Chapter 1

INTRODUCTION

This chapter has three objectives. We first offer a brief perspective on the development of electric power systems. This is not intended to be a detailed historical review, but rather it uses historical landmarks as a background to highlight the features and structure of the modern power systems, which are discussed in Section 1.2. The chapter concludes with an outline of the book.

1.1 A BRIEF HISTORY OF ELECTRIC POWER SYSTEMS

The electric power industry shapes and contributes to the welfare, progress, and technological advances of humanity. The growth of electric energy consumption in the world has been phenomenal. In the United States, for example, electric energy sales have grown to well over 400 times in the period between the turn of the century and the early 1970s. This growth rate was 50 times as much as the growth rate in all other energy forms used during the same period. The installed kW capacity per capita in the U.S. is estimated to be close to 3 kW.

Edison Electric Illuminating Company of New York inaugurated the Pearl Street Station in 1881. The station had a capacity of four 250-hp boilers supplying steam to six engine-dynamo sets. Edison's system used a 110-V dc underground distribution network with copper conductors insulated with a jute wrapping. In 1882, the first water wheel-driven generator was installed in Appleton, Wisconsin. The *low voltage of the circuits* limited the service area of a central station, and consequently, central stations proliferated throughout metropolitan areas.

The invention of the transformer, then known as the "inductorium," made ac systems possible. The first practical ac distribution system in the U.S. was installed by W. Stanley at Great Barrington, Massachusetts, in 1866 for Westinghouse, who acquired the American rights to the transformer from its British inventors Gaulard and Gibbs. Early ac distribution utilized 1000-V overhead lines. The Nikola Tesla invention of the induction motor in 1888 helped replace dc motors and hastened the advance in use of ac systems.

The first American single-phase ac system was installed in Oregon in 1889. Southern California Edison Company established the first three phase 2.3 kV system in 1893.

By 1895, Philadelphia had about twenty electric companies with distribution systems operating at 100-V and 500-V two-wire dc and 220-V three-wire dc, single-phase, two-phase, and three-phase ac, with frequencies of 60, 66, 125, and 133 cycles per second, and feeders at 1000-1200 V and 2000-2400 V.

The subsequent consolidation of electric companies enables the realization of economies of scale in generating facilities, the introduction of equipment standardization, and the utilization of the load diversity between areas. Generating unit sizes of up to 1300 MW are in service, an era that was started by the 1973 Cumberland Station of the Tennessee Valley Authority.

Underground distribution at voltages up to 5 kV was made possible by the development of rubber-base insulated cables and paper-insulated, lead-covered cables in the early 1900s. Since then, higher distribution voltages have been necessitated by load growth that would otherwise overload low-voltage circuits and by the requirement to transmit large blocks of power over great distances. Common distribution voltages presently are in 5-, 15-, 25-, 35-, and 69-kV voltage classes.

The growth in size of power plants and in the higher voltage equipment was accompanied by interconnections of the generating facilities. These interconnections decreased the probability of service interruptions, made the utilization of the most economical units possible, and decreased the total reserve capacity required to meet equipment-forced outages. This was accompanied by use of sophisticated analysis tools such as the network analyzer. Central control of the interconnected systems was introduced for reasons of economy and safety. The advent of the load dispatcher heralded the dawn of power systems engineering, an exciting area that strives to provide the best system to meet the load requirements reliably, safely, and economically, utilizing state-of-the-art computer facilities.

Extra higher voltage (EHV) has become dominant in electric power transmission over great distances. By 1896, an 11-kv three-phase line was transmitting 10 MW from Niagara Falls to Buffalo over a distance of 20 miles. Today, transmission voltages of 230 kV, 287 kV, 345 kV, 500 kV, 735 kV, and 765 kV are commonplace, with the first 1100-kV line already energized in the early 1990s. The trend is motivated by economy of scale due to the higher transmission capacities possible, more efficient use of right-of-way, lower transmission losses, and reduced environmental impact.

In 1954, the Swedish State Power Board energized the 60-mile, 100-kV dc submarine cable utilizing U. Lamm's Mercury Arc valves at the sending and receiving ends of the world's first high-voltage direct current (HVDC) link connecting the Baltic island of Gotland and the Swedish mainland. Currently, numerous installations with voltages up to 800-kV dc are in operation around the world.

In North America, the majority of electricity generation is produced by investor-owned utilities with a certain portion done by federally and provincially (in Canada) owned entities. In the United States, the Federal Energy Regulatory Commission (FERC) regulates the wholesale pricing of electricity and terms and conditions of service.

The North American transmission system is interconnected into a large power grid known as the North American Power Systems Interconnection. The grid is divided into several pools. The pools consist of several neighboring utilities which operate jointly to schedule generation in a cost-effective manner. A privately regulated organization called the North American Electric Reliability Council (NERC) is responsible for maintaining system standards and reliability. NERC works cooperatively with every provider and distributor of power to ensure reliability. NERC coordinates its efforts with FERC as well as other organizations such as the Edison Electric Institute (EEI). NERC currently has four distinct electrically separated areas. These areas are the Electric Reliability Council of Texas (ERCOT), the Western States Coordination Council (WSCC), the Eastern Interconnect, which includes all the states and provinces of Canada east of the Rocky Mountains (excluding Texas), and Hydro-Quebec. These electrically separate areas exchange with each other but are not synchronized electrically.

The electric power industry in the United States has undergone fundamental changes since the deregulation of the telecommunication, gas, and other industries. The generation business is rapidly becoming market-driven. The power industry was characterized by larger, vertically integrated entities. The advent of open transmission access has resulted in wholesale and retail markets. Utilities may be divided into power generation, transmission, and retail segments. Generating companies (GENCO) sell directly to an independent system operator (ISO). The ISO is responsible for the operation of the grid and matching demand and generation dealing with transmission companies as well (TRANSCO). This scenario is not the only possibility, as the power industry continues to evolve to create a more competitive environment for electricity markets to promote greater efficiency. The industry now faces new challenges and problems associated with the interaction of power system entities in their efforts to make crucial technical decisions while striving to achieve the highest level of human welfare.

1.2 THE STRUCTURE OF THE POWER SYSTEM

An interconnected power system is a complex enterprise that may be subdivided into the following major subsystems:

- Generation Subsystem
- Transmission and Subtransmission Subsystem
- Distribution Subsystem
- Utilization Subsystem

Generation Subsystem

This includes generators and transformers.

Generators – An essential component of power systems is the three-phase ac generator known as synchronous generator or alternator. Synchronous generators have two synchronously rotating fields: One field is produced by the rotor driven at synchronous speed and excited by dc current. The other field is produced in the stator windings by the three-phase armature currents. The dc current for the rotor windings is provided by excitation systems. In the older units, the exciters are dc generators mounted on the same shaft, providing excitation through slip rings. Current systems use ac generators with rotating rectifiers, known as *brushless* excitation systems. The excitation system maintains generator voltage and controls the reactive power flow. Because they lack the commutator, ac generators can generate high power at high voltage, typically 30 kV.

The source of the mechanical power, commonly known as the prime mover, may be hydraulic turbines, steam turbines whose energy comes from the burning of coal, gas and nuclear fuel, gas turbines, or occasionally internal combustion engines burning oil.

Steam turbines operate at relatively high speeds of 3600 or 1800 rpm. The generators to which they are coupled are cylindrical rotor, two-pole for 3600 rpm, or four-pole for 1800 rpm operation. Hydraulic turbines, particularly those operating with a low pressure, operate at low speed. Their generators are usually a salient type rotor with many poles. In a power station, several generators are operated in parallel in the power grid to provide the total power needed. They are connected at a common point called a *bus.*

With concerns for the environment and conservation of fossil fuels, many alternate sources are considered for employing the untapped energy sources of the sun and the earth for generation of power. Some alternate sources used are solar power, geothermal power, wind power, tidal power, and biomass.

Transformers – The transformer transfers power with very high efficiency from one level of voltage to another. The power transferred to the secondary is almost the same as the primary, except for losses in the transformer. Using a step-up transformer will reduce losses in the line, which makes the transmission of power over long distances possible.

Insulation requirements and other practical design problems limit the generated voltage to low values, usually 30 kV. Thus, step-up transformers are used for transmission of power. At the receiving end of the transmission lines step-down transformers are used to reduce the voltage to suitable values for distribution or utilization. The electricity in an electric power system may undergo four or five transformations between generator and consumers.

Transmission and Subtransmission Subsystem

An overhead transmission network transfers electric power from generating units to the distribution system which ultimately supplies the load. Transmission lines also interconnect neighboring utilities which allow the economic dispatch of power within regions during normal conditions, and the transfer of power between regions during emergencies.

Standard transmission voltages are established in the United States by the American National Standards Institute (ANSI). Transmission voltage lines operating at more than 60 kV are standardized at 69 kV, 115 kV, 138 kV, 161 kV, 230 kV, 345 kV, 500 kV, and 765 kV line-to-line. Transmission voltages above 230 kV are usually referred to as extra-high voltage (EHV).

High voltage transmission lines are terminated in substations, which are called *high-voltage substations*, *receiving substations*, or *primary substations*. The function of some substations is switching circuits in and out of service; they are referred to as switching stations. At the primary substations, the voltage is stepped down to a value more suitable for the next part of the flow toward the load. Very large industrial customers may be served directly from the transmission system.

The portion of the transmission system that connects the high-voltage substations through step-down transformers to the distribution substations is called the subtransmission network. There is no clear distinction between transmission and subtransmission voltage levels. Typically, the subtransmission voltage level ranges from 69 to 138 kV. Some large industrial customers may be served from the subtransmission system. Capacitor banks and reactor banks are usually installed in the substations for maintaining the transmission line voltage.

Distribution Subsystem

The distribution system connects the distribution substations to the consumers' service-entrance equipment. The primary distribution lines range from 4 to 34.5 kV and supply the load in a well-defined geographical area. Some small industrial customers are served directly by the primary feeders.

The secondary distribution network reduces the voltage for utilization by commercial and residential consumers. Lines and cables not exceeding a few hundred feet in length then deliver power to the individual consumers. The secondary distribution serves most of the customers at levels of 240/120 V, single-phase, three-wire; 208Y/120 V, three-phase, four-wire; or 480Y/277 V, three-phase, four-wire. The power for a typical home is derived from a transformer that reduces the primary feeder voltage to 240/120 V using a three-wire line.

Distribution systems utilize both *overhead* and *underground* conductors. The growth of underground distribution has been extremely rapid and as much as 70 percent of new residential construction in North America is via underground systems.

Load Subsystems

Power systems loads are divided into industrial, commercial, and residential. Industrial loads are composite loads, and induction motors form a high proportion of these loads. These composite loads are functions of voltage and frequency and form a major part of the system load. Commercial and residential loads consist largely of lighting, heating, and cooking. These loads are independent of frequency and consume negligibly small reactive power.

The load varies throughout the day, and power must be available to consumers on demand. The daily-load curve of a utility is a composite of demands made by various classes of users. The greatest value of load during a 24-hr period is called the peak or *maximum demand.* To assess the usefulness of the generating plant the *load factor* is defined. The load factor is the ratio of average load over a designated period of time to the peak load occurring in that period. Load factors may be given for a day, a month, or a year. The yearly, or annual load factor is the most useful since a year represents a full cycle of time. The daily load factor is

$$\text{Daily L.F.} = \frac{\text{average load}}{\text{peak load}} \tag{1.1}$$

Multiplying the numerator and denominator of (1.1) by a time period of 24 hr, we obtain

$$\text{Daily L.F.} = \frac{\text{average load} \times 24\text{ hr}}{\text{peak load} \times 24\text{ hr}} = \frac{\text{energy consumed during 24 hr}}{\text{peak load} \times 24\text{ hr}} \tag{1.2}$$

The annual load factor is

$$\text{Annual L.F.} = \frac{\text{total annual energy}}{\text{peak load} \times 8760\text{ hr}} \tag{1.3}$$

Generally there is diversity in the peak load between different classes of loads, which improves the overall system load factor. In order for a power plant to operate economically, it must have a high system load factor. Typical system load factors are in the range of 55 to 70 percent. Load-forecasting at all levels is an important function in the operation, operational planning, and planning of an electric power system. Other devices and systems are required for the satisfactory operation and protection of a power system. Some of the protective devices directly connected to the circuits are called *switchgear*. They include instrument transformers, circuit breakers, disconnect switches, fuses and lightning arresters. These devices are necessary to deenergize either for normal operation or on the occurrence of faults. The associated control equipment and protective relays are placed on *switchboards* in *control houses*.

For reliable and economical operation of the power system it is necessary to monitor the entire system in a so-called control center. The modern control center is called the *energy control center* (ECC). Energy control centers are equipped with on-line computers performing all signal processing through the remote acquisition system. Computers work in a hierarchical structure to properly coordinate different functional requirements in normal as well as emergency conditions. Every energy control center contains control consoles which consist of a visual display unit (VDU), keyboard, and light pen. Computers may give alarms as advance warnings to the operators (dispatchers) when deviation from the normal state occurs. The dispatcher makes decisions and executes them with the aid of a computer. Simulation tools and software packages are implemented for efficient operation and reliable control of the system. In addition, SCADA, an acronym for "supervisory control and data acquisition," systems are auxiliaries to the energy control center.

1.3 OUTLINE OF THE TEXT

Chapter 2 lays the foundations for the development in the rest of the book. The intention of the discussion offered here is to provide a brief review of fundamentals including power concepts, three-phase systems, principles of electromagnetism, and electromechanical energy conversion. Chapter 3 treats the synchronous machine from an operational modeling point of view. Emphasis here is on performance characteristics of importance to the electric power specialist. Chapter 4 provides a comprehensive treatment of transformers. This is followed, in Chapter 5, by a brief coverage of induction motors including the fractional horsepower category.

Chapter 6 is concerned with transmission lines starting from parameter evaluation for different circuit and conductor configurations. Various transmission line performance modeling approaches are covered.

Faults on electric energy systems are considered in Chapter 7. Here we start with the transient phenomenon of a symmetrical short circuit, followed by a treatment of unbalanced and balanced faults. Realizing the crucial part that system protection plays in maintaining service integrity is the basis for the remainder of this chapter. Here an introduction to this important area is given.

Chapter 8 is concerned with the Energy Control Center, its structure, and role in the operation of a modern power system. We outline the objectives and aims of many of the decision support functions adopted in these significant "smarts" of the power system. In chapter 9, we focus our attention on a number of technological challenges that face power system planners and operators. The major North East blackout of 8/14 in 2003 is discussed along with possible mitigation measures. Wherever relevant, we introduce MATLAB™ scripts that allow the student to automate many of the computational details. This feature is deemed important for this textbook's coverage.