1

Introduction

1.1 What is a Power System?

Electricity provides a clean, efficient, versatile, and economical way to deliver energy. Efficient generators have been designed to convert other forms of energy into electrical energy. Transmission lines carry large amounts of energy over long distances. Electric motors are efficient and make possible precise motion control. Electricity is also the only way to power electronic devices. However, there is one drawback to using electricity as an energy vector: storing significant amounts of energy in electrical form is not practical. Delivering significant amounts of electrical energy must therefore take place as a continuous process. The rate at which electrical energy flows (i.e., power) is the fundamental concept. Generating electric power from primary energy sources, transmitting it over long distances, and converting it into another form of power for a variety of end uses on an uninterrupted basis requires a set of devices working in a coordinated fashion. This is what we call a power system.

Power systems come in a wide range of sizes. The interconnections of Europe and North America connect thousands of generators to millions of consumers over vast meshed networks. At the other end of the scale, the smallest power system consists of a single generator converting energy from a primary source to power a single, local load. In this book, we will use examples from small systems to explain concepts, and we will also explain the techniques that engineers use to analyze and operate the largest power systems.

1.2 What are the Attributes of a Good Power System?

Three main objectives guide the planning, design, and operation of power systems:

Reliability: Because many aspects of modern life have become dependent on the availability of electric power, any interruption in its supply causes major damage or at least a significant nuisance. We expect the lights to come on when we flip the switch and sensitive industrial processes to complete without disruption, even as the system is exposed to random fluctuations or when some components fail.

Power Systems: Fundamental Concepts and the Transition to Sustainability, First Edition. Daniel S. Kirschen.

Companion website: www.wiley.com/go/kirschen/powersystems

Sustainability: Like any other large-scale human activity, power systems have an impact on our environment, through the use of finite resources and the emission of greenhouse gases and other pollutants. To achieve sustainability, we must aim to generate 100% of our electrical energy from renewable sources.

Economy: Access to a cheap supply of electricity fosters economic growth and makes it possible for households to redirect their limited financial resources to other purposes.

Clearly, these objectives conflict. For example, improving reliability typically costs money; the cheapest sources of energy are not always sustainable; increasing the proportion of energy from renewable sources creates reliability issues. Finding solutions that optimally balance these objectives is the fundamental aim of power system engineering.

1.3 Structure of a Power System

1.3.1 Physical Structure

Except for the smallest applications, power systems connect multiple generators to multiple loads because this networked structure supports the desirable attributes described in the previous section. Supplying electric power from multiple generators increases reliability because when one of them fails, the other can compensate for this loss and, most of the time, ensure that no consumer is left without power. Connecting many energy sources to many loads also improves the overall economy of the system in two ways. First, as we will see in Chapter 2, aggregating loads reduces the amount of generation capacity that must be built to keep consumers supplied at all times. Second, this aggregated load varies substantially over the course of a day or a year. When this load is low, we can supply it from the most cost-effective generators in the system and use the more expensive ones only when they are needed. Finally, aggregating generation from renewable sources such as wind and solar over a wide area supports the sustainability goal. The production of these generators is driven by wind speed and cloud cover, factors that are uncontrollable but vary from location to location. Leveraging this diversity in output levels the overall renewable generation, which makes it easier to predict and match to the overall demand for electric power.

Most power systems operate with ac rather than dc because ac voltages can be easily or lowered using transformers. This ability to operate different parts of the system at different voltages reduces losses. To illustrate this fact, consider the simple circuit shown in Figure 1.1 and suppose that we want to supply a given resistive load P at a voltage V through a line of resistance R. The relation between the power supplied to the load, the current, and the load voltage is:

$$P_{\text{load}} = V.I \tag{1.1}$$

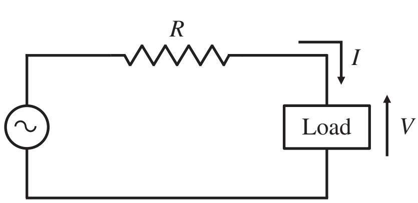

Figure 1.1 Simple circuit illustrating the effect of the supply voltage on the losses.

Table 1.1 Relative series losses for various standard operating voltages.

Voltage	Relative losses
110 V	1
220 V	0.25
13 kV	71.6×10^{-6}
132 kV	694.4×10^{-9}
345 kV	101.7×10^{-9}

The losses in the line are given by:

$$P_{\text{losses}} = I^2 R \tag{1.2}$$

Combining these two equations, we get:

$$P_{\text{losses}} = \frac{P_{\text{load}}^2}{V^2} R \tag{1.3}$$

The losses in the line are thus inversely proportional to the square of the operating voltage. Table 1.1 illustrates this effect for a few standard voltages used in power systems. Note that operating at very high voltages not only reduces losses but is also essential to maintaining the stability of the system. We will discuss this issue in Chapter 11.

Obviously, safety and practical considerations make it impossible to use very high voltages everywhere. To prevent accidents and accidental short circuits, conductors must be separated from each other and from ground by a distance or an amount of expensive insulating material that increases with the nominal operating voltage. While building tall towers in the countryside to support high-voltage transmission lines is feasible and economically justifiable, this is impossible in and around urban areas. Different parts of large power systems therefore operate at different nominal voltages, as illustrated in Figure 1.2. Design considerations typically limit the output voltage of large generators to less than 30 kV. This voltage is immediately stepped up to a voltage suitable for transmission over long distances. As the

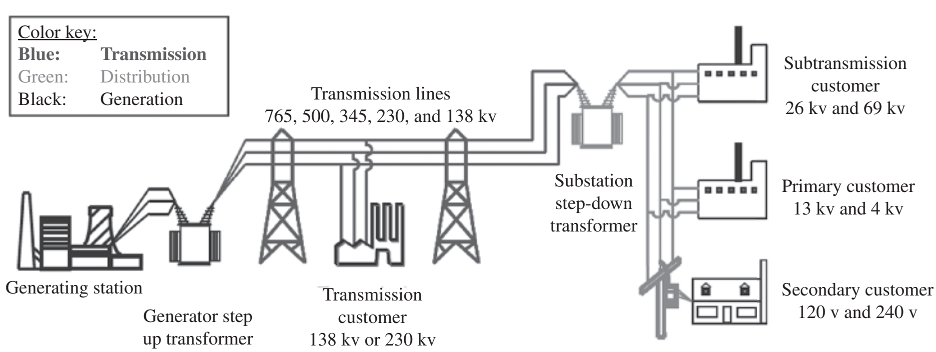

Figure 1.2 Typical operating voltages in large power systems. Source: United States Department of Energy, Blackout 2003, "Final Report on the August 14, 2003, Blackout in the United States and Canada: Causes and Recommendations".

amount of power and the distance over which it must be transmitted increase, so does the most appropriate standardized nominal voltage. This voltage is gradually stepped down to meet the needs of various classes of consumers. According to the U.S. Energy Information Agency, on average only about 5% of the electricity generated in the United States is dissipated as losses in the transmission and distribution networks. Most of these losses occur in the low-voltage distribution networks.

Very large consumers (for example steel processing plants or refineries) receive power directly at transmission voltage level and operate their own industrial power system. Smaller industrial, commercial, and residential consumers are connected at the lower voltage appropriate to their needs. The higher-voltage components constitute the transmission network, while the lower-voltage parts form the distribution network. An intermediate portion is sometimes described as the subtransmission network. Local conventions rather than universally agreed voltage thresholds define the demarcation between distribution, subtransmission, and transmission.

Transmission networks are generally meshed to further the triple objective of reliability, economy, and sustainability. Meshes indeed provide redundant paths for the flow of power from generators to loads. These redundant paths reduce the likelihood that this flow would be interrupted by the disconnection of a line. They also increase the transmission capacity, which is the maximum amount of power that cheap and renewable sources can securely provide over the network. With the exception of some densely populated urban areas, distribution networks are typically radial because protecting against the consequences of faults is easier and cheaper in a radial network than in a meshed network. However, radial networks do not provide the same level of reliability as meshed networks because the disconnection of a single component can disconnect consumers from all sources of power. This is considered acceptable in distribution networks because each occurrence of such a problem affects only a relatively small number of consumers.

Figure 1.2 reflects the operation of traditional power systems where power produced by a relatively small number of large, centrally controlled generators flows through the transmission network and down the radial distribution network to the consumers. In recent years, many small generators (typically photovoltaic) have been connected to distribution networks.

While the vast majority of transmission lines are ac, developments in power electronics have made possible the deployment of an increasing number of dc transmission lines. However, the high cost of the equipment needed to convert ac into dc and dc back into ac limits the application of this technology to instances where it has a clear advantage or where ac transmission is not possible. These include situations where:

- Transmitting a lot of power over a long distance would adversely affect the stability of the grid.
- A long underground or submarine cable is required.
- A connection must be established between two systems operating at different frequencies.

1.3.2 Cyber Infrastructure

While power plants and transmission lines are the most visible part of power systems, these systems would not operate reliably or economically without the support of an extensive set of communications, control, and computing devices. This infrastructure includes of the following types of devices:

- *Control systems* that regulate the operation of active devices, such as power plants, generators, power electronics converters and transformers, to ensure that critical variables remain close to their setpoint value.
- *Meters* that record voltages, currents, powers, and other variables for monitoring or billing.
- *Relays* that detect various types of faults on the physical components and trigger actions to avoid further damage.
- *Control centers* where human operators oversee the operation of a power plant or the overall system.
- *Communication networks* that transmit the data collected by the meters to the control centers and allow the operators to remotely control devices across the system.
- *Computers* to support the monitoring of the system, optimize its operation, and model what might happen under various scenarios.

1.3.3 Organizational Structure

Historically, most power systems were built and operated by a single entity: the electric utility. This company or government agency owned all the assets and controlled every aspect of the system's operation and development. In many parts of the world, this vertically integrated structure has been unbundled to make possible the introduction of competitive electricity markets. In this new structure, generating companies compete to sell electrical energy on a wholesale market and retailers compete to resell this energy to individual consumers. Usage of the transmission and distribution and distribution networks is shared by all participants under the watchful eye of a system operator who is responsible for maintaining the reliability of the system. Chapter 12 discusses in more detail how electricity markets function and the coordination between these various entities. In the meantime, we need not be concerned about who owns and operates each part of the power system. For simplicity, we will use the generic term "utility" to refer to the entity in charge of the part of the system under consideration.

1.4 Historical Evolution

As electricity started being used as a source of light and power in the late 19th century, power systems consisted of a few wealthy customers supplied by a single power plant in their neighborhood. Thomas Edison championed dc, while George Westinghouse and Nikola Tesla promoted ac. As demand grew and power systems needed to reach more widely spread customers and rely on more remote sources of primary energy, the advantages of ac became clear, and dc quickly fell out of favor. Electric utilities companies focused their efforts on urban areas because it is more profitable to supply customers when they are located close together rather than when they are widely spaced. Rural electrification required the emergence of electricity cooperatives and the provision of government subsidies.

Figure 1.3 Interconnected areas in North America. Source: Congressional Budget Office/https://www.cbo.gov/publication/56254/Public Domain.

Utilities quickly realized the economic and reliability benefits of interconnecting their systems. One company might have excess power capacity that it could sell to the other at a price that was advantageous for both. Each company could also provide backup power for the other in case of need. Over time, these interconnections involved more companies and became larger and larger. As Figures 1.3 and 1.4 show, the largest interconnections span continents, link thousands of generators, and supply electrical energy to tens of millions of consumers.

As the demand for electricity grew, economies of scale encouraged the construction of larger and larger power plants, often located close to remote and non-transportable sources of primary energy, such as hydroelectricity, wind, and solar. In parallel, this required the erection of transmission lines at higher and higher nominal voltages. In recent years, a slight reversal has occurred with the development of distributed energy resources, primarily solar photovoltaic (PV) generation and battery energy storage, that can be deployed cost-effectively at smaller scale. These resources are connected to the distribution network rather than the transmission network. Occasionally, when their production exceeds the local load, the flow of power in the local distribution network reverses direction, i.e., power flows from the distribution network back into the transmission network. While the deployment of distributed PV generation on homes and businesses allows these consumers to reduce their electricity bills, it is unlikely to completely displace centralized generation, as

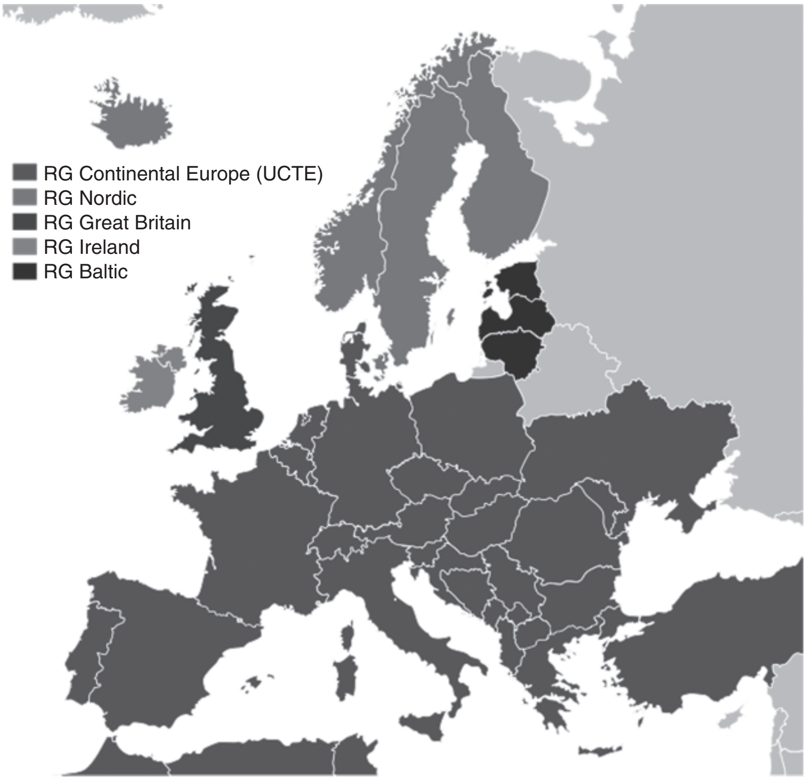

Figure 1.4 Interconnected areas in Europe. Source: Kimdime/Wikimedia Commons/Public Domain.

the economies of scale still favor larger plants and the density of solar energy is insufficient to meet the needs of urban areas.

A microgrid is a small portion of the grid that includes some form of generation and sometimes an energy storage device, and which has the ability to separate itself from the main grid and continue operating independently for some time. A microgrid is thus able to serve some loads if the main grid were to fail due to either a natural disaster, such as an earthquake or major storm, or a blackout triggered by an electrical fault. Microgrids have been attracting a growing amount of attention because they provide a way to enhance the resilience of critical facilities and communities.

Problems

P1.1 Besides electricity, what other energy delivery systems are in common use? Discuss their advantages and disadvantages compared to power systems.

P1.2 Obtain a map showing the configuration of your regional or national power system.
(a) Describe the geographical area covered by this power system.

(b) Identify the major power plants in your region. What primary energy sources do they use to generate electrical energy? What is their MW rating?
(c) Identify the major transmission lines in your region. What is their voltage rating?
(d) Load centers are areas where a significant amount of load is geographically concentrated. Identify the major load centers in your region. Specify whether they are urban or industrial.

P1.3 When was the last time your home or place of work was without electricity? How long did it last? Did you have prior warning? List the problems and inconveniences that this outage caused. What mitigation measures were in place before the incident? What mitigation measures have been implemented since to limit damage and inconvenience during a future outage?

P1.4 A load of 100 MW is supplied at 230 kV through a transmission line of resistance 5.29 Ω. Calculate the efficiency of this transmission.

P1.5 What would be the efficiency if the load of problem P1.4 were supplied at 138 kV through the same transmission line?