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Introduction

1.1 Electrification

The construction of power grids and their associated infrastructures all over the world was recognized by the US National Academy of Engineering as the top engineering accomplishment in the 20th century for the advancement of human well-being.[1] Electrification drives industrialization and increases human productivity in developed countries, significantly improving the quality of life in underdeveloped countries. Although power generation and transmission in the USA started with direct current (DC), power transmission had relied exclusively on alternating current (AC) for over 50 years until a few early high-voltage DC systems were installed. Power systems will continue to use these two modes of generation and transmission, especially with the increased integration of renewable resources using power electronic interfaces and with the emergence of smart grids.

The topics in this book cover a slice of these enormously complex, continuously operating electric power systems, namely the dynamic aspects of their components and how these components interact with each other in the prevailing central station model of power generation. It is expected that these topics will provide relevant background to prepare power engineers to deal with future power systems in which most households will be equipped with solar panels and every town will have a few wind turbines.

The objective of this introductory chapter is to provide some high-level notions of power systems that will be helpful in the later chapters. The central generating station model is useful in understanding the test systems for illustrating the main concepts and techniques presented in this book. The discussion on time-scales of power system dynamics will be helpful in understanding the assumptions used on models and in control designs.

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[1] US National Academy of Engineering Report, *Greatest Engineering Achievements of the 20th Century*. available online: http://www.greatachievements.org/.

Power System Modeling, Computation, and Control, First Edition. Joe H. Chow and Juan J. Sanchez-Gasca.

Companion website: www.wiley.com/go/chow/power-system-modeling

1.2 Generation, Transmission, and Distribution Systems

1.2.1 Central Generating Station Model

Early power systems started as a local generator supplying a neighborhood of customers. These generators were noisy and dirty, and unpopular in the relatively well-to-do communities. Before long, large efficient generators were built in relatively remote locations, using both hydraulic and steam turbines. These new generators could deliver power to large load centers using long-distance transmission lines. Figure 1.1 shows the essential structure of a modern power system. Large generating stations directly supply power to a high-voltage transmission system (230–765 kV). The power is then supplied to a medium voltage subtransmission system (69–138 kV), which is then further stepped down to lower voltage distribution systems (2–35 kV) and eventually to customers at household voltage levels. The loads shown in Figure 1.1 represent the power consumption by households, office buildings, commercial centers, and factories. A distribution system is typically a radial network like the roots of a tree that have no connections to other parts of the network, that is, they do not form loops.

This central generating station model is the basis of a traditional vertically integrated utility company in which a utility company has a monopoly of serving loads in a region and is also responsible for building generators to secure the energy supply and transmission systems for bringing the supply to the distribution systems. The transmission system is needed as the generating stations are not necessarily in the company's service area. As the transmission systems of neighboring power companies become intertwined, power pools are formed, either in a single state (like New York) or multiple states (like New England), to oversee the security of such power transfer across long distances.

Recently many US power grids, under FERC Order 888 to promote wholesale energy competition through open access,[2] have been deregulated, thus separating the traditional vertically integrated utility companies into independent generation, transmission, and distribution operators. Still, the central generating station model remains unchanged, as the distribution operators, on behalf of the loads, have to secure supplies from the large generating units, except now the energy clearing prices are settled on an open electricity market, instead of within a single company. Thus power system dynamics consideration and analysis methods, such as those discussed in this book, are still valid in the deregulation environment.

Power systems are complex because they are interconnected and constantly being expanded. The US eastern power system consists of an interconnection of the power grids in all the states east of the Rocky Mountains and northeast of Texas, as well as several Canadian provinces. Models as large as 50,000 buses have been built such that the dynamics of the systems can be studied in great detail.

Given such complexity, a reader may ask what is the best way to understand the operation of such a large system. Fortunately, the design of power systems is hierarchical. The power from the remote large generators will be supplied on high-voltage transmission systems, not low-voltage distribution systems. For example, the loads served from Bus 2 in Figure 1.1 are supplied by Generators A and B. If Generator A is out for service, the power would come from Generator B by rerouting the power flow on the transmission

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[2] See Federal Energy Regulatory Commission (FERC) website: http://www.ferc.gov/legal/maj-ord-reg/land-docs/order888.asp.

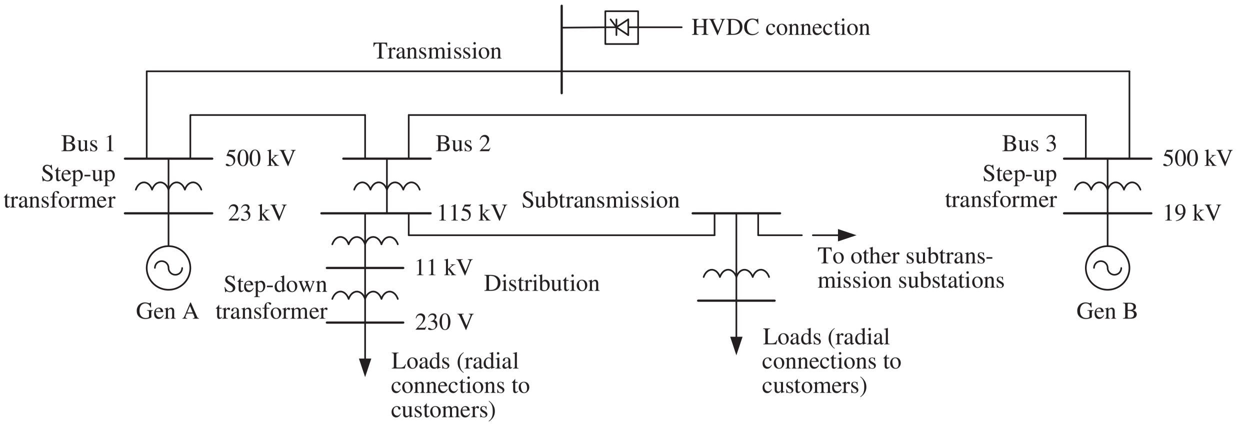

Figure 1.1 Central generation centric transmission and distribution network structure.

system. Some of the power flow may find a path through the subtransmission systems, but the amount should be small, as the effective impedance through a lower-voltage path is much higher. If this is not the case, some severe consequences such as voltage collapse may occur. Thus in the analysis of the stability of a generator or a group of generators subject to a fault, conceptually one can analyze a Single-Machine Infinite-Bus (SMIB) system to investigate critical clearing time, and a two-area system for the damping of interarea swing modes. Loads can be represented by a constant-impedance model before considering a more complex non-conforming model. A reader will find that there are many examples in the text using these two systems. Once mastered, these concepts can be applied to understand the results of power flow solutions or time responses obtained from dynamic simulations of very large realistic power systems.

1.2.2 Renewable Generation

Since the 1990s, renewable generation has been expanding at a rapid pace in many countries. Due to technology improvement, cost reduction, and government incentives for green energy, first wind-turbine generators (WTGs) were installed, which were followed by photo-voltaic (PV) systems. Modern WTGs are mostly 1–3 MW land-based units using doubly-fed induction generator (DFIG) technology and 4 MW and above off-shore units based mostly on full converter-based technology. PV plants are much smaller in power output, ranging from several kilowatts for units on the rooftops of single-family homes to much larger megawatt units, such as the 32-MW solar power plant on Long Island.[3]

As the percentage of renewable source generation becomes higher, the traditional central generating station model is being disrupted. First, the amount of generator inertias will become lower as some of the less efficient fossil generating units are displaced. PV plants have no inertia and the wind-turbine rotor and generator inertias are mostly hidden from the grid by the power electronic interface of the WTGs. Second, depending on the grid code, reactive power supply can be a challenge. On the other hand, the power electronics interface on renewable resources may be used productively for control.

The disruption to the distribution systems by renewable resources, mostly rooftop PV systems, may be more severe. Traditional distribution systems are designed with uni-directional power flowing from distribution transformers to homes. However, with high concentration, rooftop units can have the capability of supplying power back to a distribution transformer on sunny days. Such bi-directional flow complicates the design of relays and reactive power compensation. In addition, electric vehicle charging can double or triple the power consumption of a household, requiring increased transformer ratings and reactive power compensation capacity.

WTGs, because of their larger sizes and installation as wind farms, will have an impact on power system dynamics. Chapter 15 of this book discusses the modeling of WTGs. However, PV systems, because of their smaller size, faster dynamics, and limited impact on the transmission systems, will not be covered here.

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[3] See http://www.bnl.gov/SET/LISF.php.

1.2.3 Smart Grids

A further deviation from the central generation model is the establishment of smaller grid operating models that can take on a variety of forms, with designations like community grid and micro-grid. The main concept of these smart grid models is some form of self supply (local generation), via PV systems, energy storage, and small conventional diesel units, coupled to demand response or control, utilizing loads such as heating, ventilation, and air-conditioning (HVAC) systems. In normal operating conditions, these smart grids are supplied by the main power grid. When energy prices are high, these grids will reduce their intake of external power. In case of an emergency disrupting the main grid, these smart grids can operate as a standalone system supporting only the essential consumption. Smart grid models are beyond the scope of this book. Interested readers can find relevant information in many magazine articles and textbooks [1].

1.3 Time Scales

The complexity of a power system lies not only in having large interconnected control regions covering sometime immense areas, but also in the time scales of dynamics, measurements, control, and operating regimes. Figure 1.2 is a summary of the time spans of power system components and operation.

1.3.1 Dynamic Phenomena

The dynamic phenomena part of Figure 1.2 originates from [2] and can be found in various forms in many power system textbooks [3]. Lightning and switching surges are uncontrolled micro-second phenomena on transmission and distribution systems [4]. Stator transients and subsynchronous resonance are millisecond phenomena in synchronous generators. An analytical treatment of stator transients can be found in [3]. Subsynchronous oscillations are covered in Chapter 12 on turbine generators. Transient stability denoting the dynamics determined by the swing equations of synchronous generators interacting through the transmission network covers a time span from fractions of a second to tens of seconds. Governor dynamics and load frequency regulation involving the control of turbine valves and generator setpoints are on a time scale of seconds to minutes. Boiler dynamics involving steam generation will involve an even longer time span. In this text, such dynamics which require an understanding of thermal cycles will not be discussed. Here the effect of steam flow is represented by turbine time constants of several seconds. Thus this textbook covers dynamics that are important in the range of fractions of a second to 20–30 seconds, as is the case with books such as [3, 5–7].

1.3.2 Measurements and Data

Power system data consist of both analog measurements, such as 3-phase voltages and currents, and digital statuses of circuit breakers and switches. With the advent of inexpensive and yet powerful microprocessors, much traditional equipment based on analog measurements has been converted to use digital data. For example, digital relays with sampling rates of 2.8 and 5.6 kHz (for 60 Hz systems) are commonplace. Substation

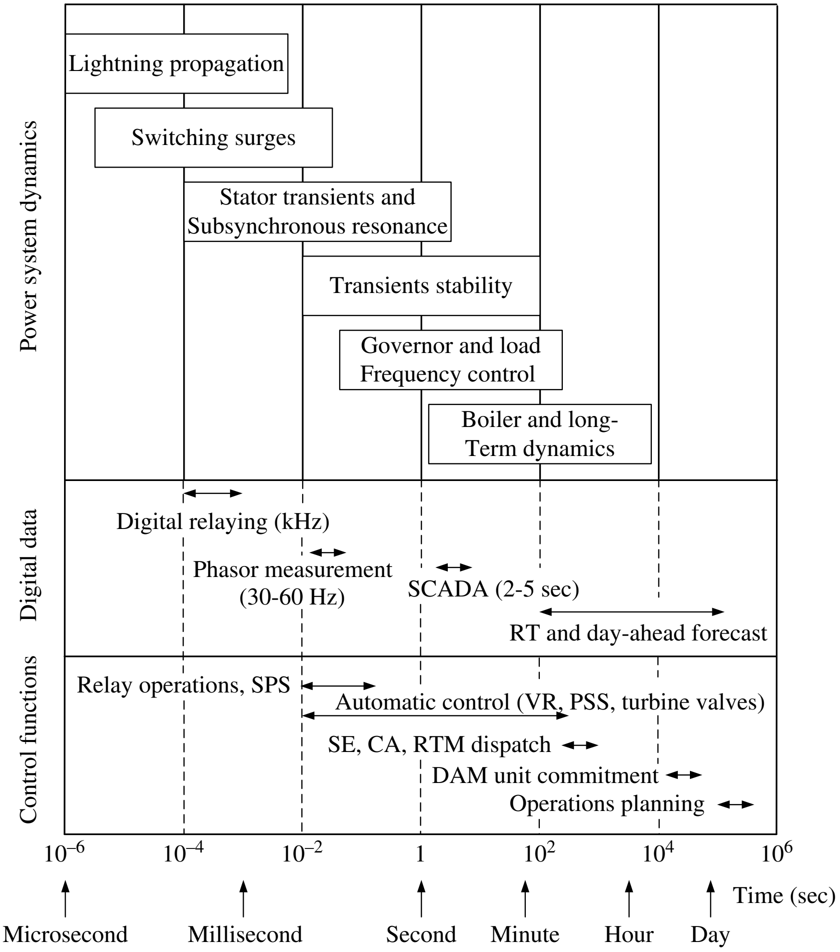

Figure 1.2 Power system time scales for dynamics, data, and control functions. SPS, special protection schemes; VR, voltage regulator; PSS, power system stabilizer; SE, state estimation; CA, contingency analysis; RTM, real-time market; DAM, day-ahead market. The dynamics part is from [3].

SCADA data (voltage, current, and power) are sampled every 2–5 seconds and sent via the internet for use in power system control centers. With the increased penetration of wind and solar power plants, some control centers are supplementing their operations with real-time and day-ahead wind and insolation forecast data obtained from complex atmospheric computer simulation models.

Perhaps the data most relevant for power system dynamics and control are voltage and current phasor data obtained from phasor measurement units (PMUs), which provide digital data at 30/60 samples per second for 60 Hz systems (50 samples per second for 50 Hz systems) [8]. Machine swing dynamics can be readily visible in PMU data. When the PMUs covering a wide region are synchronized via the GPS timing signal, the propagation of a disturbance across a power system is clearly observable from the synchrophasor data. Because a chapter on synchrophasor has already been provided in [3], the topic is not repeated here.

1.3.3 Control Functions and System Operation

Controls in power systems can be broadly grouped into two types. The first type is fast closed-loop control that needs to be implemented automatically. These controls include for active power control, frequency regulation by turbine valve governing and high-voltage direct current (HVDC) system power regulation [9], for reactive power control, voltage control by excitation systems and a flexible AC transmission system (FACTS) [10], and for damping control, supplementary signals from power system stabilizers. These topics are covered in this text.

Power system operation in control centers occurs at a much slower time scale and is also automated, except that additional discrete control inputs are computed separately. For example, real-time dispatch based on the state estimator solution and contingency analysis computes new generator setpoints every 5–10 minutes, which are then issued to the generators. Energy bids in the day-ahead market are normally submitted 12–36 hours ahead so that an independent system operator can secure and schedule generators for reliable operation. In addition, operation engineers will determine the scheduling of seasonal maintenance of transmission lines and generators to ensure normal operations will not be disrupted. A reader can find a good coverage of these topics in [11] and control center operating manuals on the websites of independent system operators.[4]

1.4 Organization of the Book

This book is organized into three parts. Part I consists of Chapters 2 to 6. These chapters cover power flow, voltage stability, and dynamic power system models based on the classical model of synchronous machines. Stability concepts, methods for power system simulation, and linear model generation are discussed. This part of the book may also be suitable for an advanced undergraduate course for students who have taken the introductory power system analysis course [12].

Part II consists of Chapters 7 to 12. They contain detailed materials on synchronous machine modeling, excitation systems and voltage regulators, power system stabilizer and damping control design, load models, and turbine-governor models and frequency control. These chapters start with a description of the equipment and its operating principles. They are then followed by modeling and analysis: steady-state operating characteristics, dynamic models, initialization (steady-state operating point computation), and dynamic simulation. With a good understanding of these models, a user of commercial power system simulation programs can literally "think" through the dynamics computation.

Part III consists of the last four chapters and can be considered as advanced topics, with contents on HVDC systems, FACTS, wind energy, and power system model reduction. At the Rensselaer Polytechnic Institute, these chapters plus the synchrophasor topic are offered as a second graduate course on power system dynamics. These chapters can also be used to supplement individualized courses on these topics, with the intention of showing how the models and techniques are used in a dynamic simulation context.

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[4] For example, the New York power system operation manuals can be found on http://www.nyiso.com.

Examples and problems are an important part of this book and serve two purposes. Some of them serve the academic purpose of illustrating analytical expressions with numerical values. Some others are motivated by practical systems. These problems can be quite interesting and perplexing at first. Furthermore, they illustrate that even seemingly complex situations can be solved by some straightforward calculations.

As this is a book on power system computation, students in a course using this book are expected to perform dynamic simulations. Those students without access to commercial power system software tools can use several free MATLAB®-based tools, such as the Power System Toolbox [13]. The computer files to run the examples can be downloaded from the Wiley website for this book.