communication networks, traffic shaping, utilizing techniques involving variations of the leaky bucket mechanism, is used to control the flow of traffic into the communication network such that the network can more efficiently handle the flow. In fact, pricing for network traffic throughput rates can be set in order to achieve an effect very similar to DR in the power grid.

Finally, a form of network management is required in both the power grid and communication networks. DNP3, ICCP, and IEC 61850 were mentioned in Section 1.2.1.9 as examples of supervisory monitoring and control protocols in the power grid. In order to properly manage and control the power grid, power flow must be either directly monitored or inferred through analysis, and is known as power flow analysis. State estimation is a technique used to infer the state of the power grid in general through many potentially erroneous measurements. Similarly, communication networks need to know the state of the communication network in order to properly manage it, including the flow of packets. Network state is often obtained via the simple network management protocol (SNMP) in communication networks.

There is a rich set of useful analogies that can be constructed. Certainly, there are many other analogies that have not been listed here, but hopefully the insight gained from the process of analogy is clear. The more obvious analogies are already being exploited by researchers applying communication to the power grid. From the analogies summarized in Table 1.1, we can see that power system and communication network engineers address similar fundamental problems and, with the proper analogy, should be able to easily understand each other's field. Much more detail will be given throughout the reminder of the book for all of the power system topics mentioned in these analogies. Section 1.3 will move on to a more thorough, but simple, introduction to power systems, beginning with fundamental physics. What is unique about this introduction and much of the rest of this book is that we will identify the relationships to communication networking along with the introduction to power systems.

1.3 Fundamentals of Electric Power

This section provides an overview of the physics required to understand power systems and communications. This can be a complex subject; however, the goal is to keep it as straightforward and elementary as possible while providing enough intuition to comfortably understand the topics covered in the remainder of the book. A reader knowledgeable in electronics could safely skip this section; however, you could miss some potentially useful intuition related to both power systems and communications. What makes this chapter and the remainder of this book unique is that an attempt will be made to discuss both power systems and communications side by side at selected points. This will hopefully stimulate the reader's thought process regarding how these topics could be integrated, perhaps in novel ways. In this section, we lay the foundation by covering charge, voltage, and ground, conductivity, Ohm's law, electric circuits, electric and magnetic fields, electromagnetic induction, circuit basics, and magnetic circuits.

1.3.1 Charge, Voltage, and Ground

Beginning from the bottom up, so to speak, the first topic that requires explanation related to power systems is "charge." Without charge, there can be no electric power and no electronic communication. Charge is a fundamental property of matter, yet one with which people tend to be least familiar. For lack of a simpler definition, consider charge to be the property of matter that causes particles to experience a force when placed near other charged particles. Early work in electromagnetic theory was based upon experiments related to the force experienced by a charge. This force is described quantitatively by a "field"; fields will be discussed in more detail later. To the best of our knowledge, charge is quantized; there exists a smallest unit of charge, and charge only exists in multiples of this smallest unit. Charge comes in two forms, positive and negative, as any youngster knows. Like charges repel; opposite charges attract. The smallest negative charge is an electron and the smallest positive charge is a proton, and these charges are equal. But that begs the question: What does it mean for these charges to be equal? How is charge measured? This requires the definition of another fundamental unit, the ampere. An ampere is the amount of charge in motion through a conductor past a give point per unit time. Thus, an ampere is a convenient measure for the flow of charge. The amount of charge itself is thus defined by an ampere-second, also known as a coulomb. One coulomb has the charge of 6.241×10^{18} electrons. As we will see, the interactive force among charges plays a large role in power systems, from generators to motors. When these fields are radiated, they play a large role in wireless communication; again, more detail will follow on this.

Because like charges repel and opposite charges attract, a local imbalance of charges will have a natural tendency to spread out if possible. In other words, too many charges of the same type will be under pressure to move such that the state of the system is at a lower energy level. This energy is also known as potential; it represents the potential energy of the charges, similar to the mechanical potential energy of a ball at the top of a hill. The potential energy is the work required to move the ball into position on the hill; similarly, the electrical potential energy is the work required of the electrical charge to move from or toward its minimal energy location. This work includes overcoming the difficulty of moving past obstacles in its path, which can result in the creation of heat within a wire.

This notion of pressure or potential is critical to understand power; both charge and potential are involved in defining the work done by a power system. A greater charge will exert more pressure, which exists as potential energy available to do more work. Note that a charge is unique to a particle, while potential energy, as we have described it, is related to a charge's location with respect to another location. This potential energy is known informally as electric voltage, or more formally as electric tension or electric potential difference; it is more rigorously defined as the potential energy of a charge divided by the amount of charge. We will use the less formal term, voltage. The electric potential energy is equivalent to the charge times the voltage, as shown in Equation 1.1, where U_{E} is the electric potential energy, q is the charge, and V is the voltage:

$$U_{\mathrm{E}} = qV. \tag{1.1}$$

From an intuitive perspective, voltage provides the pressure required for power to flow in power systems, while in communications a change in voltage often provides the signal representing the information to be transmitted.

Because electric potential energy is a quantity that is relative between two locations, the ideal reference location would be one that has no charge. Such a location is difficult to find in practice; the next best alternative is a location where positive and negative charges fully cancel or charges are easily dispersed. This is the case within the Earth. The reference location is thus commonly termed "ground." But keep in mind that just as there is a mechanical difference in potential energy when objects are at different heights, different electrical potential differences exist between any two locations. To recap, voltage is defined in terms of energy (joules) per charge (coulombs). Note that a joule can also be expressed as a watt-second.

1.3.2 Conductivity

Without going into detail on molecular structure, conductors are materials that have electrons that are free to travel. However, note that individual electrons typically do not travel far or fast. We can think of a charge applied to one end of a conductor as causing the conductor's electrons to realign due to their repulsion to the applied charge. This realignment is generally in the form of a slow drift, as shown in Equation 1.2, where I is the electric current, n is number of charged particles per unit volume (or charge carrier density), A is the cross-sectional area of the conductor, v is the drift velocity, and Q is the charge on each particle:

$$I = nAvQ. \tag{1.2}$$

Consider a copper wire with a cross-section of 0.5 mm^2 carrying a current of 5 A. The drift velocity of the electrons is on the order of only 1 mm/s. However, as we will discuss later, the change in position of the electrons establishes a magnetic field immediately outside the conductor. This field exists in the form of a wave that travels at a significant fraction of the speed of light. The conductor, in effect, guides an electromagnetic wave and is commonly known as a waveguide. This phenomenon is used frequently to couple communication with power lines, known as a power line carrier communication. More will be explained regarding this as we proceed.

While we tend to think primarily of metals as conductors, other materials can be conductors as well, and this has had an impact on both power systems, sometimes in negative sense, and for communications. For example, in 1837, Carl August von Steinheil of Munich, Germany, connected one leg of a telegraph at each station to metal plates buried in the ground, eliminating one wire of the circuit using a single wire for telegraphic communication. This led to speculation that it might be possible to eliminate both wires and transmit telegraph signals through the ground without wires. Attempts were also made to send electric current through bodies of water, in order to allow communication to span rivers. Experiments along these lines where done by Samuel F. B. Morse in the USA and James Bowman Lindsay in Great Britain. By 1832, Lindsay was giving classroom demonstrations of wireless telegraphy to his students, and by 1854 he was able to demonstrate transmission through a river for a distance of 2 miles, across the Firth of Tay from Dundee to Woodhaven, which is now part of Newport-on-Tay. From a power systems perspective, under the condition of strong electrical potential fields or high temperatures, the electrons of gas molecules can become free to travel. A gas in this state is known as a plasma. Air can become a conductor, and a dangerous discharge of electric current can take place through the air known as arcing.

Finally, there is a form of conduction in which there is no electrical resistance to the flow of electrons below a certain characteristic temperature. This clearly has many uses in power systems, ranging from superconducting power lines, through which there is no loss of power due to resistance or thermal effects, to superconducting magnetic energy storage (SMES), in which energy is stored in the magnetic field of a superconductor through which a direct current flows. From a communication standpoint, superconductivity can be leveraged for quantum computing, and particularly for quantum communication (Bush, 2010b). The concept of using superconducting power lines for both efficient power transfer and quantum communication for a smart grid is something to consider and is discussed again in Chapter 15.

An analogy with water is helpful. Current (measured in amperes) is the rate of flow of charge and is similar to water flow through a pipe, whereas voltage is similar to the water pressure difference between the ends of a pipe. Amperes are measured in charge per unit time, or coulombs per second. The impact of the current flow is fast, a significant percentage of the speed of light. However, as mentioned, electrons themselves do not actually travel nearly this fast; it is the impact of the electric field that is propagating through a conductor, analogous to ripples in a pond. The water does not actually flow away from a pebble; it is only the waves that are moving. This brings up the question of timing in power systems and communications. A large power grid can experience a measurable delay in the time it takes a current to propagate from one end of the grid to another. In addition, a communication signal, like all matter, is theoretically limited by the speed of light. Typically in electronics, propagation delay becomes an issue only at the extremes; that is, at the very small scale (for example, high-precision timing) and at the very large scale (namely, power grids). In most cases for power systems, propagation delay is ignored; such a circuit is called a "lumped circuit." On the other hand, for communication, overcoming, or least managing, propagation delay is a central issue. In communication systems, the bandwidth–delay product of a channel considers the communication channel as a pipe; the bandwidth times the delay of the channel is the amount of water the pipe can hold when it is full. The bandwidth–delay product is a characteristic that drives how efficiently communication protocols can take advantage of a channel. Delays – both the delay for current to flow through a line and for the communication required to control it – will remain an extremely important issue for the smart grid. From a power systems perspective, consider a 500-mile transmission line. It takes 2.7 ms to travel that distance at the speed of light (although the actual electromagnetic rate would be slower in reality). A 60 Hz alternating current has a zero crossing (that is, changes of direction) of 60 times per second, or once every 16.7 ms. Thus, we can see that propagation begins to become a significant part of the cycle time.

1.3.3 Ohm's Law

We have discussed current and voltage at an intuitive level, and now we need to relate them. If voltage is the pressure difference between charges and if current is the flow of charges, then voltage should cause a proportional amount of current to flow. However, as we mentioned, charges run into obstacles in their path through a typical conductor; this causes friction or resistance to the flow and maintains the pressure difference. We can think of this resistance as a constant of proportionality between voltage and current. Thus, the famous equation that most people take for granted is shown in Equation 1.3, where V is voltage, I is current, and R is resistance.

$$V = IR. \tag{1.3}$$

It should be understood that Equation 1.3 is an idealization, assuming a linear relationship between current and voltage. In reality, this is not true. For some materials, the relationship between voltage and current may change significantly with different values of voltage and current. Also, the relationship is dependent upon temperature. For example, the resistance of some metals increases as the temperature increases. Finally, the shape of the conductor plays a large role in its resistance. The term resistivity refers to the inherent property of a material to resist the flow of current, which is denoted ρ. This property can be quantified based upon the length and area of a cross-section of the conductor, as shown in Equation 1.4, where R is the resistance, ρ is the resistivity, l is the length of the conductor, and A is the area of a cross-section of the conductor:

$$R = \frac{\rho l}{A}. \tag{1.4}$$

Intuitively, it should make sense that increasing length increases resistance since the current flow has a longer path, and reducing the cross-sectional area also increases the resistance since the current is constrained within a thinner pipe. Resistance is measured in units of ohms or volts per ampere, as is apparent by rearranging Equation 1.3, while the unit of resistivity is the ohm-meter.

Conductance is the inverse of resistance, $G = 1/R$, and conductivity is the inverse of resistivity, $\sigma = 1/\rho$. Thus, conductance can be derived from resistance, as shown in Equation 1.5, where G is the conductance, σ is the conductivity, l is the length of the conductor, and A is the area of a cross-section of the conductor:

$$G = \frac{\sigma A}{l}. \tag{1.5}$$

For power systems, insulation becomes an important material property, with the goal of obtaining high resistance or low conductivity, in order to keep current contained and safely flowing. Plastics and ceramics are often used for this purpose. An old technique for estimating the amount of voltage on a power line is to count the number of ceramic insulation bells holding the power line to the tower. The number of bells grows roughly in proportion to the power on the line. The exact proportion of bells to kilovolts on the power line can depend upon the climate because, as mentioned earlier, air can become ionized and support current flow, and wetter, more humid air will more easily conduct current, thus requiring more insulation.

1.3.4 Circuits

An important point from a power systems perspective is voltage drop. As already discussed in Section 1.3.3, voltage is proportional to the current and resistance. In a power line, resistance can be significant. However, current will vary depending upon the load; that is, on the consumer and industrial appliances using the power transported by the power line. As more customers use more appliances, current flow increases, which increases the voltage drop. The result can be insufficient voltage and a brownout.

As alluded to earlier, charges collide against obstacles as they flow through a conductor, and these collisions cause friction which results in resistive heating. Heating is the work done as the charges travel toward a lower potential. This heat can be desirable for use in heating an electric heating element or it may be undesirable and potentially dangerous, as when it occurs in a power line or electrical equipment for example. A power line's goal is to transfer energy as efficiently possible; converting some of the energy into work as heat is not the desired goal for a power line. Similarly, an electronic device such as a transformer is designed to convert power from one voltage to another, not to generate heat. As we have mentioned, such heat tends to increase the resistance, increasing the voltage drop. The heat may eventually build up to the point where it may melt wiring or damage insulation, leading to power faults, which will be discussed in detail later. An entire subfield of power systems is devoted to preventing or mitigating such problems and is known as protection.

From a communication perspective, resistive heating is less of an issue; and herein lies an obvious, but fundamental, difference between power systems and communication. Communication is focused upon maximizing channel capacity while typically minimizing power consumption. Extraneous power in communications often results in noise; it reduces the signal-to-noise ratio. Communication systems strive to maximize the signal-to-noise ratio in a channel. This often implies increasing the power level of a signal, but communication power levels are many orders of magnitude lower than those in power systems. Thus, whereas power systems seek to maximize power flow as efficiently as possible, communication systems seek to maximize the reception of a signal with as little power as possible.

Resistive heating brings us to the first instance in which we have discussed useful work, in the form of the intentional generation of heat. Let us examine this further. The heat generated can be measured in terms of power, which is the energy generated per unit time. This is the rate at which energy is being converted into heat, which we assume in this case is useful work. Let us see how this relates to the electrical parameters we have discussed so far. Recall that voltage is in units of energy per charge. Thus, the units of voltage contain the energy that we require for power, which is energy per unit time. However, voltage by itself is missing the notion of time. But recall that current is flow of charge, or the rate of flow of charge. Thus, current contains the notion of time since it involves a rate, namely something changing over time. As shown in Equation 1.6, it is not too difficult to see how voltage and current are related to power:

$$\frac{\text{charge}}{\text{time}}\frac{\text{energy}}{\text{charge}} = \frac{\text{energy}}{\text{time}}. \tag{1.6}$$

Equation 1.7 shows this same relationship of power in terms of current and voltage.

$$P = IV. \tag{1.7}$$

This comes from Joule's law, which originally had another form, as shown in Equation 1.8, where I is current and R is resistance. This can be derived simply be using Ohm's law, $V = IR$, and substituting V in Equation 1.7:

$$P = I^2R. \tag{1.8}$$

Power is measured in units of watts, which we can see from Equation 1.8 is amperes^2-ohms. Note that current is squared, so it has a greater impact on power as it increases than resistance does. However, it is important to take into account other relationships when applying this equation; in other words, the equation cannot be applied blindly. As a simple example, one cannot, in general, simply increase resistance in order to increase power from the electric power grid. The utilities intentionally keep residential input voltage at a constant 120 V, regardless of the power drawn from the grid. Since Ohm's law applies and voltage is held relatively constant, then decreasing resistance causes an increase in current. The increase in current impacts power by its value squared. Thus, decreasing resistance in this case actually causes a significant increase in power. The extreme limit of this would be setting the resistance to zero, causing a short circuit, also known as a power fault.

The power line experiences a different situation: current is effectively constant while voltage changes. The current drawn by the loads on the line controls the current flow over the line; the line resistance has a negligible impact on the current relative to the consumers. Thus, from the power line's perspective, current is constant and the voltage drop along the line changes. Thus, utilities have to address this voltage drop in order to maintain a constant 120 V power supply to all consumers along the entire power line. The I^2R formula shows that resistive heating, which is lost power, is directly proportional to the resistance in the line.

Now consider the voltage level and transmission line losses in light of Equations 1.7 and 1.8. There are many choices of I and V that yield a given power P. However, since thermal losses are proportional to I^2, these can be minimized by choosing a low value of I and a correspondingly higher value for V. Thus, high-voltage transmission appears to be more efficient, and that is what is used. In the early days of power distribution, the transformer had not yet been invented; distances were limited to only a few miles due to the relatively large current and low voltage. The trade-off with modern high-voltage transmission and distribution is the greater cost and care required to keep the higher electrical potentials insulated.

1.3.5 Electric and Magnetic Fields

Fields were developed as a means to quantify how objects that are not in physical contact were able to exert forces upon one another. A field may seem like an abstract mathematical map, like a topological map of elevation, but without apparent physical reality. The attraction and repulsion of charges is a classic example of a field, although gravitation is probably a more commonly encountered field for us. We are attracted to the Earth without any apparent force pushing or pulling us to the Earth. There is a clear direction and force that objects are attracted to the Earth that can be mapped at all points in space. This mapping is a field. However, a field is more than an abstract mathematical map. During his investigations into magnetism, Michael Faraday first realized the importance of a field as a real physical object. He realized that fields have an independent physical reality because they carry energy.

Fields are extremely important in both power systems and communications. Fields create the power that flows through the electric power grid, fields pulsate along the transmission and distribution lines, and fields move the machines for the power consumer. In communications, fields are a critical component of electric oscillators, and they ultimately transport signals through space. Fields are truly the workhorse for both power systems and communications.

Recall that the electrical potential energy quantifies the potential energy of a specific charge given its attraction and repulsion to all other charges. If the other charges remain fixed, then the potential energy changes with the location of the specific charge that we are discussing. Conceptually, the charge can be moved to every location and the potential energy recorded, thus creating something analogous to a topographical map, where altitude on the map corresponds to the amount of energy at that location. In a topographical map, lines are drawn along paths of constant altitude; lines that are closer together indicate a more rapid change in altitude. The topographical map would be analogous to the electric field, but with a significant difference. The electric field maps the force on the charge at a given location, not the potential energy. The force on the charges decreases at a rate that is the square of the distance.

There is another type of field that is distinct from the electric field: the magnetic field. A charge in motion creates a magnetic field. This occurs at the subatomic level as well as the macroscopic level. Electrons are charges in motion, they have both orbital motion and spin. When these motions are aligned, a material becomes magnetic. However, unlike charge, a magnetic field has two poles, positive and negative, or north and south from its use on a compass; the magnetic field must exist as a dipole. Since moving charge creates a magnetic field, it stands to reason that a current, which is a set of charges in motion, should also create a magnetic field. This is remembered by every student as the right-hand rule: using your right hand, point your thumb in the direction of the current, then your fingers will curl in the direction of the magnetic field. One can increase the current to increase the magnetic field or, alternatively, place more wires with current near each other going in the same direction, in which case the magnetic fields will add. This can be done conveniently by looping a wire upon itself. The magnetic field lines that are concentrated near the center will add to one another, creating a strong field in the center. We can again visualize our topographical map with many lines near the center of the coil representing the strong magnetic field. The right-hand rule is shown in Figure 1.5.

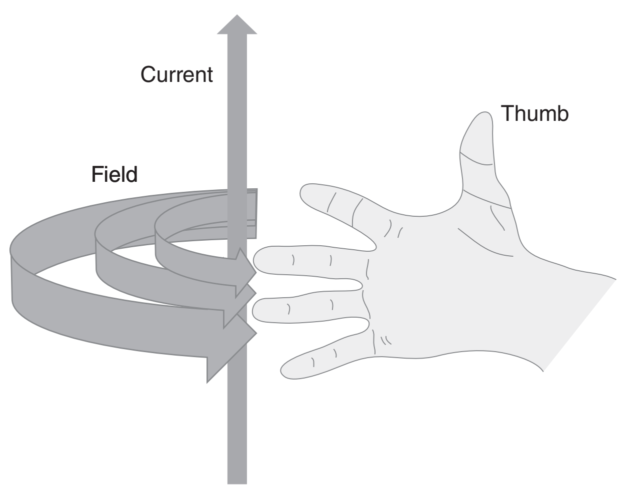

Figure 1.5 The right-hand rule, in which the straight thumb points in the direction of the current and the curled fingers in the direction of the magnetic field. Source: By Jfmelero (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0-2.5-2.0-1.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons.

The magnetic field has a direction and is denoted by the vector $\vec{B}$ and is quantified in units of teslas (T) or gauss (G). A tesla is equal to one newton per ampere-meter. This can be seen as a particle with a charge of one coulomb passing through a magnetic field of one tesla at a speed of one meter per second experiencing a force of one newton. A tesla is simply 10 000 G. A related measure is magnetic flux, which has to do with the density of the magnetic field. Magnetic flux, denoted by ϕ, is the amount of magnetic field passing through a given surface; its unit is the weber (Wb), but it may also be commonly expressed in derived units of tesla-square meters.

1.3.6 Electromagnetic Induction

We have just seen that motion of an electric charge creates a magnetic field and, as mentioned in Section 1.3.5, the magnetic field can exert a force on a charge, causing charges to move and creating an electric current. This process of creating current is extremely important as it is the basis of electric power generation and is involved in the operation of electric motors, among other applications. However, in order to create a continuous electric current, the magnetic field must be continuously moving. Let us look at the geometry involved in this production of current. Imagine that the magnetic field lines are pointed upwards coming out of this page, like spikes. Now imagine a wire lying on this page from the top to the bottom of the page and sliding across the page from left to right. This motion of the wire across the page would cause a current to flow through the wire, forcing the negative electrons to flow out the bottom of the wire. The Lorentz equation describes this:

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}, \tag{1.9}$$

where q is the charge, $\mathbf{F}$ is the force vector, and $\mathbf{B}$ is the magnetic field. The cross product can be remembered by again using the right hand. Point the index finger in the direction of the motion of the wire v and the middle finger in the direction of the magnetic field B. The thumb points in the direction of current flow. The cross product is defined as $\mathbf{a} \times \mathbf{b} = ab \sin\theta\mathbf{n}$, where n is defined by the right-hand rule just mentioned and θ is the angle between a and b. Thus, as the angle formed by the direction of the velocity of the wire with respect to the direction of the magnetic field becomes less than a right angle, current flow decreases. If the wire moves parallel with the magnetic field, then no current will flow. Both the motion of the wire and a changing magnetic field strength will cause current to flow. Both methods are used in the generation of current. This process of creating a current is known as electromagnetic induction.

Electromagnetic induction plays a significant role in sensing and communications, as well as within generators and motors for power systems. As a simple example, conductive loops embedded within the pavement at traffic intersections are used to sense when a vehicle is located directly above. This is detectable because the metal within the vehicle changes the inductance of the loop; an LCR oscillation with the loop changes frequency, indicating the presence of a vehicle – usually this is used to change a traffic signal. Induction is used for both power and communications for implanted medical devices, such as hearing aids. As a final example, induction was used in early radio-frequency identification (RFID). An RFID reading device emits electromagnetic waves that are used to communicate with an RFID tag. The magnetic component of the electromagnetic waves of the reader can induce a current in the tag not only to transmit information, but also to supply power to the tag. Thus, the tag can be completely passive; it does not require a power supply. However, it required a conductive coil that was not always as small as users would have liked. Later, capacitive coupling was used involving carbon ink on paper. Finally, active tags were used in which tags could store a significant amount of their power and actively transmit radio-frequency signals. The goal here is not to go into detail on traffic detectors or RFID technology, but simply to highlight the relationship between power, communications, and, in this case, inductance.

We have now been introduced to enough background information to address an interesting phenomenom: the propagation of electromagnetic fields; namely, electromagnetic waves. Almost every grade-school student knows about radio waves; most of us grow up having been "taught" about radio waves and take this fact for granted, but what are electromagnetic waves? How do we know they are waves at all? Why should this energy propagate and what precisely leads us to believe that this propagation takes the form of waves? Since electromagnetic waves play such a large role in communications, it is important to take some time to address this. For now, let us continue the discussion assuming we know they are waves; the wave aspect will be discussed a bit more precisely later.

As mentioned previously, an electric charge of a field in motion creates a magnetic field. An electric field with a pulsing wavelike shape is continuously in motion; thus, its motion creates a magnetic field at right angles to the electric field. The wave is self-propagating, with each field inducing the other. The wave frequency is measured in cycles per second or hertz and the wavelength is the distance from one wave crest to the next wave crest. The frequency in cycles per second multiplied by the wavelength, or length from one cycle to another, yields the velocity of the propagating wave. The speed of a propagating wave happens to be constant: the speed of light, or 3×10^8 m/s or 186 000 miles per hour. Thus, there is a fixed relationship between wavelength and frequency, since the product is constant. A faster frequency results in a shorter wavelength. The speed of light makes physical sense since it is the speed at which the electromagnetic fields are able to induce each other at the same strength. If the wave propagation were faster, the fields would create energy, which is impossible. If they were slower, they would lose energy that could not be accounted for in the conservation of energy. Thus, from the conservation of energy, one can derive the speed of electromagnetic propagation; that is, the speed of light.

This propagation phenomenon has been utilized in many different ways for communication, from fiber-optic cable carrying light waves to wireless radio communication. Wireless communication is particularly instructive to consider. In the transmitter, electric charges move or oscillate in a manner that conveys information. This electric charge, moving through the antenna, creates an electric field. This electric field creates a corresponding magnetic field that radiates into space. When the self-propagating electromagnetic radiation reaches a wire, as discussed earlier, the motion of the magnetic field relative to the wire causes charge to flow through the wire. This charge will have the same frequency as the magnetic field that created it. Thus, the information embedded in the characteristics of the magnetic wave, such as its amplitude or frequency, will be reflected in the charge induced in the antenna. However, it is important to note that an electromagnetic field does not "know" whether a wire or other conductor happens to be a receiving antenna. It will obviously induce a corresponding current in any conductor. Thus, electromagnetic radiation from the sun occasionally impacts the Earth with enough energy to induce dangerous levels of current within power lines. This can be enough current to cause transformers to melt or breakers to trip. In other words, the power lines of the power grid become a planetary antenna.

1.3.7 Circuit Basics

Now that we have completed a very brief and intuitive look at the role of the fundamental physics, including electromagnetic wave propagation, let us return to a very brief and intuitive review of electric and magnetic circuits. Along with the rest of this section, this is a quick review and we will assume that the reader has some background in basic electronics. Thus, this section will move quickly over basic material, dwelling only on those aspects of particular importance in either power systems or communications.

We begin with resistance, or load, from a power systems perspective. Resistance is summed when the resistances are in series with one another. Conductance is the inverse of resistance. Conductance is summed when the resistances are in parallel with one another:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots \tag{1.10}$$

Assuming three resistors in parallel, simple algebraic manipulation yields

$$R = \frac{R_1 R_2 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3}. \tag{1.11}$$

The solution to complex random resistor networks can be found using matrix analysis and is discussed in Bush, 2010b, pp. 102–106. This will be discussed further in Chapter 6 on network topology and complexity; the important point here is that current and voltage through a circuit are primarily a network topology problem.

In power systems, customer loads are designed to be connected in parallel with the power grid. This allows the voltage to remain constant for all customer loads. However, the loads will draw more or less current as their operation varies in order to provide the appropriate amount of power. Thus, with loads in parallel, each load can remain independent of the other loads on the same line. Interdependence among loads will only occur under abnormal conditions; that is, if such a large amount of current is drawn that it impacts the local voltage, then all other voltages on the line will be impacted.

Kirchhoff's voltage law simply states that the sum of the voltages around a closed loop must be zero. There are many intuitive ways to arrive at this law. For one example, picking any point in a circuit and measuring the voltage at points around the circuit (with reference to another common point for all measurements), it only makes sense that when we reach all the way around the circuit back to the initial point that we should measure the same voltage; there would be no reason for it to be different. Also, this is a form of conservation of energy; if the electrical potential around the loop did not sum to zero, then one could propel a charge around the loop indefinitely. This would be similar to the famous painting by Escher in which a waterway forms a loop, yet all the waterfalls along the way seem to flow down hill, an impossibility illustrated in his painting entitled *Waterfall*.

The Kirchhoff laws exist within Maxwell's fundamental equations. To see this for Kirchhoff's voltage law, start with Equation 6.40, Faraday's law of induction (this will be introduced in detail in Chapter 6) in a static field. Then consider that $\nabla \times \vec{E} = 0$. Next apply the Kelvin–Stokes theorem shown in Equation 1.12:

$$\int_{\Sigma} \nabla \times \mathbf{F} \cdot d\mathbf{\Sigma} = \oint_{\partial\Sigma} \mathbf{F} \cdot d\mathbf{r}. \tag{1.12}$$

This results in

$$\oint_{C} \mathbf{E} \cdot d\mathbf{l} = 0. \tag{1.13}$$

This equation shows that the line integral of the closed loop C around the electric field is zero. In other words, there is no potential difference around the closed loop C, where C is any arbitrary closed loop.

Kirchhoff's current law states that the sum of current entering and leaving a point in an electric circuit must sum to zero. This is simply another conservation law: charge cannot be created, destroyed, or stored in some hidden form, within the circuit. Kirchhoff's current law can be found in both Gauss's law (6.37) and Ampère's law (6.41).

Kirchhoff's voltage and current laws are extremely simple, yet they form an underlying basis for much of power systems today. Given an electric circuit, it is possible to use the Kirchhoff laws to construct a matrix of linear independent equations that can be used to solve for the currents and voltages for all components of a circuit. In fact, the Kirchhoff or admittance matrix plays a large role in studying network topology, since the network topology defines the electrical circuit. It is also worth noting here that researchers are exploring ways of using the operators that appear in Maxwell's equations, such as the divergence operator, within network graphs. The primary difference is that the operators, such as the Laplacian, that appear in Maxwell's equations are continuous operators; that is, they apply to continuous spaces and flows. The analogous operators on graphs are discrete, such as the discrete Laplacian; they apply to discrete values related to nodes within the network.

There is also a superposition principle that applies to electrical circuits. This principle states that the combined impact of multiple current or voltage sources within a circuit can be analyzed independently and the effects can be summed. Conceptually, for example, each generator in a DG system can be analyzed independently as delivering power to a set of customers; the sum of the transmission flows on a power line can then be added. Since, as we mentioned earlier, voltage is held constant, each source can be thought of as supplying current, where the currents through the transmission and distribution networks are additive. The superposition principle can be applied strategically to help simplify analysis.

1.3.8 Magnetic Circuits

We just completed a very brief review of electrical circuits by covering a few of the more important highlights. We continue the pattern that began early in this chapter of finding a magnetic analog for each electrical topic. Here, we discuss the analog to electrical circuits; that is, magnetic circuits. An electrical circuit is quite familiar to everyone; usually it is thought of as wire conductors carrying current from an electrical power source through a load and back to the power source. Current is the flow of electric charge. Recall the discussion of a magnetic field; there is no magnetic charge. The magnetic field is comprised of loops; there is no beginning and no end to magnetic field lines. The density of the magnetic field lines is described by the magnetic flux. Magnetic flux is a measure of the amount of magnetic field passing through a given surface area. Note that, technically, it is the net number of magnetic field lines passing through a given surface area; magnetic field lines that pass in the opposite direction through the surface are subtracted from the total. Also, the amount of flux ϕ depends upon the angle of the field lines through the surface; field lines perpendicular to the surface increase the flux more than lines that have a component that is parallel with the given surface.

Magnetic circuits carry magnetic flux just as electric circuits carry electric current. Since the magnetic field lines always form a loop, there is a natural circuit-like path for the magnetic flux. A magnet, as a source of magnetic field lines and thus magnetic flux, has a stronger flux closer to the magnet and a smaller flux farther away. Magnetic circuits play a significant role in generators and transformers, and generally anywhere there are strong magnetic fields and coils involved.

Reluctance $\mathcal{R}_{\mathrm{m}}$, used in the analysis of magnetic circuits, is analogous to resistance in an electrical circuit. It quantifies the difficulty magnetic flux has in flowing through a material. Similar to the way an electric field causes an electric current to follow the path of least resistance, a magnetic field causes magnetic flux to follow a path of least magnetic reluctance. The magnetic permeability is the ease with which a magnetic field flows through a substance and is denoted by μ. The reluctance is related to the physical property of a material by

$$\mathcal{R} = \frac{l}{\mu A}, \tag{1.14}$$

where l is the length of the material and A is the area of a cross-section of the material. μ is to the magnetic flux as conductivity is to electric current. A significant difference between magnetic flux and electric current is that the conductivity of metals is so much higher than other materials commonly encountered that current remains confined to the conductive element. μ_0, the permeability of a vacuum, is not zero and air has a permeability that supports magnetic flux. Thus, magnetic flux is not confined as neatly as current to conductive media. There is usually the notion of a leakage flux that must be taken into account.

While we know the **B** field, it becomes modified within a material due to magnetic fields produced by the material itself, and this modified field is known as the **H** field. As previously mentioned, the permeability μ is a property of a material's ability to permit the magnetic field to flow through it. The relationship between the **B** and the **H** fields is as follows:

$$\mathbf{B} = \mu\mathbf{H}. \tag{1.15}$$

We know that magnetic flux is the analog of current in an electric circuit, but what is the analog of voltage? There is a magnetomotive force (mmf) analogous to the electromotive force that is thought of as generating the magnetic field. As we know, the strength of the magnetic field depends upon the flow of electric current that creates it. By looping wire into a coil, the impact of the current flow adds up in creating the magnetic field. Thus, Equation 1.16

quantifies the mmf, where N is the number of turns in the coil and i is the current flow through the coil:

$$\text{mmf} = Ni. \tag{1.16}$$

As mentioned earlier, Ohm's law relates voltage to current and resistance, $V = IR$. Hopkinson's law is the corresponding analog in magnetic circuits:

$$\text{mmf} = \phi\mathcal{R}_{\text{m}}, \tag{1.17}$$

where ϕ is the magnetomotive force (mmf) across a magnetic element, ϕ is the magnetic flux through the magnetic element, and $\mathcal{R}_{\text{m}}$ is the magnetic reluctance of the element. A simple algebraic manipulation is

$$\phi = \frac{\text{mmf}}{\mathcal{R}}. \tag{1.18}$$

The reluctance is generally not linear with the magnetic flux for most materials; thus, reluctance is not as simple to use as resistance. However, the reluctance in series is additive in a similar manner to resistance.

As mentioned earlier, the magnetic flux is a measure of the magnetic field lines flowing through a given surface area. That surface can be the turn of a coil. Magnetic flux flowing through the turns of a coil is said to link the coils. Flux linkage λ is a measure of the impact of the magnetic flux through the coils:

$$\lambda = N\phi, \tag{1.19}$$

where N is the number of turns of the coil and ϕ is the magnetic flux.

Recall that the charge through the coil creates the magnetic field, and thus the flux, but also the magnetic field stores energy and can create a current flow back into the coils. In the latter process, known as induction as we have already discussed, the role of the flux linkage is shown in

$$\lambda = Li, \tag{1.20}$$

where L is the inductance measured in henries, which will be discussed in more detail in a later section. Looking at the last two equations, inductance is conceptually a measure of how much flux linkage is associated with a given amount of current.

This section has covered the foundation by explaining charge, voltage, ground, conductivity, Ohm's law, electric circuits, electric and magnetic fields, electromagnetic induction, circuit basics, and magnetic circuits. There is more to cover on the fundamentals of power systems and communications; this material will be continued in the following chapters where it more closely pertains to the chapter topic. The material covered in the above sections will be used in later chapters on generation, transmission, distribution, and consumption. For the remaining sections of this chapter, the important point is that there is a set of complex physical phenomena taking place in power systems. As the power grid becomes larger and more interconnected, complexity increases. Therefore, let us change perspective and look briefly at a study of power system failures to motivate how and why the power grid could be improved. Following that, we will discuss the driving forces and goals of the smart grid. Finally, we will complete the chapter with a foreshadowing of the notion of entropy and information as it relates to power systems.

1.4 Case Studies: Postmortem Analysis of Blackouts

We are taking a short break from the basic physics of power systems to examine how the power grid operates at a higher, more abstract level. It is important to keep both low-level operation and high-level system interconnectivity in mind when thinking about the power grid. Focusing solely on the low-level physics can cause one to miss important, potentially catastrophic, high-level characteristics. More specifically, we will look at how the power grid can fail from a system-level, network perspective. We want to look at actual faults that have occurred in the power grid in an effort to understand why they occur and how the power grid might evolve in such a manner as to lead to improvement. We want to take a critical look at smart grids and consider carefully where this could lead, whether to more reliable and improved systems or whether it could take us closer to a “tipping point.” Much of the smart-grid research has focused on attempting to improve system efficiency assuming that they operate perfectly. It is also possible to learn from mistakes.

1.4.1 Blackouts Have Something to Teach Us

As the reader may begin to imagine from the introduction to the fundamentals of power systems that has been covered so far, the electric power grid is a large, interconnected, dynamic system. It has been called the most complex machine ever built by humans. It is a complex system in which the rules of complex systems should apply and provide insight into its operation. A complex system is one that lives at the boundary between order and chaos. If too ordered, the system is locked into an equilibrium state and therefore slow and unable to adapt to changing conditions. If too chaotic, it responds too quickly and breaks apart into random components and loses coherence as a single system. Thus, many complexity theories focus on systems that naturally live at the transition between order and chaos. In such systems, an attractor is a state of a system toward which the system will naturally tend to gravitate, even if perturbed.

One of the most simple and intuitive examples of a complex system has been a growing sand pile: adding a single grain of sand to a sand pile may have no effect or it may cause a catastrophic avalanche that impacts all grains of sand in the pile. A common feature of such complex systems is scale invariance, also related to self-similarity, the notion of correlation of behavior, at all scales, throughout the entire system. A complex system is able to respond globally, as a single coherent system, to local events. Somehow, information is propagated throughout the system to bring it back to its natural state, its attractor. This particular form of complex systems theory has been called self-organized criticality (Bak *et al.*, 1987). The power grid appears to show signs of this behavior, as we will see. Power grid failure is analogous to adding a grain of sand on a sand pile: there is either no effect or a large avalanche, the equivalent of a cascade event, or catastrophic failure. This is the scale-invariance aspect; there is no correlation between the perturbation and the resulting impact. Thus, even a small perturbation can lead to a large power grid cascade. This is related to brittle systems theory (Bush *et al.*, 1999), in which high-performing systems tend to fail less often, but when they do fail they tend to fail catastrophically rather than degrade gracefully. If our complex system happens to be the power grid, we would like to know if the smart grid, which seeks greater efficiency and pushes the power grid closer to its limits of operation, is unwittingly designing an attractor that takes us into this high-performing, but catastrophic, failure regime.

Scale invariance can be expressed mathematically rather simply by the power law. Given a relation $f(x) = ax^k$, changing the magnitude of the argument x by a constant amount c results in a proportionate change in magnitude of the function itself, as shown in Equation 1.21:

$$f(cx) = a(cx)^k = c^k f(x) \propto f(x). \tag{1.21}$$

In other words, scaling by a constant c simply multiplies the original power-law function by a constant value c^k. All power laws with a given scaling exponent k are equivalent within a constant factor, since each is simply a scaled version of the other. This creates a linear relationship that becomes apparent when logarithms are taken of $f(x)$ and x. Of course, one must be careful in making generalizations, because only a finite amount of real data can be plotted, the straight-line signature on a logarithmic plot indicative of a power law is a necessary, but not a sufficient, condition of a true power-law relation. So, does the power grid really exhibit the characteristics of a complex system? And if so, what does that imply for a smart grid? We can address the first question directly. The second question is one that you, the reader, who will likely be engineering the smart grid, will need to answer as we dive deeper into the power grid throughout this book.

Many networks have degree distributions that follow a power law as shown in Equation 1.22, with the exponent γ typically lying between 2 and 3:

$$P(k) \approx k^{-\gamma}. \tag{1.22}$$

A typical network analysis examines the percolation, or connectivity, of the network as nodes either fail or are maliciously attacked. The goal is to examine the robustness of the network structure; that is, the ability to keep all nodes in the network connected as nodes or edges are removed, representing faults or attacks. A typical assumption is that faults will occur to nodes at random, while attacks will occur to more highly connected nodes. The critical fraction f_c is the fraction of nodes removed from the network before the network disintegrates; that is, the network is no longer a single connected component (Cohen *et al.*, 2000). The critical fraction f_c can be determined analytically from a specific network topology. A study of the European power grid (Solé *et al.*, 2007) compared real outages with the theoretical critical fraction. For larger power law exponents $\gamma > 1.5$, the expected f_c values are very similar to those predicted by theory. These are referred to as robust networks in the discussion that follows. However, power grids having lower exponents (when $\gamma < 1.5$) strongly deviate from the predicted values. These are referred to as fragile networks in the discussion that follows. While no clear reason for this distinction was found, the suggestion was put forward regarding the growing interconnectivity in aging power infrastructures. Specifically, to increase the reliability of the power grid, more redundant connections are added, increasing the interconnectivity of the power grid network. However, while the intention of increasing reliability is good, unintended effects could be that faults can also propagate more easily through such highly interconnected

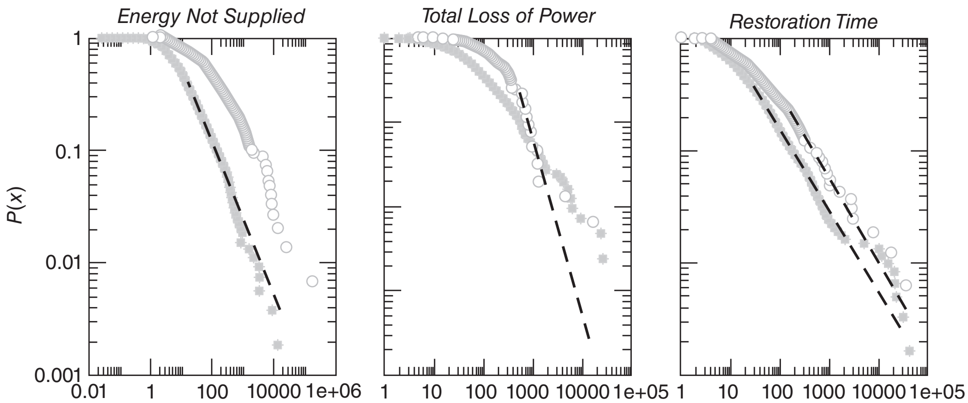

Figure 1.6 The occurrence versus severity of blackouts is expressed in the amount of energy that was not supplied, the loss of power, and the power restoration time. Energy is in units of megawatt-hours, power is in units of megawatts, and time is in units of minutes. The open circles indicate "robust" network topologies (that is, they have a relatively high degree of interconnectivity) and solid asterisks indicate more fragile topologies (that is, those with less interconnectivity). How is the evolution of smart-grid technology impacting these curves and what will be the impact of smart-grid communication? Will a more complex system, operating closer to its limits, lead to fewer but more severe catastrophes? Source: Rosas-Casals, 2010. Reproduced with permission of IEEE.

networks and that it can become a more complex process to isolate faulted segments of such highly interconnected networks. Ideally, smart-grid communication should be able to make complex wide-area fault detection, isolation, and restoration more efficient and help dampen instability problems before they propagate too far in such highly interconnected networks. However, it is always important to beware of unintended consequences.

Figure 1.6 clearly shows the scale-invariant nature of historical power faults in the European power grid. As we discussed regarding self-organized criticality, these scale-invariant features can be signs of complex, brittle systems. As smart-grid communication is added to the power grid and the power grid becomes more sophisticated they will become more complex, and we could expect the power law exponents to continue to increase. The power grid will become more efficient and operate closer to its limits; for example, its thermal limits. Power faults will become few and far between. However, in order to maintain the power law, when faults do occur, they will be larger and more catastrophic. Again, we need to watch for unintended consequences and avoid a brittle system (Bush *et al.*, 1999).

Taking a step beyond solely network structure, research has looked at how load capacity of networks interacts with network structure (Zhao *et al.*, 2004), where load is a general commodity; for example, data, power, or water flow. In other words, it is addressing the problem of how well a system can redistribute load when the network structure is perturbed. The concept here is that homogeneous loads – that is, an equal distribution of loads on all links – tend to survive better than heterogeneous loads in such systems. The notion of power flow entropy has been defined to address this issue.

In discussing communication in the smart grid, we need to be cognizant of the fact that communication is most needed and most critical when the power grid is under stress; that is, when the network is on the verge of undergoing catastrophic failure. However, when the power

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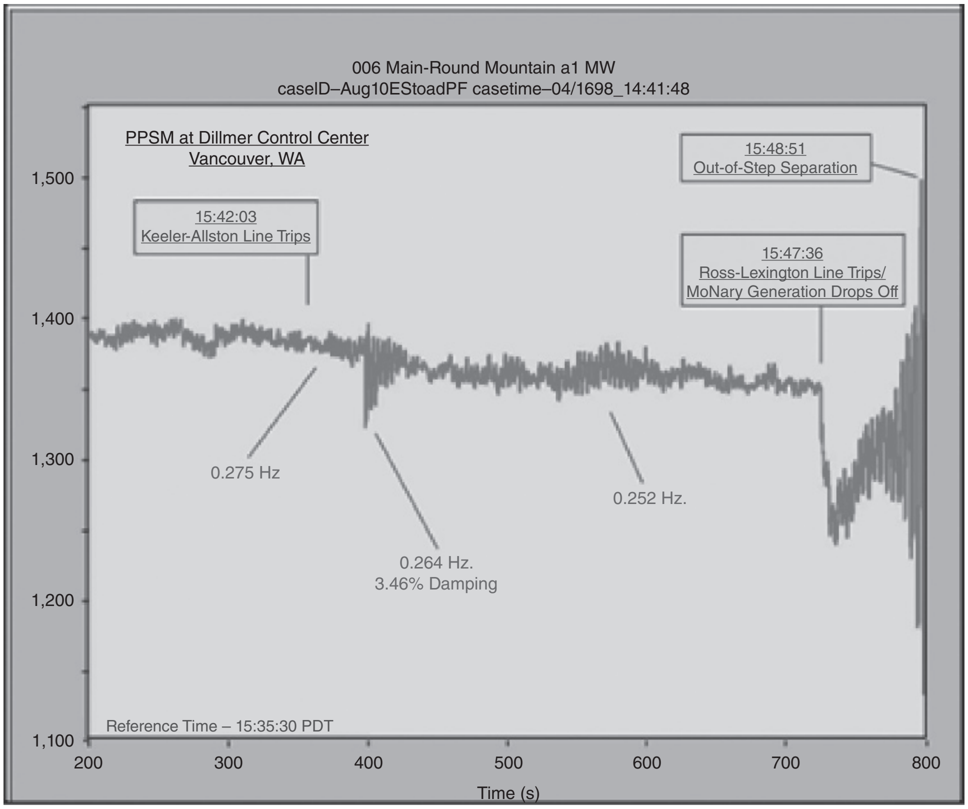

Figure 1.7 Voltage versus time is shown for a power grid that is encountering problems. Communication is most needed when the system is stressed and large amounts of difficult-to-compress data must be transferred. Source: Dagle, 2006. Reproduced with permission of IEEE.

grid is under stress, the information being measured and transmitted becomes more erratic, harder to compress, and requires more bandwidth to represent with the same fidelity. In fact, the current modus operandi, without communication, is to analyze power grid data in detail *after* a system collapse. As an example, Figure 1.7 shows voltage versus time for a power grid that is in trouble. The voltage is no longer constant as it should be, but fluctuating wildly. Since we have been previously discussing scale-free systems, scale-free data has few patterns; it is similar to white noise and nearly incompressible, potentially requiring large amounts of bandwidth. In fact, research has been done on determining the health of a system by examining the compressibility of its measured parameters (Bush, 2002).

1.4.2 A Brief Case Study

One of the largest blackouts occurred in the northeastern USA in August of 2003. We can try to understand this tragic event as a real-life example of a power system failure to stimulate thinking about what a "smart grid" might do in the future to improve the situation. We should

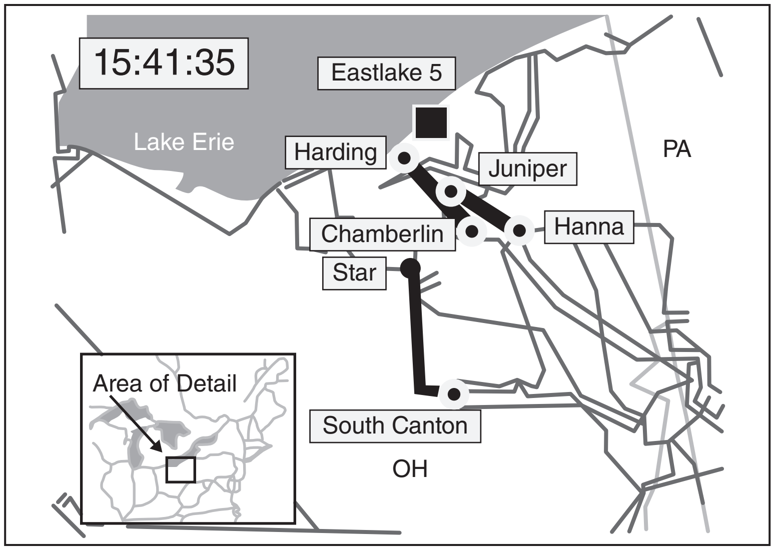

Figure 1.8 Location of the origin of the 2003 US northeastern blackout highlighting the major locations of events that escalated into the blackout. Source: Makarov *et al.*, 2005. Reproduced with permission of IEEE.

also be thinking about what role communications did play, or could have played, in this real-life cascading blackout.

August 14, 2003, began as a typical day, and remained typical until 3:05 p.m. EDT. There was no impending sign of a blackout. It was a hot day and electric power demand was, as is typical, high for use in air-conditioners. However, the demand was not excessively high. There was a heavy draw of power from both the south and west, through Ohio, to the north, including Michigan and Ontario, and the east, including New York. As we will learn later, alternating current frequency is a significant indicator of power grid health. The frequency was variable, but not excessive. Several generators were out of service that day; however, the power system operators, as they normally should, ran contingency analyses for that day and determined that there was still a safe operating margin. In fact, after the incident, investigation found that the Northeastern Interconnect was able to withstand any of at least 800 of the most likely contingencies that were modeled. In other words, the system should have had capacity to spare even with generators out of service. The epicenter of the blackout is shown in Figure 1.8.

Voltage was low in northern Ohio during the morning and early afternoon of August 14; but again, apparently not excessively so from a historical perspective. The area around northern Ohio was, in fact, operating near a voltage collapse, although this fact by itself was not found to be the direct cause of the blackout. The high power demand for air-conditioning and the lack of reactive power, to be explained in more detail later, caused the system to approach a voltage collapse. It was later determined that power system operators had not sufficiently studied the minimum voltage and reactive power supply that was required in the Cleveland–Akron area. Owing to the heavy load, northern Ohio was a net importer of power that day, importing a peak of 2853 MW, which also caused a high consumption of reactive power. Heavy use of inductive motors, such as those used in air-conditioning, causes the power factor to decrease and increases reactive power consumption. As mentioned, some generators in the area that could have helped supply reactive power were out of service due to scheduled maintenance; however, this was also not found to be a direct cause of the blackout.

Around noon on August 14 some protective relays began to trip in the area. These trips were not yet considered a direct cause of the blackout, but they had an impact. First, the Columbus–Bedford line tripped due to tree contact; tree contact was soon to play a significant role in later trips that led to the blackout. Then the Bloomington–Denois Creek 230 kV line tripped due to a downed conductor caused by a conductor sleeve failure. This was important because the loss of this line was not included in the system's state estimation procedure. State estimation, to be discussed in detail later, is used to improve accuracy when determining the state of power flows through the system given limited sampling information. Around 1:30 p.m. EDT, the Eastlake Unit 5 generator, which was capable of supplying much-needed reactive power and being pushed to its limits to meet demand, tripped, taking the system offline. This further increased the need to import more power into the area, although transmission line loads were still well within the limits of their maximum capacities.

The operators were clearly aware of the impending voltage problem and took steps to address the issue (NERC Steering Group, 2004), making the following calls.

- Sammis plant at 13:13: "Could you pump up your 138 voltage?"
- West Lorain at 13:15: "Thanks. We're starting to sag all over the system."
- Eastlake at 13:16: "We got a way bigger load than we thought we would have. So we're starting to sag all over the system."
- Three calls to other plants between 13:20 and 13:23, stating to one: "We're sagging all over the system. I need some help." Asking another: "Can you pump up your voltage?"
- "Unit 9" at 13:24: "Could you boost your 345?" Two more at 13:26 and at 13:28: "Could you give me a few more volts?"
- Bayshore at 13:41 and Perry 1 operator at 13:43: "Give me what you can, I'm hurting."
- 14:41 to Bayshore: "I need some help with the voltage … I'm sagging all over the system…" The response: "We're fresh out of vars."

The operators also requested that capacitors at the Avon substation be restored to service. We will see later in the book the impact of adding capacitance to correct the power factor.

Now we can see that the system was close to a voltage collapse, but no generators were asked to give up active power to generate reactive power. As previously mentioned, relatively large power transfers were taking place through northern Ohio from the southwest toward the northeast. One question that was considered was whether the voltage problems in northern Ohio were due to the high demand of the power transfers that were taking place. It was determined that the power transfers had minimal impact; the inability to supply reactive power given the high demand was the main cause of the voltage problem.

Analysis of the alternating current frequency in the area showed a mean drop in frequency precisely at noon; however, this was a planned event in order to implement a time correction. Frequency was in general variable, but not outside what was considered normal. There was a pattern to spikes in frequency prior to the blackout, but this can be explained by the scheduled ramping-up of generation attempting to meet demand.

Now that we have painted the picture of the situation leading up to the blackout, we now proceed to what has been determined as the direct causes of the blackout. The first cause was already mentioned: the loss of the Bloomington–Denois Creek 230 kV line and, more significantly, the fact that the line loss was not reflected in the state estimator, causing the state estimator to become inaccurate. A series of local events occurred that then led to the Sammis–Star 345 kV transmission line tripping, which began the uncontrolled cascade that spread through much of northeastern North America. So how did these events occur?

First, as mentioned, the Eastlake 5 generator tripped. There was speculation that if Eastlake 5 had not tripped there would have been a remote possibility that the cascade and corresponding blackout could have been avoided. However, the Eastlake 5 trip is not officially considered a primary cause of the blackout, because even with the loss of the Eastlake 5 generator the system was still within secure operating limits. A more direct cause of the blackout occurred at 2:14 p.m. EDT when the alarm and logging systems in the control room failed, causing operators to lose awareness of the situation as it evolved. This obviously impacted the capability of the EMS and severely degraded the ability of the operators to monitor and control the system. This only appears to have become evident around 2:30 p.m. EDT when a telephone call was received that indicated the Star–South Canton 345 kV tie line opened and reclosed. Until the phone call was received, the local operators had no knowledge of this event; this was the first clear indication to the operators that they were flying blind. The next local event leading directly to the blackout was the loss of two more key 345 kV lines in northern Ohio due to power line contact with trees. This shifted power flows from the 345 kV lines onto a network of smaller capacity 138 kV lines. Here we begin to see a cascade in action. The 138 kV lines were not designed to carry such large amounts of power and they quickly became overloaded. At the same time this happened, voltage suddenly decreased in the Akron, OH, area. Now it becomes important to understand distance relay protection, which will be explained in detail in later chapters. For now, simply put, the increased loading and decaying voltages caused 16 138 kV lines to trip sequentially between 3:39 p.m. EDT and 4:09 p.m. EDT. To put it another way, the 138 kV system in northern Ohio was in the process of a cascading failure. The heavily loaded lines were sagging into vegetation, other distribution lines, and onto other objects, causing widespread electrical faults. There was now a tremendous need for power to meet demand in the area over the only remaining transmission line, the Sammis–Star 345 kV line. The Sammis–Star transmission line finally gave way, tripping at precisely 16:05:57 on August 14, beginning an uncontrollable cascade of the Northeastern Interconnect power system. The tripping of this line was a “phase transition,” or interface, between the local cascade, confined to northeastern Ohio, to the rest of the interconnect system. Loss of this heavily loaded line began a domino effect of overloaded lines that spread west to Michigan and then east, isolating New York from Pennsylvania and New Jersey.

There are many fascinating details that occurred throughout this entire ordeal that relate in various ways to communication, although communication was never mentioned as a key factor at the time. Recall that after the Bloomington–Denois Creek 230 kV line tripped, the state estimator was not updated with this information and the mismatch between the state estimator and measured values became unacceptably large. Although this problem was quickly corrected, the analyst running the state estimator forgot to reset the estimator to run automatically at 5 min intervals as it normally should. By 2:40 p.m. EDT, the failure to enable the automatic operation of the state estimator was discovered soon after the Stuart–Atlanta 345 kV line tripped. However, the estimator was restarted without the information about the last line trip. Thus, the state estimator was again giving unacceptably large errors. The state estimator was finally corrected around 4:04 p.m. EDT, too late to provide a critical warning of the impending cascade.

It is clear that by 3:46 p.m. EDT, even without the control room alerts and the incorrect state estimator, that both the ISO and the local operators knew the situation was extremely serious. At this point, the only alternative left to save the system would have been to shed load, to deliberately shut off power to local customers in order to at least keep the system running and perhaps save a portion of it. However, even if they had wanted to do so, given the alarm malfunction and the state estimation error, the local operators lacked the monitoring and control necessary to do so. In fact, even if everything had been working perfectly, the local operators had no plan in place for shedding load as quickly as would have been required. So, by this point, any hope of avoiding the impending blackout appears to have been lost.

Investigation later found that an Eastlake 5 generator configuration error caused reactive power to go to zero when the unit automatically tripped from automatic to manual control. The unit finally went completely out of service as operators tried to place it back under automatic control. Finally, a pump valve would not reseat properly, causing significant delay in trying to get the unit back online. It turns out that the net effect of the efforts to keep the generator running with reactive power set to zero actually exacerbated the loss of reactive power in the area rather than helping to alleviate it.

There is another interesting and critical detail. The key cause of the cascade, the Sammis–Star line trip, did *not* occur due to an electrical fault. Rather, high current flows above the power line's emergency rating simultaneous with the low voltage in the area caused the overload to *appear* to the protective relays as a remote fault on the system. In other words, there was no actual electrical fault, but rather the appearance of a fault that caused the protective relay to trip and drop the transmission line. The protection relay could not distinguish between a remote electrical fault and high line load condition. Again, we will discuss operation of the distance protection mechanisms in more detail in future chapters.

Eventually, as the cascade spread, the now-isolated northeast power island was deficient in generation and unstable with large power surges and swings in frequency and voltage. Many lines and generators across the area tripped, breaking the area into several smaller islands. Although much of the disturbance area was fully blacked out, some islands were able to reach equilibrium without total loss of load, including most of New England and approximately half of western New York.

So what do we make of this cascading failure? There were several tree–power line contacts that appeared to be the "grains of sand" that caused the avalanche, using our self-organized criticality metaphor. Clearly, detecting and removing potentially dangerous vegetation is a problem. There was also a computer malfunction that caused operators to lose the ability to monitor the system in near-real time. Finally, as the disaster began to escalate, no one appeared willing or able to pull the plug and purposely shut down power to customers, also known as load shedding, in order to save the system. Clearly, more reliable sensing, communication, and even visualization of the system may have enabled the operators to take action to prevent the cascade. However, even with reliable sensing and communication, network management would have been required. This is because operators were unaware that the computer alarm system was nonfunctional. They had no real-time status of their computer and communication systems in order to check the health of their monitoring and communication systems. While, as mentioned, there was a contingency analysis (CA) done for that day, it was not updated and repeated frequently enough to keep up with the loss of safe margin as the day progressed. The ISO overseeing system reliability for the region was not using real-time network topology in its state estimation. Thus, it was not estimating state properly as transmission lines were tripping.

Finally, neighboring ISO organizations lacked the ability to coordinate activities when they realized faults were occurring in the neighboring ISO's grid. Let us now consider what is driving the smart grid, but also keeping in mind how it might have worked in this tragic event.

1.5 Drivers Toward the Smart Grid

Now that we have considered power grid faults, let us try to hone in more precisely on what the "smart grid" is. This section discusses the economic and social drivers leading toward the smart grid and how the smart grid has been conceived. It is important to keep in mind that there is no absolute, technical, concise definition of the smart grid, only general policies. Trying to unearth the first use of the term "smart grid," like any claim to the oldest evidence for anything in archeology, will quickly be made obsolete by a claim of older evidence; someone will undoubtedly claim to have used the term even earlier. The term "smart grid" became current in the industry around 2003 after the Northeast Blackout of 2003. Current evidence for its first use in the academic community came later in a paper by Massoud Amin in 2004 entitled "Balancing market priorities with security issues" in the *IEEE Power and Energy Magazine* (Amin, 2004). While a few papers mentioned the term afterward, it was not until 2010 when the use of the term exploded in publication. Not surprisingly, this explosion of publications came soon after funding announced in the US federal government's Recovery Act, stimulating researchers to chase funding on the topic of the smart grid. Of course, funding is always the big driver for new research. The term "smart grid" is found in the US code, the official record of Acts of Congress, along with other terms beginning with the word "smart." Specifically, the code from 2007 stipulates:

> It is the policy of the United States to support the modernization of the Nation's electricity transmission and distribution system to maintain a reliable and secure electricity infrastructure that can meet future demand growth and to achieve each of the following, which together characterize a Smart Grid:
>
> 1. Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid.
> 2. Dynamic optimization of grid operations and resources, with full cybersecurity.
> 3. Deployment and integration of distributed resources and generation, including renewable resources.
> 4. Development and incorporation of demand response, demand-side resources, and energy-efficiency resources.
> 5. Deployment of "smart" technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation.
> 6. Integration of "smart" appliances and consumer devices.
> 7. Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning.
> 8. Provision to consumers of timely information and control options.

9. Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid.
10. Identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services.

In Europe, the smart grid was initiated in 2006 by the European Technology Platform for Smart Grids, which is supported by the European Commission.

> A smart grid employs innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies in order to:
>
> 1. Better facilitate the connection and operation of generators of all sizes and technologies;
> 2. Allow consumers to play a part in optimizing the operation of the system;
> 3. Provide consumers with greater information and options for choice of supply;
> 4. Significantly reduce the environmental impact of the whole electricity supply system;
> 5. Maintain or even improve the existing high levels of system reliability, quality and security of supply;
> 6. Maintain and improve the existing services efficiently.

There are many social drivers leading toward the smart grid. Such topics are not within the scope of this book; however, some are mentioned here more for the sake of understanding where the momentum behind the smart grid began. First, grid infrastructure around much of the world is aging; the time will be ripe for replacing power system components within the grid, and we may as well replace those components with new technology. In addition, public interest groups have been pressuring politicians for a "greener" environment by reducing carbon dioxide output and increasing the efficiency of the system. Many of the more environmentally friendly systems, such as wind and solar power, provide intermittent power generation and will require greater grid intelligence and a new grid design with features such as energy storage in order be safe, reliable, and cost effective. Almost everyone would welcome lower energy prices; this puts pressure on regulators to increase competition to reduce prices. This, in turn, requires greater communication among competing entities in order to operate together smoothly. On top of all this, the demand by society for more power is rapidly increasing. This could be exacerbated by the widespread use of electric vehicles.

1.6 Goals of the Smart Grid

The defining characteristics of a smart grid have been summarized by the US Department of Energy's Office of Electricity Delivery and Energy Reliability as:

- provide power quality for the range of needs in a digital economy;
- accommodate all generation and storage options;
- enable new products, services, and markets;
- enable active participation by consumers;

- operate resiliently against physical and cyberattack and natural disasters;
- anticipate and respond to system disturbances in a self-healing manner;
- optimize asset utilization and operating efficiency.

The following subsections briefly discuss each of the goals.

1.6.1 Provide Power Quality for the Range of Needs in a Digital Economy

The assumption is that, as the precision and coverage of power monitoring and control increase throughout the power grid, delivered power quality will come into sharper focus and control. It will become possible to provide distinct levels of power quality and at different costs. One of the challenges with this goal is that there are many definitions and aspects to power quality, as we will see in the following chapters of this book. Certainly, there is a notion of power quality, but as yet there is no clear, defining standard that everyone can agree upon and, more importantly, base a pricing model upon.

1.6.2 Accommodate All Generation and Storage Options

The smart grid should become a "plug-and-play" interface for all forms of DG and energy storage technologies. Of course, this will require a corresponding development of standards. Clearly, the goal is to ease the introduction of new forms of renewable energy onto the power grid. Large-scale energy storage will reduce peak demand for power generation, thus reducing the cost of starting up large plants for short periods of time, which is both wasteful and expensive.

Measurements of success in this area could simply be the number and coverage of interoperable DG and storage standards. The ratio of power generated by DG to centralized generation is one metric, as well as the amount of energy that can be stored. Finally, the reduction in time to install a distributed generator or energy storage device will also be a relevant metric.

1.6.3 Enable New Products, Services, and Markets

Utilities, independent power producers, ISOs, and RTOs have been the primary purchasers of power grid equipment and applications. As communication becomes a more integrated part of power products and applications, these organizations will serve as the traditional market for new smart-grid products. However, it was envisioned that, with the smart grid, it will be possible for the electric power consumer to become a direct purchaser of smart-grid products. This refers not just to large industrial consumers, but downward in scale to individual residential consumers as well. This means that the smart grid must enable enough monitoring and control by the individual residential consumer that it becomes feasible for individual residential consumers to be able to purchase useful and desirable products that are not already feasible today. This goal is tightly coupled with the next goal.

1.6.4 Enable Active Participation by Consumers

Active participation by consumers in the operation of the power grid seems to have initially been related to DR, the idea that consumers should be able to have high-resolution monitoring and control of their property's power usage and the ability to bid for precisely the amount of power they wish to purchase. This requires that every consumer will have the proper communication system to perform monitoring and issue pricing signals for their power bidding.

However, it does not take too much imagination to see that this can be extended to include consumer participation by generating and selling their own power, given the advances in microgrid technology. In this case, the consumer has been called a "prosumer," as in one who may both consume and produce electric power. The idea of zero-energy buildings and zero-energy communities becomes possible when the prosumer or community of prosumers remains self-sufficient.

Measures of active participation by consumers have typically been simply counting the number of consumers with "smart meters." However, this measure will have to become sophisticated as consumers become more savvy. For example, the number of zero-energy entities or the amount of consumer-managed load may be better measures.

1.6.5 Operate Resiliently against Physical and Cyberattack and Natural Disasters

This goal suggests that cyberattacks (malicious attacks against the power grid that are likely to exploit the grid's communication network) are included with natural disasters (natural physical events that disrupt the power grid) when considering resilience. In both cases, cyberattacks and natural disasters, the power grid should operate in a fault-tolerant manner. The notion of resiliency and its opposite, brittleness, are defined analytically in Bush *et al.* (1999). The notion is that a resilient power grid will continue to operate with a loss in performance that is proportional, hopefully a small proportion, to the severity of losses due to cyberattack or natural disaster. In other words, there is no point at which the system suddenly and catastrophically collapses. However, this goal may be competing with other goals, such as optimizing operating efficiency. This is because a system that is highly optimized, operating close to its limits, also tends to be brittle, as discussed in Bush *et al.* (1999). Thus, this goal needs to be kept in mind and given careful consideration when implementing other goals.

1.6.6 Anticipate and Respond to System Disturbances in a Self-healing Manner

A key word in this goal is "anticipate," to provide the power grid with the ability to foresee and avoid potential disturbances. It would be ideal if disturbances could be avoided in the first place. If they do occur, they should be contained quickly to have as little impact as possible. Finally, the impact of a disturbance, if it does occur, should be corrected as quickly as possible. All aspects of this goal point toward automated solutions. A "disturbance" is kept sufficiently vague to encompass any type of event that could interfere with operation of the system. This may range from instability, an abnormal oscillation in power flow, to a fault, a short circuit in the line.

1.6.7 Optimize Asset Utilization and Operating Efficiency

This is the notion of "replacing iron with bits." In other words, utilizing knowledge of power grid assets to extract the most value from them with the goal of avoiding the purchase

Table 1.2 Illustration of some of the technologies' capabilities to fulfill the smart grid definition. The technologies are GISs, AMIs, outage management systems (OMSs), DMSs, DA, and SCADAs.

Definition	GIS	AMI	OMS	DMS	DA	SCADA
Power quality (Section 1.6.1)	✓			✓	✓	✓
DG + DER (Section 1.6.2)	✓			✓		✓
New services (Section 1.6.3)	✓	✓	✓	✓	✓	✓
Participation (Section 1.6.4)	✓	✓	✓	✓		
Cyber + disaster (Section 1.6.5)	✓	✓	✓	✓	✓	✓
Self-healing (Section 1.6.6)	✓			✓	✓	✓
Optimize assets (Section 1.6.7)	✓		✓	✓	✓	✓

and deployment of heavy equipment. This can include something as simple as an accurate geographic information system (GIS) that keeps track of where assets are located. It could also include analysis (for example, optimization techniques) and modeling to utilize the available assets in the most efficient manner. This could also include prognostics and health monitoring in order to determine precisely when and how to extract the most value from an asset before replacing it. Clearly, improving efficiency of the power grid is a theme that is apparent throughout this book.

So how are all of the goals being implemented? Table 1.2 maps the goals of the smart grid to a select set of high-level technologies that are being developed to help meet those goals.

1.7 A Few Words on Standards

For the practical-minded reader eager to see how the smart grid phenomenon can be implemented today, international standards are incorporating and codifying smart grid concepts. Chapter 10 reviews the state of smart grid standards in more detail. Some of the standards-related bodies developing smart grid standards include:

- National Institute of Standards and Technology (NIST) Smart Grid Interoperability Panel (SGIP)
  www.nist.gov/smartgrid/
- Institute of Electrical and Electronics Engineers (IEEE) Standards Association
  http://grouper.ieee.org/groups/scc21/2030/2030_index.html
- International Telecommunication Union (ITU) ITU-T Focus Group on Smart Grid (FG Smart)
  www.itu.int/en/ITU-T/focusgroups/smart/Pages/default.aspx
- Microsoft Power and Utilities Smart Energy Reference Architecture (SERA)
  www.microsoft.com/enterprise/industry/power-utilities/solutions/smart-energy-reference-architecture.aspx
- International Electrotechnical Commission (IEC)
  www.iec.ch/smartgrid/roadmap/
- Conseil International des Grands Reseaux Electriques (International Council on Large Electric Systems) (CIGRE)
  www.cigre.org/

- Electric Power Research Institute (EPRI)
  http://smartgrid.epri.com/
- United States Department of Energy
  www.oe.energy.gov/smartgrid.htm

1.8 From Energy and Information to Smart Grid and Communications

There is a deep relationship between the electric power grid and communication; much of it has yet to be discovered. Hopefully, this book will stimulate the reader to think beyond simply adding communication links to today's power grid or even the power grid as it has been projected to operate when it becomes "smart." Instead, new ways of thinking about the power grid and communication might be inspired by the relationship between energy and information. Power is the flow of energy just as communication is the flow of information, and there has been a long and deep history between and energy and information.

Researchers concerned with the energy requirements and battery life of large sensor networks have explored this topic, as illustrated in Figure 1.9. From their point of view, a unit of information requires energy to create, transmit, route, and be received. The goal has been to understand the energy requirements for each of these steps and minimize the overall energy consumption. Now consider a unit of energy instead of a unit of information. The unit of energy requires information to generate and manage, route, protect, and be purchased by the consumer, as illustrated in Figure 1.10. In other words, if we were to scale up the power normally used to create a communication signal, it could instead become energy supplied to consumers. This reinforces the notion mentioned at the beginning of this chapter and throughout the book that the power grid and communication are related closely enough to draw inspiration from one another.

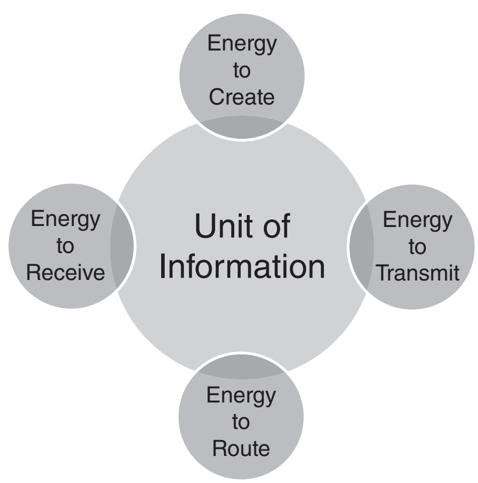

Figure 1.9 The notion of minimizing the amount of energy used to communicate is illustrated. Here the goal has been to minimize the amount of energy needed to communicate. Source: Bush, 2010.

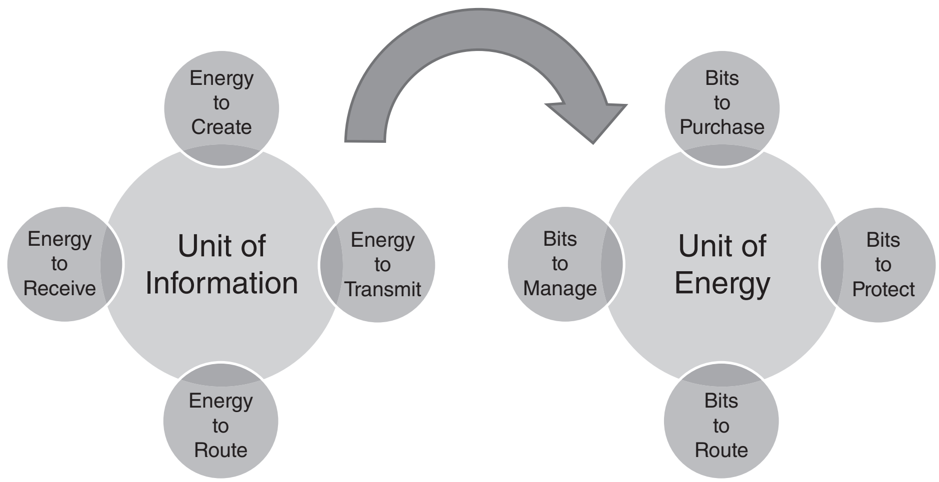

Figure 1.10 The notion of communicating information about energy is illustrated. Here the goal is to minimize the number of bits required to communicate information about energy. More on this topic is covered in Chapter 6. Source: Bush, 2010.

1.9 Summary

This chapter discussed the background and context in which the smart grid is emerging. It is important to realize the depth and breadth of the evolving power grid; many technical components of the grid are emerging independently while being claimed as part of the smart grid. Later in this chapter we saw how legislation and public policy defined the goals for the smart grid.

Historically, we saw how the power grid has evolved into its current state. It was noted how many of the current trends are actually moving toward those that existed when the power grid was in its infancy – in particular, many smaller DG systems. It was also noted how communication has been part of the power grid from its inception in the late 1800s. We also took a small digression to discuss the need for the communication, namely early control systems for the power grid back to the time of analog computing for the power grid. We also covered early SCADAs, since they evolved into the foundations upon which much of today's power grid communication exists and will influence the future direction of communication in the power grid. Next we covered the impact of deregulation and market forces on the power grid; this had a significant impact on its more recent evolution toward our current notion of the smart grid.

Then we constructed an analogy between the electric power grid and communication networks. Elements of this analogy will recur throughout the book. This analogy has been very helpful in quickly enabling power systems engineers to learn about communications and communications engineers to learn about the power grid.

This chapter also began the process of introducing the fundamentals of the physics of the power grid, assuming no prior background in power systems. We covered the topics of charge and voltage to electromagnetic circuits and fields. Knowledge of this material is crucial to understanding the rest of the book. It applies equally well to communications.

Following the introduction to power grid physics, which will be picked up in Chapter 2, we transitioned to a discussion of a blackout in the power grid. This brought us head-on with real problems that have been manifested in the power grid. While many may feel that the smart grid is about making a great leap and redefining electric power transport, this section was a sobering reminder that we had better make sure the changes are addressing real and potentially life-threatening problems. In particular, we noted that introducing complexity into the smart grid can have unintended, adverse consequences on a trend toward less frequent but larger and more devastating blackouts.

The next two sections discussed the drivers and goals of the smart grid. We noted that the goals for the smart grid involved extending the capability of the power grid by introducing new features and services; however, if the smart grid cannot reduce the likelihood of a blackout, then all of its other features and services are pointless. In the next section we considered both where the term “smart grid” originated and how it has been shaped.

Next we considered in more detail public policy concerning the goals of a smart grid. By considering these goals in detail, we can gain an intuitive, nontechnical sense of what the smart grid is supposed to be.

The power grid is too large an entity and there are too many entities involved for it to be constructed without standards to guide how the pieces fit together. Both the power electronics and communication components will require standards and guidelines in order to ensure that components are interoperable and that the architecture takes shape in the desired manner. Later in the book there is an entire chapter devoted to smart grid standardization efforts. However, in order to understand and appreciate the standards, the fundamentals covered in this book are required.

Next, we took an excursion back to fundamental theory to discuss energy and information. The goal was to intuitively motivate the reader to consider that incorporating communication and computation within the power grid may be done effectively only from a fundamental understanding of the relationship between energy and information. Specifically, we considered the derivation of the channel capacity from communication theory and then applied it to an analogy with the compression of an ideal gas. Gases and fluids turn turbines that produce electricity; this analogy inspires us to consider more deeply the relationship between information and communication and power efficiency.

Exercises at the end of this and every chapter are available to help test and solidify understanding of the material covered. Some higher numbered questions require information from later chapters of the book and are designed to motivate the reader to think about issues that will be dealt with later.

It should be clear from this chapter that communication and power systems have had a long history together. Power systems are complex dynamic systems that can be understood from an information theory and communication theory vantage point for the smart grid. Now that we have laid the context for the smart grid, let us look at each component of the power system in a little more detail in the succeeding chapters following the classic description of the power grid; namely, starting from generation to transmission, fanning out to distribution and finally reaching the consumer.

Chapter 2 will focus upon pre-smart-grid power generation. In particular, we will build upon the fundamentals of electric power physics established in this chapter to include aspects related to generation, particularly centralized power generation. This includes basics of alternating current, the notion of complex and reactive power, and finally a review of how generators operate. This basic knowledge is required in order to hope to understand the smart grid; these are fundamental physical aspects that will remain valid with DG. Communication and control play a central role in generation regardless of whether it is centralized or distributed. Thus, in Chapter 2 we go into detail on the SCADA systems used to control generation. Finally, Chapter 2 ends with a discussion of pre-smart-grid energy storage systems. These systems and their characteristics will also remain valid in the smart grid. An understanding of electric power generation and storage will build the foundation for later communication and control concepts for the smart grid.

1.10 Exercises

Exercise 1.1 Resistance

1. Consider one power cord that is twice the diameter of another power cord. If the cords are of the same length and material, how do their resistances compare?
2. Consider the current in a 20 foot, 16-gauge cord is 5 A. What is the voltage difference between the two ends of each conductor?

Exercise 1.2 Heat Dissipation

1. Consider an oven that draws 8 A at a voltage of 120 V. How much power does it dissipate in the form of heat?

Exercise 1.3 Power Drawn by a Load

1. Consider two incandescent light bulbs, with resistances of 320 Ω and 500 Ω. How much power does each draw when connected to a 120 V outlet?

Exercise 1.4 Series Voltage

1. A string of Christmas lights in a 120 V outlet has 60 identical bulbs connected in series. What is the voltage across each bulb?

Exercise 1.5 Current Flow

1. Consider several appliances operating from the same power cord: one at 40 Ω, one at 80 Ω, and one at 20 Ω. The cord has a resistance of 0.1 Ω on each wire. What is the current through each device when all are in use?

Exercise 1.6 RMS Voltage

1. If 120 V is the standard for RMS voltage, what is its magnitude?

Exercise 1.7 Impedance

1. An electrical device contains a resistance, an inductance, and a capacitance, all connected in series. Their values are $R = 1$ Ω, $L = 0.01$ H, and $C = 0.001$ F, respectively. At an a.c. frequency of 60 cycles, what is the impedance of the device?

Exercise 1.8 Reactance

1. Consider a transmission line that has a resistance $R = 1\ \Omega$ that is small compared with its reactance $X = 10\ \Omega$. What are the approximate conductance and susceptance?

Exercise 1.9 Ohms Law

1. Consider an incandescent bulb rated at 60 W. This means that the filament dissipates energy at the rate of 60 W when presented with a given voltage, which we assume to be the normal household voltage, 120 V. The current is 0.5 A. Now compute the power used by the bulb in terms of its resistance.

Exercise 1.10 Power Factor

1. Consider an appliance that draws 750 W of real power at a voltage of 120 V a.c. and a power factor of 0.75 lagging. How much current does it draw?

Exercise 1.11 Reactive Power

1. For the preceding example, how much reactive power does the appliance draw?
2. What is the impedance of the appliance?

Exercise 1.12 Power Factor and Line Loss

1. For the preceding example, how much of a reduction in line losses could be achieved by improving the power factor to 0.9, assuming that real power remains unchanged?
2. How much capacity is freed up on the substation transformer that supplies this line?

Exercise 1.13 Voltage Conservation

1. Compare the power consumption of a 100 W light bulb at 114 V versus 126 V.

Exercise 1.14 Resistance and Heat Dissipation

1. A 100 W incandescent light bulb in a 120 V circuit is dimmed to half its power output using an old-fashioned rheostat, or variable resistor, as a dimmer. What is the value of the resistance in the dimmer at this setting, and how much power is dissipated by the rheostat itself?

Exercise 1.15 Phase-to-Phase Voltage

1. A service to a business comprises three conductors – Phase A, Phase B, and neutral – where each phase-to-ground voltage is 120 V. The 120 V loads around the store, such as light and regular outlets, may be alternatively connected to Phase A or B. Heavier loads, would be connected phase-to-phase between A and B. What is the voltage that the heavier loads see?

Exercise 1.16 Wye-Delta Transformer

1. A wye-delta transformer with a 10:1 ratio steps voltage down from a 230 kV transmission line to a distribution circuit. What is the voltage on the secondary side?

Exercise 1.17 Clock Frequency

1. Suppose the 60 Hz frequency remains low, at 59.9 Hz for 1 day. How much time is lost in clocks that depend directly upon the alternating current cycle to keep time?

Exercise 1.18 Vehicle Battery Storage

1. A car battery has a storage capacity of 80 Ah (amp-hours) at 12 V. Assuming losses are negligible, how many such batteries would be required to supply a residential load of 5 kW for 24 h?

Exercise 1.19 Per Unit

Consider a three-phase power transmission system that deals with power at 500 MW and uses a voltage of 138 kV for transmission. Arbitrarily select S_{base} = 500 MVA and use the voltage 138 kV as the base voltage V_{base}. We then have:

$$I_{base} = \frac{S_{base}}{V_{base} \times \sqrt{3}} = 2.09 \text{ kA}, \qquad Z_{base} = \frac{V_{base}}{I_{base} \times \sqrt{3}} = \frac{V_{base}^2}{S_{base}} = 38.1\ \Omega,$$

$$Y_{base} = \frac{1}{Z_{base}} = 26.3 \text{ mS}.$$

1. If the actual voltage at one of the buses is measured to be 136 kV, then what is its per-unit (pu) value?

Exercise 1.20 Symmetric Components

The symmetrical components of a set of unbalanced, three-phase voltages are $V_0 = 0.6\angle 90°$, $V_1 = 1.0\angle 30°$, and $V_2 = 0.8\angle -30°$.

1. Obtain the original unbalanced phasors.

Exercise 1.21 Transformer

1. How does a line tap transformer work?
2. There are many sources of energy loss in a transformer. Describe at least three.

Exercise 1.22 Types of Power

1. Explain how real, reactive, and complex power are drawn on a complex plane. How is the phase of voltage relative to current represented on such a diagram?

Exercise 1.23 FACTS

Recall that a FACTS can manipulate the impedance of a line X in order to control or optimize power flow.

1. Show mathematically why reactive power provided to a FACTS-controlled transmission line must be increased as the impedance is decreased.

Exercise 1.24 Fault Analysis

1. Explain how symmetric components can be used to analyze a fault.
2. If the above process is automated, what communication is required?

Exercise 1.25 Energy and Information

1. How is Shannon channel capacity similar to compression of an ideal gas?

Exercise 1.26 Substation

1. Explain the following hierarchical levels in a power grid and the types of communication each would require: control center level, substation level, bay level, and process level.
2. What are the general communication requirements for each level?

Exercise 1.27 Energy Efficiency

1. What is the difference between maximizing power transfer and maximizing efficiency? Why are these not the same?
2. What is the parallel, or similarity, with communication systems in utilizing maximum power transfer and maximizing efficiency?