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Introduction

1.1 Background

The modern power grid has become more complex with the addition of many devices both in terms of transmission and generating sources. But the central generating systems station concept supported by a highly interconnected system remains the major part of power delivery network. The techniques for analysis and operation of the grid have been influenced both by advanced computational techniques and GPS-based communication such as synchronized phasor measurements for monitoring and control purposes.

Compared to other disciplines within electrical engineering, the analytical techniques of power systems were often based on experience and heuristic assumptions. The impact of control, system theory, and in recent years, communication and signal processing techniques has been significant. It is necessary to develop a sound theoretical basis for the area of power system dynamics, stability, and control. The purpose of this book is to achieve these objectives.

The subject of power system dynamics, stability, and control is an extremely broad topic with a long history and volumes of published literature. There are many ways to divide and categorize this subject for both education and research. While a substantial amount of information about the dynamic behavior of power systems can be gained through experience, working with and testing individual pieces of equipment, the complex problems and operating practices of large interconnected systems can be better understood if this experience is coupled with a mathematical model. There are several main divisions in the study of power system dynamics and stability [1].

F. P. deMello classified dynamic processes into three categories:

1. Electrical machine and system dynamics
2. System governing and generation control
3. Prime-mover energy supply dynamics and control

In the same reference, C. Concordia and R. P. Schulz classify dynamic studies according to four concepts:

1. The time of the system condition: past, present, or future
2. The time range of the study: microsecond through hourly response

Power System Dynamics and Stability: With Synchrophasor Measurement and Power System Toolbox,
Second Edition. Peter W. Sauer, M. A. Pai and Joe H. Chow.

Companion Website: www.wiley.com/go/sauer/powersystemdynamics

3. The nature of the system under study: new station, new line, etc.
4. The technical scope of the study: fault analysis, load shedding, sub-synchronous resonance, etc.

All of these classifications share a common thread: They emphasize that the system is not in steady state and that many models for various components must be used in varying degrees of detail to allow efficient and practical analysis. The first six chapters of this book are thus devoted to the subject of modeling. The next the next three chapters discuss the use of the interconnected models for common dynamic studies. Finally we discuss the use of synchro phasor measurements for monitoring the system in real time. It forms the foundation for modern control techniques optimization and security analysis of the grid.

1.2 Physical Structures

The major components of a power system can be represented in a block-diagram format, as shown in Figure 1.1. While this block-diagram representation does not show all of the complex dynamic interaction between components and their controls, it serves to broadly describe the dynamic structures involved. Historically, there has been a major division into the mechanical and electrical subsystems as shown. This division is not absolute, however, since the electrical side clearly contains components with mechanical

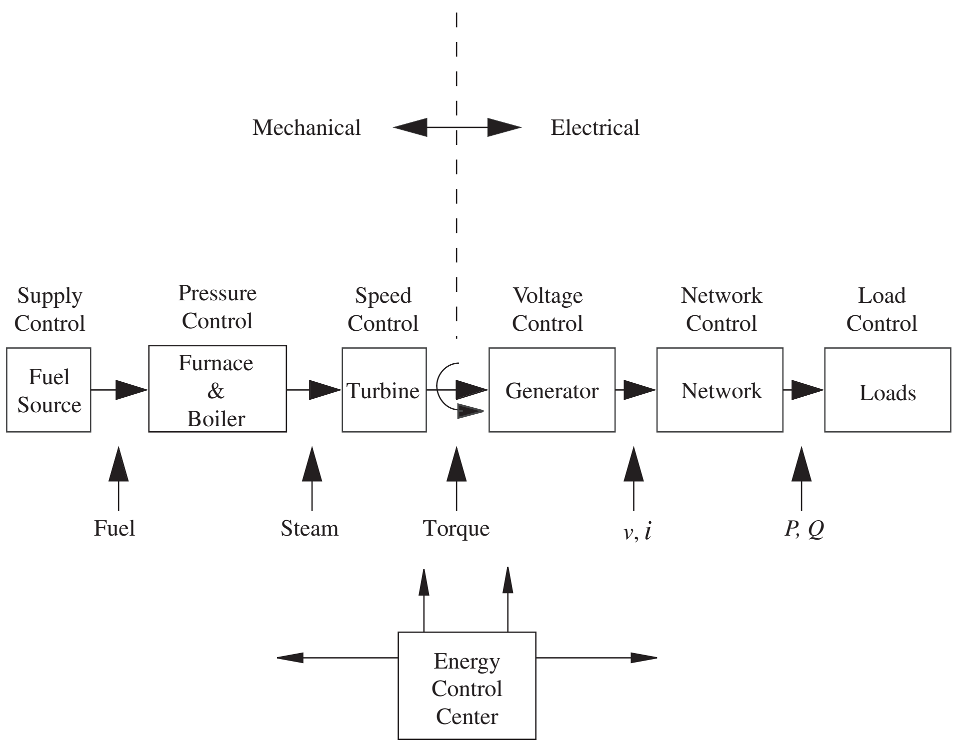

Figure 1.1 System dynamic structure.

dynamics (tap-changing-under-load (TCUL) transformers, motor loads, etc.) and the mechanical side clearly contains components with electrical dynamics (auxiliary motor drives, process controls, etc.). Furthermore, both sides are coupled through the monitoring and control functions of the energy control center. The energy control center gets information about the states of the system, that is, voltages and phase angles at various buses, through the phasor measurement units (PMUs) positioned all over the network.

1.3 Time-Scale Structures

Perhaps the most important classification of dynamic phenomena is their natural time range of response. A typical classification is shown in Figure 1.2. A similar concept is presented in [6]. This time-range classification is important because of its impact on component modeling. It should be intuitively obvious that it is not necessary to solve the complex transmission line wave equations to investigate the impact of a change in boiler control set points. This confirms a statement made earlier that "the system is not in steady state." Evidently, depending on the nature of the dynamic disturbance, portions of the power system can be considered in "quasi-steady state." This rather ambiguous term will be explained fully in the context of time-scale modeling [2].

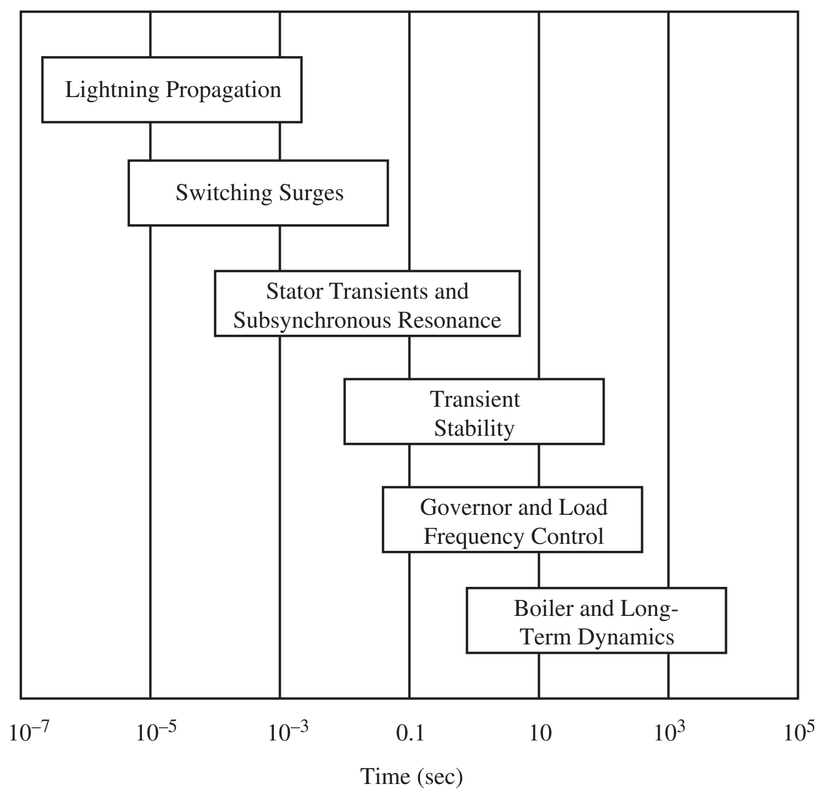

Figure 1.2 Time ranges of dynamic phenomena.

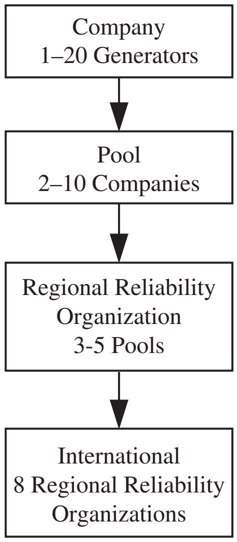

Figure 1.3 System organizational structure.

1.4 Political Structures

The dynamic structure and time-range classifications of dynamic phenomena illustrate the potential complexity of even small or moderate-sized problems. The problems of power system dynamics and stability are compounded immensely by the current size of interconnected systems. A general system structure is shown in Figure 1.3. While this structure is not necessarily common to interconnected systems throughout the world, it represents a typical North American system and serves to illustrate the concept of a "large-scale system." If we speculate about the possible size of a single interconnected system containing 8 regional reliability organizations, 4 pools per regional reliability organization, 6 companies per pool, and 10 generators per company, the total possible number of generating stations can exceed 2000. The bulk power transmission network (138–765 kV) then typically consists of over 10,000 buses. Indeed, the current demand in the 8 regional reliability organizations within the North American Electric Reliability Corporation (NERC) exceeds 500,000 MW [3]. At an average 250 MW per generator, this roughly confirms the estimate of over 2000 generators in the interconnected North American grid.

Dynamic studies are routinely performed on systems ranging in size from the smallest company to the largest regional reliability organization. These are made at both the planning/design and operating stages. These studies provide information about local capabilities as well as regional power interchange capabilities. In view of the potential size, dynamic studies must be capable of sufficiently accurate representation without prohibitive computational cost. The nature of system engineering problems inherent in such a complex task was emphasized in two benchmark reports by the Department of Energy (DOE) and the Electric Power Research Institute (EPRI) [4, 5]. These reports resulted in a meeting of international leaders to identify directions for the future of this technology. These reports set the stage for a whole new era of power system planning and operation. The volume of follow-on research and industry application has been tremendous. Perhaps the most significant impact of these reports was the stimulation of new ideas that grew into student interest and eventual manpower.

1.5 The Phenomena of Interest

The dynamic performance of power systems is important to both the system organizations, from an economic viewpoint, and society in general, from a reliability viewpoint. The analysis of power system dynamics and stability is increasing daily in terms of number and frequency of studies, as well as in complexity and size. Dynamic phenomena have been discussed according to basic function, time-scale properties, and problem size. These three fundamental concepts are very closely related and represent the essence of the challenges of effective simulation of power system dynamics. When properly performed, modeling and simulation capture the phenomena of interest at minimal cost. The first step in this process is understanding the phenomena of interest. Only with a solid physical *and* mathematical understanding can the modeling and simulation properly reflect the critical system behavior. This means that the origin of mathematical models must be understood, and their purpose must be well defined. Once this is accomplished, the minimal cost is achieved by model reduction and simplification without significant loss in accuracy.

1.6 New Chapters Added to this Edition

Two new chapters have been added in this edition of the book to reaffirm learning from the existing chapters. For generations, most power students had to take "faith" in the generator swing equations and excitation system control to determine power system dynamics. However, with high-sampling-rate digital recording of power system signals using the phasor measurement technology and the ability to precisely time tag the measurements over wide geographical areas using a timing signal from the Global Positioning System (GPS), the propagation of a disturbance can be observed as it travels through a power grid. This observation can be used to corroborate the dynamic models of power systems. Synchrophasor measurement is covered in Chapter 10.

Chapter 11 on the Power System Toolbox (PST) is a timely addition to this edition, as the first edition was published before PST was developed. Although limited in the availability of exciter and governor models, the PST program structure is in many aspects similar to those of several commercial power system simulation tools. In addition to a description on the fundamentals of power system computer simulation, Chapter 11 also provides useful pointers for the proper use of such simulation programs. An ambitious reader may even try to incorporate additional models into PST.

The Power System Toolbox, the PMU Simulator, and the data and MATLAB™ code for selected examples and problems can be downloaded from the website https://ecse.rpi.edu/~chowj/.