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INTRODUCTION TO POWER SYSTEMS: A CHANGING LANDSCAPE

Electric power systems are technical wonders; and according to the National Academy of Engineering [1], electricity and its accessibility are the greatest engineering achievements of the twentieth century, ahead of computers and airplanes. In many respects, electricity is a basic human right. It is a highly refined “commodity,” without which it is difficult to imagine how a modern society could function. It has saved countless millions from the daily drudgery of backbreaking menial tasks.

Unfortunately, a billion people in the world have either no access or no reliable access to electricity [2]. Added to this challenge is the fact that burning fossil fuels such as coal and natural gas to produce electricity results in carbon dioxide and other greenhouse gases. These greenhouse gases are causing global warming and climate change, the gravest threat facing human civilization.

Therefore, we as electric power engineers are faced with twin challenges. How we generate electricity using renewables such as wind and solar, how we transmit and deliver it, and how we use it are key factors to meet these challenges.

1.1 NATURE OF POWER SYSTEMS

Power systems encompass the generation of electricity to its ultimate consumption in operating everything from computers to hairdryers. In the most simplistic form, a power system is shown in Figure 1.1, where power from a single generating station is being supplied to consumers.

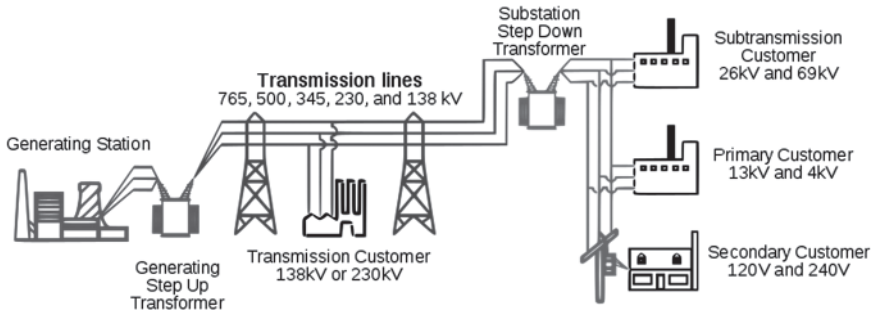


FIGURE 1.1 A single generating station supplying consumers (in color on the accompanying website). Source: [3] / U.S Department of Energy / Public Domain.

The system shown in Figure 1.1 is for illustration purposes only and shows the various components of a power system if such a system were to be constructed. It consists of a generating station, possibly producing voltages at a 20 kV level, a transformer that steps up this voltage to much higher transmission voltages for long-distance transmission of power, and then another transformer to step down the voltage to supply consumers at various voltages. In this book, we will look at all these components.

However, as mentioned, the system in Figure 1.1 is for illustration only. In practice, for example, the North American grid in the United States and Canada consists of thousands of generators, all operating in synchronism. These generators are interconnected by over 200,000 miles of transmission lines at 230 kV voltage levels and above, as shown in Figure 1.2. Such an interconnected system results in the continuity and reliability of service if there is an outage in one part of the system and provides electricity at the lowest cost by utilizing the lowest-cost generation as much as possible at a given time.

This power system has evolved over several decades, and a good history of it can be read in [5].

As mentioned earlier, even though the actual power system may consist of tens of thousands of generators and hundreds of thousands of miles of transmission lines, it is possible to zoom in on a subset of such an extremely large system. This is illustrated in Figure 1.3, as an example, which consists of only 10 generators. Although power transmission systems are always three-phase

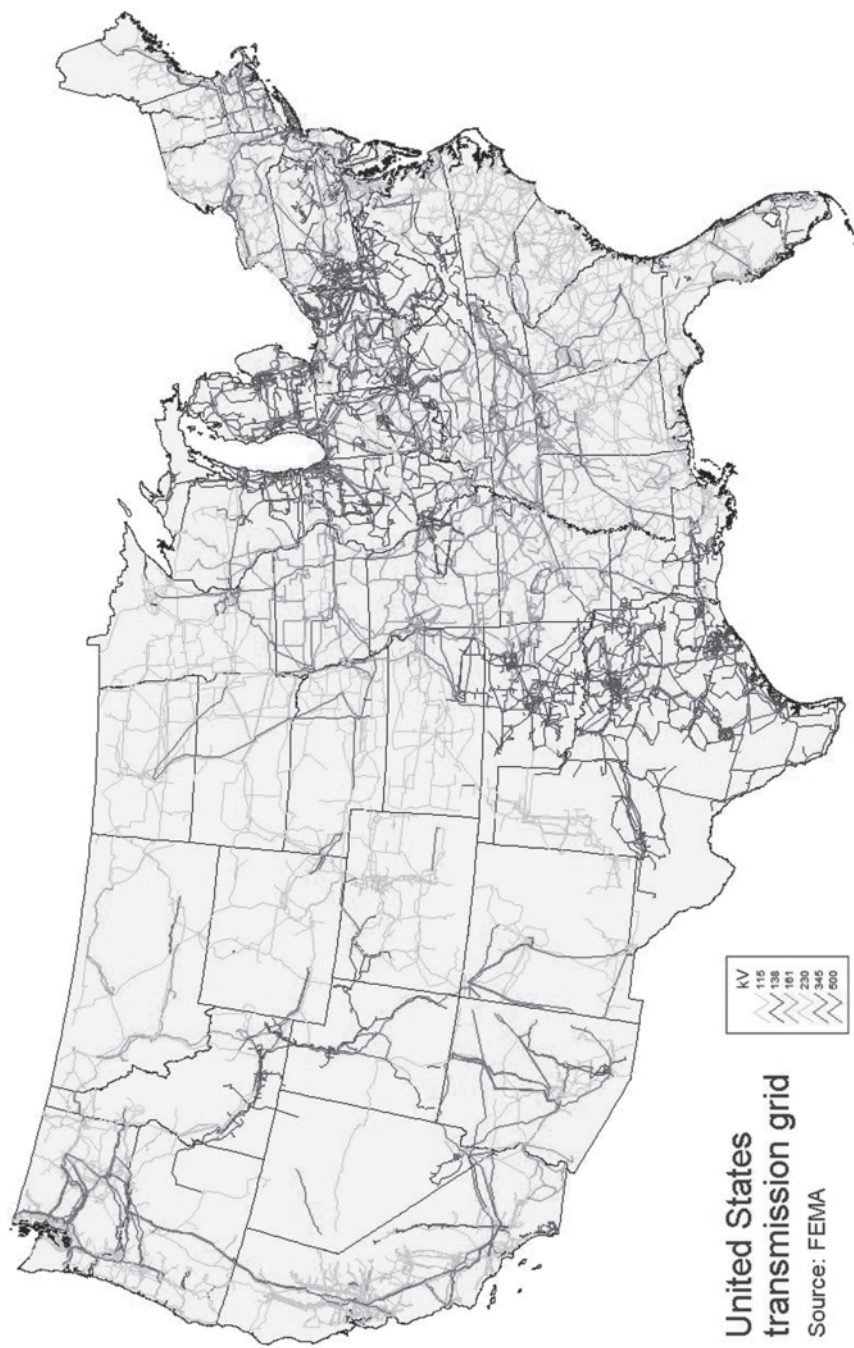


FIGURE 1.2 Interconnected North American power grid (in color on the accompanying website). Source: [4].

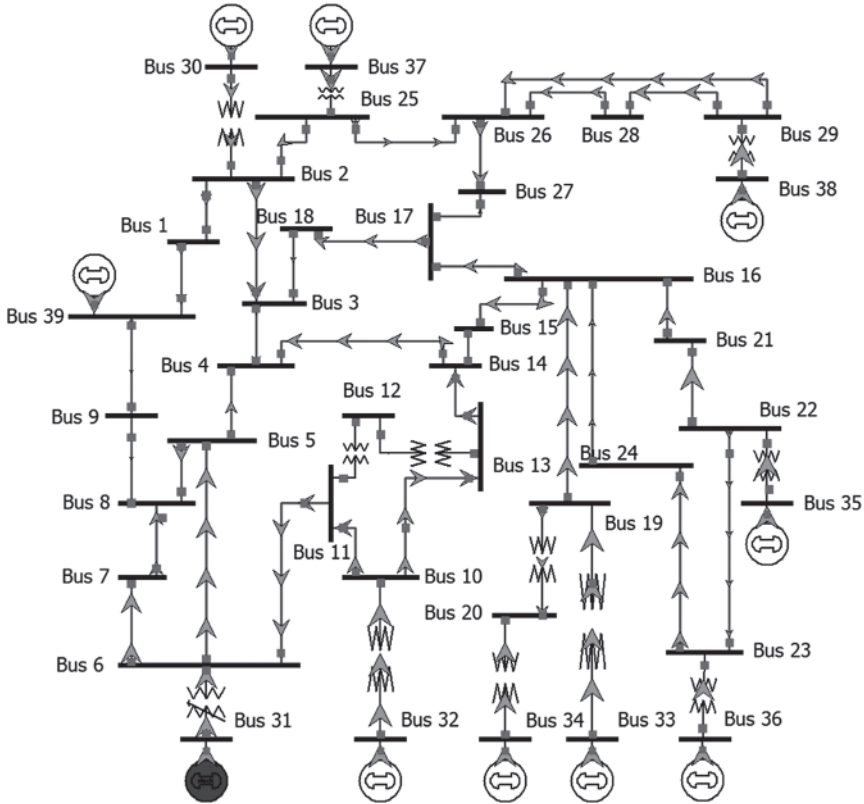


FIGURE 1.3 A one-line diagram of the IEEE 39 bus system, known as the 10-machine New England Power System (in color on the accompanying web-site). It has 10 generators and 46 lines. Source: [6].

(except in high-voltage DC [HVDC] transmission systems), we represent them with one line in the figure, in a so-called *one-line diagram*.

1.2 CHANGING LANDSCAPE OF POWER SYSTEMS DUE TO UTILITY DEREGULATION

Power systems today are undergoing major changes in how they are evolving in their structure and meeting load demand. In the past (and still true to some extent), electric utilities were highly centralized, owning large central power plants as well as the transmission and distribution systems, all the way down to the consumer loads. These utilities were monopolies: consumers had no choice but to buy power from their local utilities. For oversight purposes, utilities were highly regulated by Public Service Commissions that acted as consumer

watchdogs, preventing utilities from price gouging, and as custodians of the environment by not allowing avoidable polluting practices.

The structure and operation of power systems are beginning to change, and the utilities have been divided into separate generation and transmission/distribution companies. There is distributed generation (DG) by independent power producers (IPPs), and there are distributed energy resources (DERs) to generate electricity by whatever means (wind, for example); they must be allowed access to the transmission grid to sell power to consumers. The impetus for the breakup of the utility structure was provided by the enormous benefits of deregulation in the telecommunication and airline industries, which fostered a large degree of competition, resulting in much lower rates and much better service to consumers. Despite the inherent differences between these two industries and the utility industry, it was perceived that utility deregulation would similarly profit consumers with lower electricity rates.

This deregulation is in transition, with some states and countries pursuing it more aggressively and others more cautiously. To promote open competition, utilities are forced to restructure by unbundling their generation units from their transmission and distribution units. The objective is that the independent transmission system operators (TSOs) wheel power for a charge from anywhere and from anyone to the customer site. This fosters competition, allowing open transmission access to everyone: for example, IPPs. Many such small IPPs have gone into business, producing power using gas turbines, windmills, and PV plants.

Operation in a reliable manner is ensured by independent system operators (ISOs), and financial transactions are governed by real-time bidding to buy and sell power. Energy traders have gotten into the act for profit: buying energy at lower prices and selling it at higher prices in the spot market. Utilities are signing long-term contracts for energy, such as gas. This is all based on the rules of the financial world: forecasting, risks, options, reliability, etc.

As mentioned earlier, the outcome of this deregulation, still in transition, is far from certain. However, there is every reason to believe that the deregulation now in progress will continue, with little possibility that the clock will be turned back. Some fixes are needed. The transmission grid has become a bottleneck, with little financial incentive for TSOs to increase capacity. If the transmission system is congested, TSOs can charge higher prices. The number of transactions and the complexity of these transactions have increased dramatically. These factors point to anticipated legislative actions needed to maintain electric system reliability.

1.3 INTEGRATION OF RENEWABLES INTO THE GRID

In addition to the deregulation mentioned, there is a great deal of emphasis on generating power using renewables such as wind and solar rather than fossil fuels such as coal and natural gas that emit greenhouse gases. The cost of power from these renewables has been declining and, in many cases, is lower than the

cost of conventional sources. In making this comparison, we must realize that renewables are intermittent, and thus their value goes down as their penetration into the grid increases.

At present, the amount of electricity produced by renewables is small, as shown in Figure 1.4 for the United States.

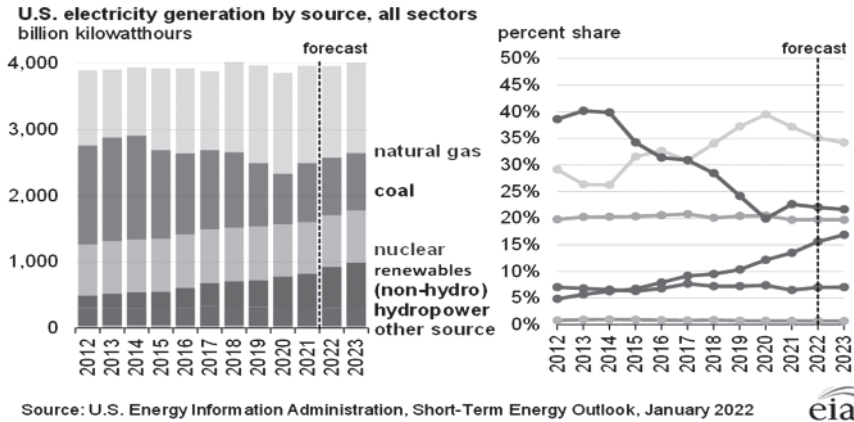


FIGURE 1.4 Generation of electricity by various sources in the United States (in color on the accompanying website). Source: [7].

However, due to climate concerns, the portion of electricity from renewable sources will undoubtedly grow, and our study of power systems must include how we can accommodate them in the grid.

1.4 TOPICS IN POWER SYSTEMS

The purpose of this textbook is to provide a complete overview of power systems meeting present and future energy needs. As we can appreciate, the interconnected power system with thousands of generators and hundreds of thousands of transmission lines between them is vast and complex. Therefore, the question in front of us is how we can impart the fundamental concepts and learn the workings of various components while pointing to the real tools used in industry to study such systems in their entirety.

It should be recognized that there can be planning studies that may have over 90,000 buses—e.g. the entire Eastern Interconnection System in the United States. However, the authors have taken the three-bus example shown in Figure 1.5 to explore various fundamental concepts. To extend these concepts to the study of the real system, the authors have decided to use PSS®E [8] from Siemens, which is one of the most widely used software packages in the utility industry in over 140 countries. The analysis of this three-bus simple system is shown in Figure 1.6 using PSS®E.

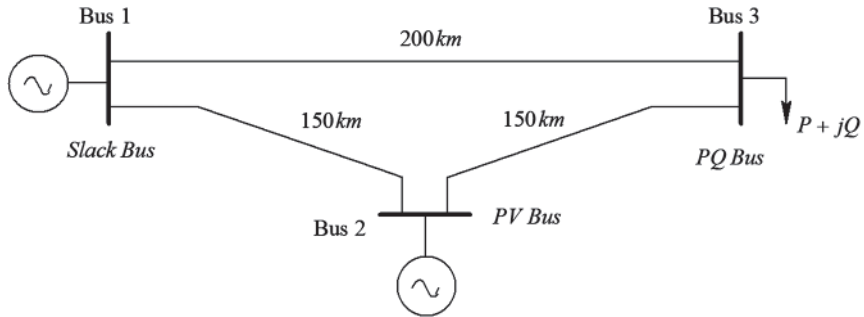


FIGURE 1.5 A three-bus example system.

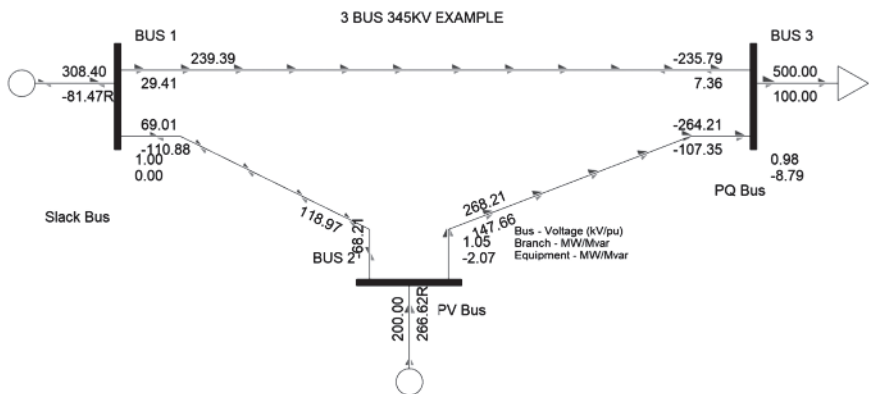


FIGURE 1.6 Simulation of the three-bus example system in Figure 1.5 using PSS®E.

The topics covered by this book's chapters are described next and arranged to associate the lecture material with the laboratory exercises chronologically. All of these topics are supplemented by simulations in PSS®E as appropriate.

Chapter 2: This chapter describes the basic concepts that are fundamental to the analysis of power system circuits. These include phasor representation in sinusoidal steady state, power, reactive power, and power factors. The chapter describes the three-phase circuit analysis, expressing quantities in per-unit, the energy efficiency of power system apparatus, and electromagnetic concepts essential to understanding transformers and electrical generators.

Chapter 3: We have a choice of using various resources for generating electricity, but there are always consequences to any selection. These are briefly discussed, including hydro plants, fossil fuel-based power plants, nuclear power, and the increasing role of renewable energy sources such as wind and solar. The environmental consequences of these choices are discussed.

Chapter 4: This chapter describes the need for transmission lines and cables, AC transmission lines and their parameters, and various representations. It also includes a brief discussion of cables. It shows the use of PSS®E for calculating line constants.

Chapter 5: For the purposes of planning and operating securely under contingencies caused by outages, it is important to know how power flows on various transmission lines. This chapter describes various power-flow techniques that include the Newton-Raphson method, the fast-decoupled technique, the Gauss-Siedel approach, and the DC power-flow method. Examples using PSS®E are given.

Chapter 6: Voltages produced by generators are stepped up by transformers for long-distance hauling of power over transmission lines. This chapter includes basic principles of transformer operation, simplified transformer models, per-unit representation, regulation, phase shifts introduced by transformers, and auto-transformers. It shows how transformers are represented in calculating power flow using PSS®E.

Chapter 7: This chapter describes the role of inverter-based resources (IBRs) and HVDC transmission systems, including those using voltage source converters (VSCs) and line-commutated converters (LCCs). It also includes a brief discussion of the IEEE P2800. Examples using PSS®E are given for integrating IBRs and using HVDC-VSC.

Chapter 8: This chapter describes consumer loads and the role of power electronics, which are changing their nature. It also describes how these loads react to voltage fluctuations and their impact on power quality.

Chapter 9: To generate electricity, steam and natural gas are utilized to run turbines that provide mechanical input to synchronous generators to produce three-phase electrical voltages. Synchronous generators are described in this chapter. It shows how generators are represented for power flow and transient stability analysis.

Chapter 10: Transmission lines are being loaded more than ever, making voltage stability a concern, as discussed in this chapter. Power electronics have a growing role in power systems in the form of flexible AC transmission systems (FACTS), which are described in this chapter for improving voltage stability. It includes an example of adding a static synchronous compensator (STATCOM) at a bus in the power-flow analysis using PSS®E.

Chapter 11: Maintaining stability so that various generators operate in synchronism is described in this chapter, which discusses how the stability in an interconnected system, with thousands of generators operating in synchronism, can be maintained in response to transient conditions, such as transmission-line faults, when there is a mismatch between the mechanical power input to the turbines and the electrical power that can be transmitted.

Chapter 12: This chapter discusses economic dispatch, where generators are loaded in such a way as to provide overall economy of operation. The operation of interconnected systems is also described, so that the power system frequency and voltages are maintained at their nominal values and purchasing and

selling agreements between various utilities are honored. An example of optimal power flow (OPF) is given using PSS®E.

Chapter 13: Power systems are spread over large areas. Being exposed to the elements of nature, they are subjected to occasional faults against which they must be designed and protected so that such events result only in momentary loss of power and no permanent equipment damage accrues. Short circuits on transmission systems are discussed in this chapter, which describes how relays detect faults and cause circuit breakers to open the circuit, interrupting the fault current and then reclosing the circuit breakers to bring the operation back to normal as soon as possible.

Chapter 14: Lightning strikes and switching of extra-high-voltage transmission lines during reenergizing, particularly with trapped charge, can result in very high-voltage surges, which can cause insulation to flash over. To avoid this, surge arresters are used and are properly coordinated with the insulation level of the power systems apparatus to prevent damage. These topics are discussed in this chapter.

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PROBLEMS

- 1.1 What are the advantages of a highly interconnected system?
- 1.2 What are the changes taking place in the utility industry?
- 1.3 What is meant by the following terms: DG, DER, IPP, TSO, and ISO?
- 1.4 What are the different topics in power systems for understanding its basic nature?

