CHAPTER 1

POWER SYSTEM STABILITY

1.1 INTRODUCTION

Since the industrial revolution the worldwide demand for and consumption of energy has increased steadily. The invention of the induction motor by Nikola Tesla in 1888 signaled the growing importance of electrical energy in the industrial world as well as its use for artificial lighting. A major portion of the energy needs of a modern society is supplied in the form of electrical energy.

Industrially developed societies need an economical and reliable supply of electrical power, and the demand on the North American continent has steadily grown and stabilized since 2015. Very complex power systems have been built to satisfy this demand. Increasingly the demand is being met by renewable resources consisting primarily of wind and solar generation. The trend in electric power production is toward an interconnected network of transmission lines, linking generators and loads into large integrated systems, some of which span entire continents. Indeed, in the United States and Canada, generators located thousands of miles apart operate in parallel.

This vast enterprise of supplying electrical energy presents many engineering problems that provide the engineer with a variety of challenges. The planning, construction, and operation of such systems become exceedingly complex. Some of the problems stimulate the engineer's managerial talents; others tax his/her knowledge and experience in system design. The entire design must be predicated on automatic control and not on the slow response of human operators. To be able to predict the performance of such complex systems, the engineer is forced to seek ever more powerful tools of analysis and synthesis.

This book is concerned with some aspects of the design problem, particularly the dynamic performance of interconnected power systems. Characteristics of the various components of a power system during normal operating conditions and during disturbances will be examined, and effects on the overall system performance will be analyzed. Emphasis will be given to the transient behavior in which the system is described mathematically by ordinary differential equations. Detailed analysis and modeling of synchronous generators is introduced. In this edition of the book, an enhancement of the synchronous machine model including a fictitious *G*-winding is introduced to extend the accuracy of the model.

The previous edition of the book primarily focused on the modeling of generation associated with synchronous generators. Additionally, since the previous edition of the book was published, a range of new devices for generating and control of electric energy have been developed. This edition incorporates these changes as identified below.

Significant new material on modeling and analyzing renewable energy sources, primarily consisting of wind and solar, is included. These resources are interconnected to the electric grid via power electronic interfaces. Salient features of the power electronic interface and the associated dynamic characteristics are also introduced and detailed.

Power System Control and Stability, Third Edition. Vijay Vittal, James D. McCalley, Paul M. Anderson, and A. A. Fouad.

A joint effort by the IEEE Power and Energy Society (PES) and CIGRÉ (International Council on Large Electric Systems) has led to a systematic definition of power system stability and its various manifestations. These new definitions are presented and discussed. The topic of voltage stability, which has gained significance around the world, is introduced. Large-signal voltage stability analysis is also examined.

Power system stabilizers have played a critical role in stabilizing power system oscillations. Major advances in designing and tuning power system stabilizers for multimachine systems have been designed and implemented. These new advancements are introduced and described.

Flexible AC transmission system (FACTS) devices have played a significant role in shaping and altering power system dynamic behavior, and so FACTS devices and their modeling and representation are introduced and presented.

The chapter on small-signal stability analysis has been expanded to include a detailed treatment of multimachine small-signal stability analysis, together with an extensive description of the formulation of the $\boldsymbol{A}$ matrix for multimachine systems. Additionally, new material on modeling and incorporating dynamic loads is included. Advanced models for induction machines, motor drives, and performance models for single-phase induction machines are also introduced.

A new chapter on representation of protections systems that are critical in transient stability analysis has also been introduced.

1.2 REQUIREMENTS OF A RELIABLE ELECTRICAL POWER SERVICE

The interconnected power system is made up of an elaborate and complex interconnection of power system components. When we refer to the reliability and security of the electrical power system, we are primarily interested in what is referred to as the “bulk electric system” (BES). According to the definition provided by the North American Electric Reliability Corporation (NERC), the BES consists of all transmission elements operated at 100 kV or higher and active and reactive power resources connected at 100 kV or higher. Any interruptions in the BES are considered very serious, as many users are affected, and can result in significant economic impacts. Thus, much effort is invested in avoiding interruptions to the BES.

The reliability of the interconnected BES is broadly defined using the following two terms:

Adequacy – The ability of the electric systems to supply the aggregate electrical demand and energy requirements of customers at all times taking into account scheduled and reasonably expected unscheduled outages of system elements.

Security – The ability of the electric systems to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements.

The following are among the more important requirements of a reliable electric power service:

- Voltage and frequency must be held within close tolerances.
- Synchronous generators must be kept running in synchronism with adequate capacity to meet the load demand.
- The “integrity” of the BES must be maintained to avoid cascading outages.

In the United States, NERC serves as the electric reliability organization (ERO) for the Federal Energy Regulatory Commission (FERC). The main goal of NERC is to augment the reliability of the BES in the electricity systems of North America. NERC is composed of eight regional reliability councils and encompasses all the electric power systems in the United States and Canada and a small portion of Mexico. NERC sets the reliability standards and criteria for planning and operating the interconnected network in the United States and Canada. When designing and operating the interconnected electric power network, it is necessary to take into consideration the dynamic performance of the system because power systems are subjected to changes (small and large). It is also important that when these changes are completed and the system settles to new operating conditions, no constraints are violated. In other words, not only should the new operating conditions be acceptable (as revealed by steady-state analysis), but also the system must survive the transition to the new conditions. The study of the survival of the transition requires dynamic analysis.

An important aspect of reliability is the ability of the system to withstand sudden changes called disturbances. A disturbance could be a sudden change in a system parameter or operating condition. A disturbance is characterized as "small" when the equations governing system behavior can be linearized for the purpose of analysis. The analysis of system stability behavior when subjected to small disturbances is referred to as small-signal stability analysis. On the other hand, a disturbance is characterized as "large" when the equations governing the system behavior cannot be linearized for the purpose of analysis. The analysis of system behavior when subjected to large disturbances is referred to as transient stability analysis.

1.3 STATEMENT OF THE PROBLEM

Over the years, several textbooks, papers, and documents have provided definitions of power system stability. There also exist strict analytical definitions of stability for nonlinear systems. These earlier efforts did not fully encompass existing needs, practical experiences, and understanding of the problems at hand. In 2000, a joint IEEE PES and CIGRÉ effort was initiated to define and classify power system stability. The task force created for this effort produced a comprehensive document [1], which addresses the issue of definition and classification of power system stability from first principles, while paying close attention to important practical aspects related to the problem. This section of the book will borrow extensively from the PES and CIGRÉ publication to define and classify power system stability without reinventing the wheel.

1.3.1 Definition of Stability

Definition [1]: Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.

Power systems are nonlinear systems that operate with significant time varying changes: loads, generation output, network topologies, and operating parameters. When subjected to changes or disturbances, the stability of the system is dependent on two factors: the initial operating condition and the severity of the disturbance. As an analogy, consider a pitcher filled with water. The level of water in the pitcher is analogous to the operating condition in the power system. Now consider a pebble being dropped in this pitcher. The size of the pebble corresponds to the severity of the disturbance. The stability problem in this case is defined by water spilling out of the pitcher when the pebble is dropped. Consider the pitcher to be half full, and a small pebble is dropped. In this case, no water will spill over and the system at hand will be stable. Now consider two alternatives: (a) with the pitcher being half full, a large-sized pebble is dropped, causing water to be spilled, and (b) with the pitcher being filled close to the brim, either the same small pebble considered earlier or a moderate-sized pebble is dropped, which causes water to spill out of the pitcher. It should be noted that in case (a) the system becomes unstable due to the severity of the disturbance (large-sized pebble) and in case (b) the system becomes unstable due to a highly stressed operating condition when subjected to a disturbance that is not so severe. Hence, this analogy illustrates that both the operating condition and the severity of the disturbance can impact the stability behavior of the system.

Based on the above definition, it should be noted that stability analysis deals with the examination of the property of system dynamics around an equilibrium set. Stability analysis consists of examining whether the power system attains a new equilibrium state with system integrity preserved following a disturbance. In [1] system integrity is characterized by the statement "with practically all generators and loads connected through a single contiguous transmission system.” This allows for some generators and loads to be disconnected due to protective relay actions to isolate faulted elements or intentional tripping so as to maintain the integrity of the bulk electric system.

1.3.2 Classification of Stability Problems

Power system stability as the definition above suggests is a unique characteristic of system dynamics. However, this characterization precludes a proper analysis and understanding of the phenomenon because a power system can undergo different forms of instabilities. Additionally, due to the large size and complexity of the stability problems, we make simplified assumptions in order to analyze specific types of problems and use appropriate degrees of detail for system representation and analysis methods that are suited to the problem at hand. As a result, a stability analysis of the system, which includes identifying key factors that impact stability, as well as determining appropriate methods to mitigate the detrimental impacts of the instability, can be facilitated by a systematic classification of the stability problems [1, 2]. Figure 1.1 (obtained from [1]) depicts the classification of the power system stability problems, including identifying the various categories and subcategories.

An excellent description of each form the stability phenomenon is provided in [1]. A brief description of the phenomenon addressed in this book is provided next.

1.3.3 Description of Stability Phenomenon

Rotor Angle Stability

This stability phenomenon is associated with the response of interconnected synchronous machines that remain in synchronism after being subjected to a disturbance. The physics of the associated problem will be discussed and developed in detail in the chapters that follow. Simply put, a synchronous machine remains in synchronism following a disturbance when the balance between output electromagnetic torque and input mechanical torque can be restored/maintained. When this balance is lost, instability manifests itself as increasing or decreasing angular swings of generators, resulting in loss of synchronism with other interconnected generators.

Subsequent chapters in this book deal with the development of models and analysis techniques related to both electromagnetic torque and mechanical torque. Mathematical models for synchronous

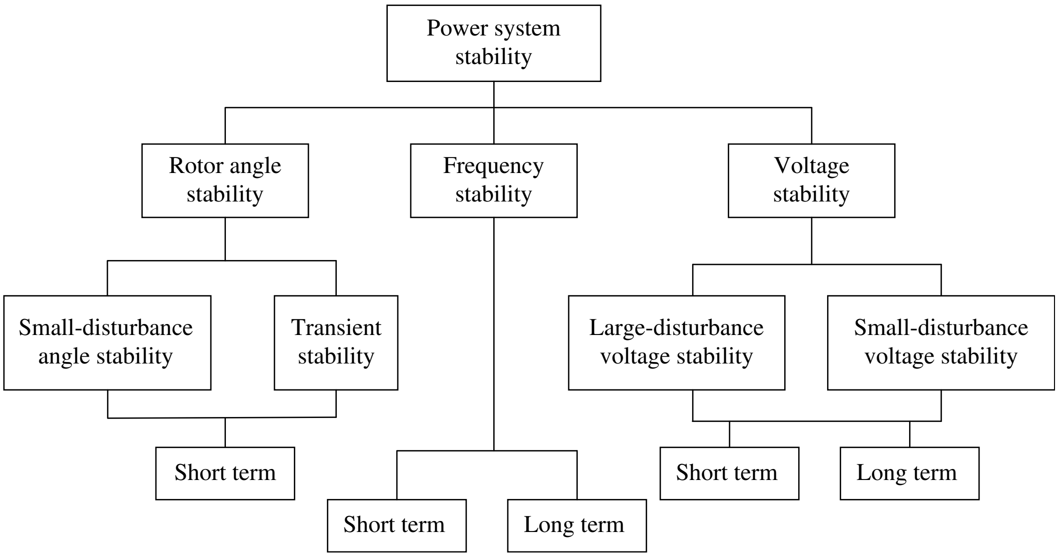

Figure 1.1 Classification of power system stability [1].

machines that accurately represent the developed electromagnetic torque and mechanical torque will be derived.

The change in electromagnetic torque of a synchronous machine following a disturbance can be decomposed into:

Synchronizing torque, which is in phase with the rotor angle deviation.

Damping torque, which is in phase with the speed deviation.

Both components of torque are essential in maintaining system stability. Lack of sufficient synchronizing torque leads to aperiodic instability, and lack of sufficient damping torque leads to oscillatory instability.

Rotor angle stability is associated with both large disturbances and small disturbances. Large-disturbance rotor angle stability, also referred to as transient stability, deals with the ability of the power system to remain in synchronism when subjected to large disturbances. An analysis in this case necessitates the nonlinear representation of all the associated components of the power system.

Small-disturbance rotor angle stability is associated with maintaining synchronism when subjected to small disturbances. The analysis of small-disturbance rotor angle stability is primarily conducted by linearizing the system equations.

Voltage Stability

This stability phenomenon relates to the power system's ability to maintain steady voltages at all buses in the system after being subjected to a disturbance at a given operating point. Akin to rotor angle stability, voltage stability is associated with the ability to restore/maintain balance between load supply and load demand in the power system. Voltage instability manifests itself as a progressive fall or rise of voltages at certain buses. A loss of voltage stability could result in localized tripping of load and transmission outages due to protective relaying action, resulting in cascading outages or loss of synchronism in generators caused by field current limit violations.

Similar to rotor angle stability, voltage stability can also be classified as large-disturbance voltage stability and small-disturbance voltage stability. Large-disturbance voltage stability pertains to the ability of the system to maintain steady voltages when subjected to large disturbances, such as short circuits, generation tripping, or transmission outages. The system and load characteristics and the interactions with continuous and discrete controls and protection systems greatly impact large-disturbance voltage stability. As in the case of large-disturbance rotor angle stability, large-disturbance voltage stability analysis requires the nonlinear analysis of system response over a sufficient amount of time to capture the effect of the discrete control and dynamic load components, including motors and excitation field current limiters. This analysis needs to be carefully conducted with all requisite components appropriately modeled.

Small-disturbance voltage stability is associated with the ability of the system to maintain steady voltages when subjected to small disturbances, including changes in system load. The behavior and characteristics of loads and continuous and discrete controls greatly influence this behavior. As in the case of small-disturbance rotor angle stability, the study of small-disturbance voltage stability can be analyzed by linearizing the system equations. However, this linearization cannot account for tap changers, limiters, deadbands, and delays. As a result, in many instances, small-disturbance voltage stability analysis would involve the use of both nonlinear and linear approaches in a complementary manner.

1.4 EFFECT OF IMPACT ON SYSTEM COMPONENTS

In this section, a survey of the effect of impacts is made to estimate the elements that should be considered in a stability study. A convenient starting point is to relate an impact to a change in power somewhere in the network. Our "test" stimulus will be a change in power, and we will use the point of impact as our reference point. The following effects, in whole or in part, may be felt. The system frequency will change because, until the input power is adjusted by the machine governors, the power change will go to or come from the energy in the rotating masses. The change in frequency will affect the loads, especially the motor loads. A common rule of thumb used among power system engineers is that a decrease in frequency results in a load decrease of equal percentage, i.e., load regulation is 100%. The network bus voltages will be affected to a lesser degree unless the change in power is accompanied by a change in reactive power.

1.4.1 Loss of Synchronism

Any unbalance between the generation and load initiates a transient that causes the rotors of the synchronous machines to "swing" because net accelerating (or decelerating) torques are exerted on these rotors. If the net torques are sufficiently large to cause some of the rotors to swing far enough so that one or more machines "slip a pole," then synchronism is lost. To assure stability, a new equilibrium state must be reached before any of the machines experience this condition. Loss of synchronism can also occur in stages, e.g., if the initial transient causes an electrical link in the transmission network to be interrupted during the swing. This creates another transient, which when superimposed on the first may cause synchronism to be lost.

Let us now consider a severe impact initiated by a sizable generation unbalance, say, excess generation. The major portion of the excess energy will be converted into kinetic energy. Thus, most of the machine rotor angular velocities will increase. A lesser part will be consumed in the loads and through various losses in the system. However, an appreciable increase in machine speeds may not necessarily mean that synchronism will be lost. The important factor here is the *angle difference* between machines, where the rotor angle is measured with respect to a synchronously rotating reference. This is illustrated in Figure 1.2 in which the rotor angles of the machines in a hypothetical four-machine system are plotted against time during a transient.

In case (a) all the rotor angles increase beyond π radians, but all the angle differences are small, and the system will be stable if it eventually settles to a new angle. In case (b) it is evident that the machines are separated into two groups where the rotor angles continue to drift apart. This system is unstable.

1.4.2 Synchronous Machine During a Transient

During a transient, the system, when seen by a synchronous machine, causes the machine terminal voltage, rotor angle, and frequency to change. The impedance seen "looking into" the network at the machine terminal may also change. The field-winding voltage will be affected by:

1. Induced currents in the damper windings (or rotor iron) due to sudden changes in armature currents. The time constants for these currents are usually on the order of less than 0.1 s and are often referred to as "subtransient" effects.
2. Induced currents in the field winding due to sudden changes in armature currents. The time constants for this transient are on the order of seconds and are referred to as "transient" effects.
3. Change in rotor voltage due to change in exciter voltage if activated by changes at the machine terminal. Both subtransient and transient effects are observed. Since the subtransient effects decay very rapidly, they are usually neglected, and only the transient effects are considered important.

Note that the behavior discussed above depends on the network impedance as well as the machine parameters.

The machine output power will be affected by the change in the rotor-winding EMF and rotor position, in addition to any changes in the impedance "seen" by the machine terminals. However,

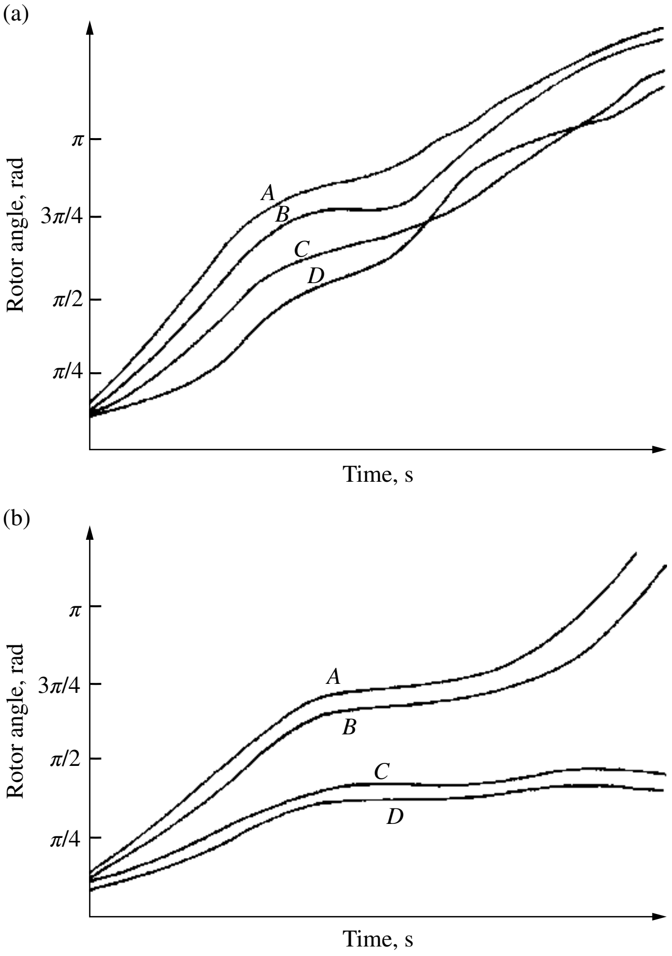

Figure 1.2 Response of a four-machine system during a transient: (a) stable system and (b) unstable system.

until the speed changes to the point where it is sensed and corrected by the governor, the change in the output power will come from the stored energy in the rotating masses. The important parameters here are the kinetic energy in MW-s per-unit MVA (usually called *H*) or the machine mechanical time constant τ_j, which is twice the stored kinetic energy per MVA.

When the impact is large, the speeds of *all* machines change so that they are sensed by their speed governors. Machines under load frequency control will correct for the power change. Until this correction is made, each machine's share will depend on its regulation or droop characteristic. Thus, the controlled machines are the ones responsible for maintaining the system frequency. The dynamics of the transition period, however, are important. The key parameters are the governor dynamic characteristics.

In addition, the flow of the tie lines may be altered slightly. As a result, some machines are assigned the requirement of maintaining scheduled flow in the ties. Supplementary controls are provided to these machines, the basic functions of which are to permit each control area to supply a given load. The responses of these controls are relatively slow, and their time constants are on the order of seconds. This is appropriate since the scheduled economic loading of machines is secondary in importance to stability.

1.5 METHODS OF SIMULATION

If we look at a large power system with its numerous machines, lines, and loads and consider the complexity of the consequences of any impact, we may tend to think it is hopeless to attempt analysis. Fortunately, however, the time constants associated with the phenomena may be appreciably different, allowing concentration on the key elements affecting the transient and the area under study.

The first step in a stability study is to construct a mathematical model of the system during the transient. The elements included in the model are those affecting the acceleration (or deceleration) of the machine rotors. The complexity of the model depends on the type of transient and system being investigated. Generally, the components of the power system that influence the electrical and mechanical torques of the machines should be included in the model. These components are:

1. The network before, during, and after the transient.
2. The loads and their characteristics.
3. The parameters of the synchronous machines.
4. The excitation systems of the synchronous machines.
5. The mechanical turbine and speed governor.
6. Other important components of the power plant that influence the mechanical torque.
7. Renewable generation associated with both wind and solar resources. (The modeling and representation of this type of generation is important new content in this edition of the book.)
8. Network control, devices including FACTS devices, such static VAr systems and thyristor-controlled series capacitors (TCSC) and their associated controls.
9. Other supplementary controls, such as tie-line controls, deemed necessary in the mathematical description of the system.

The basic ingredients for the solution are, thus, the knowledge of the initial conditions of the power system prior to the start of the transient and the mathematical description of the main components of the system that affect the transient behavior of the synchronous machines.

The number of power system components included in the study and the complexity of their mathematical description will depend on many factors. In general, however, differential equations are used to describe the various components. Study of the dynamic behavior of the system is contingent on the nature of these differential equations.

1.5.1 Linearized System Equations

If the system equations are linear (or have been linearized), the techniques of linear system analysis are used to study dynamic behavior. The most common method is to simulate each component by its transfer function. The various transfer function blocks are connected to represent the system under study. The system performance may then be analyzed by such methods as root-locus plots, frequency domain analysis (Nyquist criteria), and Routh's criterion.

The above methods have been frequently used in studies pertaining to small systems or a small number of machines. For larger systems the state-space model has been used more frequently in connection with system studies described by linear differential equations. Stability characteristics may be determined by examining the eigenvalues of the **A** matrix, where **A** is defined by the equation

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{1.1}$$

where **x** is an n vector denoting the states of the system and **A** is a coefficient matrix. The system inputs are represented by the $\boldsymbol{r}$ vector **u**, and these inputs are related mathematically to differential equations by an $n \times r$ matrix **B**. This description has the advantage that **A** may be time varying and **u** may be used to represent several inputs if necessary.

1.5.2 Large System with Nonlinear Equations

The system equations for a transient stability study are usually nonlinear. Here the system is described by a large set of coupled nonlinear differential equations of the form

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}, t) \tag{1.2}$$

where **f** is an n vector of nonlinear functions.

Determining the dynamic behavior of the system described by (1.2) is a more difficult task than that of the linearized system of (1.1). Usually *time solutions* of the nonlinear differential equations are obtained by numerical methods with the aid of digital computers, a method typically used in power system stability studies. Stability of synchronous machines is usually decided by behavior of their rotor angles, as discussed in Section 1.4.1. More recently, modern theories of stability of nonlinear systems have been applied to the study of power system transients to determine the stability of synchronous machines without obtaining time solutions. Such efforts, while they seem to offer considerable promise, are not in common use because of the limitations associated with applying these methods to detailed models of power system components. Both linear and nonlinear equations will be developed in following chapters.

1.6 PLANNING AND OPERATING STANDARDS

A question that commonly arises in the context of stability studies is, “Why is there a need to conduct stability studies?” The answer to this question is that stability studies are needed to determine if the system satisfies planning and operation guidelines or the standards for the area in which the system operates. These guidelines or standards are typically set up by regulatory bodies with jurisdiction over the grid in a specific geographical area or country. In the United States, Canada, and a small portion of the Baja peninsula, this responsibility lies with the NERC, which serves as the ERO subject to oversight by the FERC.

NERC has an extensive list of reliability standards available at http://www.nerc.com/pa/Stand/Reliability%20Standards%20Complete%20Set/RSCompleteSet.pdf. These standards cover aspects of planning standards for the BES and include operating standards as well. Other countries and interconnections also have similar grid codes or standards. Stability studies are conducted either in a planning horizon or operating horizon to make sure the BES meets the planning and operating standards or codes, respectively.

The reliability criteria or grid codes are used in the power system planning function to make decisions on size, type, and timing of generation and transmission facilities. They are also used to design the transmission network to withstand normal and (prescribed) emergency conditions. This would include examination of the design subjected to short circuits, loss of major system components, and other large disturbances.

In the power system operating function, the reliability criteria are primarily used to:

- Establish the most economical operation conditions under normal operating conditions.
- Operate the system such that if an unscheduled event occurs, it does not result in uncontrolled (or cascading) outages.
- Establish safe operating limits for all probable situations.
- In the new market environment, the hourly day-ahead schedules obtained via an auction mechanism will also be examined to see if the operating conditions associated with the schedules satisfy the reliability criteria.

An example of a typical reliability criteria or grid code is provided in Table 1.1 (obtained from the NERC Standard TPL-001-4 – Transmission System Planning Performance Requirements). This

TABLE 1.1 NERC Standard TPL-001-4 – Transmission System Planning Performance Requirements

Steady State and Stability Performance Planning Events

Steady State and Stability:

a. The system shall remain stable. Cascading and uncontrolled islanding shall not occur.

b. Consequential load loss as well as generation loss is acceptable as a consequence of any event excluding P0.

c. Simulate the removal of all elements that protection systems and other controls are expected to automatically disconnect for each event.

d. Simulate normal clearing unless otherwise specified.

e. Planned system adjustments such as transmission configuration changes and re-dispatch of generation are allowed if such adjustments are executable within the time duration applicable to the Facility Ratings.

Steady State Only:

f. Applicable facility ratings shall not be exceeded.

g. System steady state voltages and post-contingency voltage deviations shall be within acceptable limits as established by the planning coordinator and the transmission planner.

h. Planning event P0 is applicable to steady state only.

i. The response of voltage sensitive load that is disconnected from the system by end-user equipment associated with an event shall not be used to meet steady state performance requirements.

Stability Only:

j. Transient voltage response shall be within acceptable limits established by the planning coordinator and the transmission planner.

Category	Initial Condition	Event[1]	Fault Type[2]	BES Level[3]	Interruption of Firm Transmission Service Allowed[4]	Non-Consequential Load Loss Allowed
P0 No Contingency	Normal System	None	N/ A	EHV, HV	No	No
P1 Single Contingency	Normal System	Loss of one of the following: **1.** Generator **2.** Transmission circuit **3.** Transformer[5] **4.** Shunt device[6]	3ϕ	EHV, HV	No[9]	No[12]
		5. Single pole of a DC line	SLG			
P2 Single Contingency	Normal System	**1.** Opening of a line section w/o a fault[7]	N/A	EHV, HV	No[9]	No[12]
		2. Bus section fault	SLG	EHV	No[9]	No
				HV	Yes	Yes
		3. Internal breaker fault[8] (non-bus-tie-breaker)	SLG	EHV	No[9]	No
				HV	Yes	Yes
		4. Internal breaker fault (bus-tie breaker)	SLG	EHV, HV	Yes	Yes

Category	Initial Condition	Event[1]	Fault Type[2]	BES Level[3]	Interruption of Firm Transmission Service Allowed[4]	Non-Consequential Load Loss Allowed
P3 Multiple Contingency	Loss of generator unit followed by system adjustments[9]	Loss of one of the following:				
		1. Generator	3ϕ	EHV, HV	No[9]	No[12]
		2. Transmission circuit				
		3. Transformer[5]				
		4. Shunt device[6]				
		5. Single pole of a DC line	SLG			
P4 Multiple contingency (*Fault plus stuck breaker*[10])	Normal System	Loss of multiple elements caused by a stuck breaker[10] (non-bus-tie breaker) attempting to clear a fault on one of the following:		EHV HV	No[9] Yes	No Yes
		1. Generator	SLG			
		2. Transmission circuit				
		3. Transformer[5]				
		4. Shunt device[6]				
		5. Bus section				
		6. Loss of multiple elements caused by a stuck breaker[10] (bus-tie breaker) attempting to clear a fault on the associated bus	SLG	EHV, HV	Yes	Yes
P5 Multiple contingency (*Fault plus relay failure to operate*)	Normal System	Delayed fault clearing due to failure of non-redundant relay[13] protecting the faulted element to operate as designed, for one of the following:	SLG	EHV HV	No[9] Yes	No Yes
		1. Generator				
		2. Transmission circuit				
		3. Transformer[5]				
		4. Shunt device[6]				
		5. Bus section				

(*Continued*)

TABLE 1.1 (*Continued*)

Category	Initial Condition	Event[1]	Fault Type[2]	BES Level[3]	Interruption of Firm Transmission Service Allowed[4]	Non-Consequential Load Loss Allowed
P6 Multiple contingency (*Two overlapping singles*)	Loss of one of the following followed by system adjustments.[9]	Loss one of the following: **1.** Transmission circuit **2.** Transformer[5]	3ϕ	EHV	No[9]	No
	1. Transmission circuit **2.** Tranformer[5] **3.** Shunt device[6] **4.** Single pole of a DC line	**3.** Shunt device[6] **4.** Single pole of a DC line	SLG	HV	Yes	Yes
P7 Multiple contingency (*Common structure*)	Normal System	Los of: **1.** Any two adjacent (vertically or horizontally) circuits on common structure[11] **2.** Loss of bipolar DC line	SLG	EHV, HV	Yes	Yes

Steady State and Stability Performance Extreme Events

Steady State and Stability

For all extreme events evaluated:

a. Simulate the removal of all elements that protection systems and automatic controls are expected to disconnect for each contingency.

b. Simulate normal clearing unless otherwise specified.

Steady State

1. Loss of a single generator, transmission circuit, single pole of a DC Line, shunt device, or transformer forced out of service followed by another single generator, transmission circuit, single pole of a different DC line, shunt device, or transformer forced out of service prior to system adjustments.
2. Local area events affecting the transmission system such as:
   - **a.** Loss of a tower line with three or more circuits.[11]
   - **b.** Loss of all transmission lines on a common right-of-way[11].
   - **c.** Loss of a switching station or substation (loss of one voltage level plus transformers).
   - **d.** Loss of all generating units at a generating station.
   - **e.** Loss of a large load or major load center.

Stability

1. With an initial condition of a single generator, Transmission circuit, single pole of a DC line, shunt device, or transformer forced out of service, apply a 3Ø fault on another single generator, Transmission circuit, single pole of a different DC line, shunt device, or transformer prior to system adjustments.
2. Local or wide area events affecting the transmission system such as:
   - **a.** 3Ø fault on generator with stuck breaker[10] or a relay failure[13] resulting in delayed fault clearing.
   - **b.** 3Ø fault on transmission circuit with stuck breaker[10] or a relay failure[13] resulting in delayed fault clearing.

Steady State and Stability Performance Extreme Events

3. Wide area events affecting the transmission system based on system topology such as:
  - **a.** Loss of two generating stations resulting from conditions such as:
    - i. Loss of a large gas pipeline into a region or multiple regions that have significant gas-fired generation.
    - ii. Loss of the use of a large body of water as the cooling source for generation.
    - iii. Wildfires.
    - iv. Severe weather, e.g., hurricanes, tornadoes, etc.
    - v. A successful cyber-attack.
    - vi. Shutdown of a nuclear power plant(s) and related facilities for a day or more for common causes such as problems with similarly designed plants.
  - **b.** Other events based upon operating experience that may result in wide area disturbances.
  - **c.** 3Ø fault on transformer with stuck breaker[10] or a relay failure[13] resulting in delayed fault clearing.
  - **d.** 3Ø fault on bus section with stuck breaker[10] or a relay failure[13] resulting in delayed fault clearing.
  - **e.** 3Ø internal breaker fault.
  - **f.** Other events based upon operating experience, such as consideration of initiating events that experience suggests may result in wide area disturbances.

Steady State and Stability Performance Footnotes
(Planning Events and Extreme Events)

1. If the event analyzed involves BES elements at multiple System voltage levels, the lowest system voltage level of the element(s) removed for the analyzed event determines the stated performance criteria regarding allowances for interruptions of firm transmission service and non-consequential load loss.
2. Unless specified otherwise, simulate normal clearing of faults. Single line to ground (SLG) or three-phase (3Ø) are the fault types that must be evaluated in Stability simulations for the event described. A 3Ø or a double line to ground fault study indicating the criteria are being met is sufficient evidence that a SLG condition would also meet the criteria.
3. Bulk electric system (BES) level references include extra-high voltage (EHV) facilities, defined as greater than 300 kV, and high voltage (HV) facilities defined as the 300 kV and lower voltage systems. The designation of EHV and HV is used to distinguish between stated performance criteria allowances for interruption of firm transmission service and non-consequential load loss.
4. Curtailment of conditional firm transmission service is allowed when the conditions and/or events being studied formed the basis for the conditional firm transmission service.
5. For non-generator step up transformer outage events, the reference voltage, as used in footnote 1, applies to the low-side winding (excluding tertiary windings). For generator and generator step up transformer outage events, the reference voltage applies to the BES connected voltage (high-side of the generator step up transformer). Requirements which are applicable to transformers also apply to variable frequency transformers and phase shifting transformers.
6. Requirements which are applicable to shunt devices also apply to FACTS devices that are connected to ground.
7. Opening one end of a line section without a fault on a normally networked transmission circuit such that the line is possibly serving load radial from a single source point.
8. An internal breaker fault means a breaker failing internally, thus creating a system fault which must be cleared by protection on both sides of the breaker.

(*Continued*)

TABLE 1.1 (*Continued*)

9. An objective of the planning process should be to minimize the likelihood and magnitude of interruption of firm transmission service following contingency events. Curtailment of firm transmission service is allowed both as a system adjustment (as identified in the column entitled “initial condition”) and a corrective action when achieved through the appropriate re-dispatch of resources obligated to re-dispatch, where it can be demonstrated that Facilities, internal and external to the transmission planner’s planning region, remain within applicable facility ratings and the re-dispatch does not result in any non-consequential load loss. Where limited options for re-dispatch exist, sensitivities associated with the availability of those resources should be considered.

10. A stuck breaker means that for a gang-operated breaker, all three phases of the breaker have remained closed. For an independent pole operated (IPO) or an independent pole tripping (IPT) breaker, only one pole is assumed to remain closed. A stuck breaker results in delayed fault clearing.

11. Excludes circuits that share a common structure (Planning event P7, Extreme event steady state 2a) or common right-of-way (extreme event, steady state 2b) for 1 mile or less.

12. An objective of the planning process is to minimize the likelihood and magnitude of non-consequential load loss following planning events. In limited circumstances, non-consequential load loss may be needed throughout the planning horizon to ensure that BES performance requirements are met. However, when non-consequential Load Loss is utilized under footnote 12 within the near-term transmission planning horizon to address BES performance requirements, such interruption is limited to circumstances where the non-consequential load loss meets the conditions shown in Attachment 1. In no case can the planned non-consequential load loss under footnote 12 exceed 75 MW for US registered entities. The amount of planned non-consequential load loss for a non-US registered entity should be implemented in a manner that is consistent with, or under the direction of, the applicable governmental authority or its agency in the non-US jurisdiction.

13. Applies to the following relay functions or types: pilot (#85), distance (#21), differential (#87), current (#50, 51, and 67), voltage (#27 & 59), directional (#32, & 67), and tripping (#86, & 94).

table provides a clear example of the extensive analysis that should be conducted in order to satisfy the standard.

Table 1.1 shows that stability studies need to be conducted with the system in normal conditions (with all elements in service) and for multiple contingencies. The studies also involve cases that include stuck breakers and relay failures. The cases identified in Table 1.1 are the minimum requirement set by NERC. Additionally, each regional reliability council could set stricter requirements based on distinctive system characteristics in each regional jurisdiction.

The nature of the stability studies to be conducted according to Table 1.1 is complex and involves the examination of a wide range of operating conditions and contingencies. The range and scope of the analysis to be conducted is comprehensive and requires careful consideration of an exhaustive list of probable contingencies and disturbances, thus making transient stability analysis a daunting task that requires meticulous attention to detail and careful choice of the model features to capture details of the phenomenon being examined.

PROBLEMS

1.1. Suggest definitions for the following terms:

- **a.** Power system reliability
- **b.** Power system security
- **c.** Power system stability

1.2. Distinguish between steady-state (dynamic) and transient stability according to

- **a.** The type of disturbance
- **b.** The nature of the defining equations

1.3. What is a tie line? Is every line a tie line?

1.4. What is an impact insofar as power system stability is concerned?

1.5. Consider the system shown in Figure P1.5 where a mass M is pulled by a driving force $f(t)$ and is restrained by a linear spring K and an ideal dashpot B.

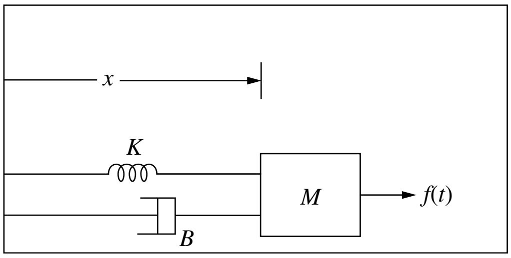

Figure P1.5

Write the differential equation for the system in terms of the displacement variable x and determine the relative values of B and K to provide critical damping when $f(t)$ is a unit step function.

1.6. Repeat Problem 1.5 but convert the equations to the state-space form of (1.1).

1.7. Consider the rotational system shown in Figure P1.7 where two rotating masses are connected by a small shaft with rotational spring constant K_θ and viscous friction B_θ. Assume that J_1 is a DC shunt motor and J_2 is a DC shunt generator that is loaded suddenly at $t = 0$ by closing the switch. Measure all mechanical angles from a fixed reference.

- **a.** State all necessary assumptions and write the equations of the system.
- **b.** Repeat part (a) but let the angular reference move clockwise at a constant speed equal to the no load speed of the rotating system.

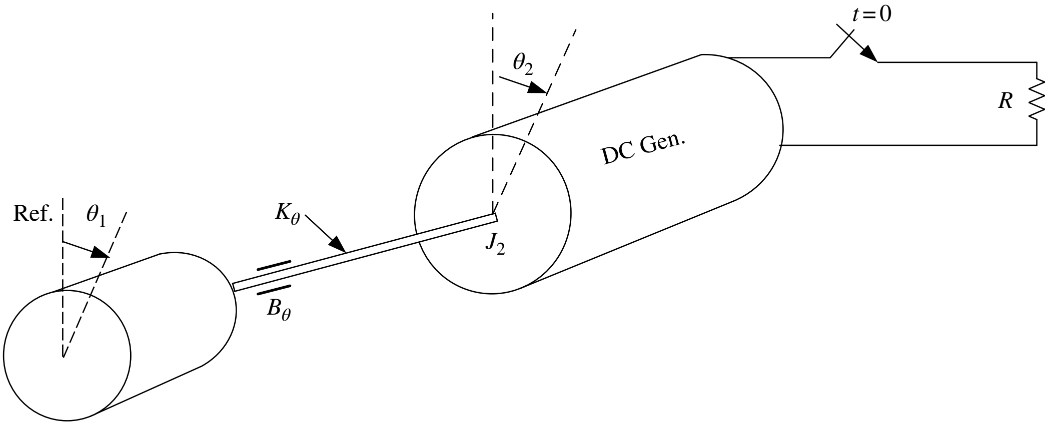

Figure P1.7

c. Sketch the torque speed characteristics for the motor and for the generator.

d. Repeat part (a) using state-space notation.

1.8. A schematic representation of the turbine-generator unit is shown in Figure P1.8. The shaft is *not* rigid and has five masses associated with the various turbine stages, generator and exciter as shown.

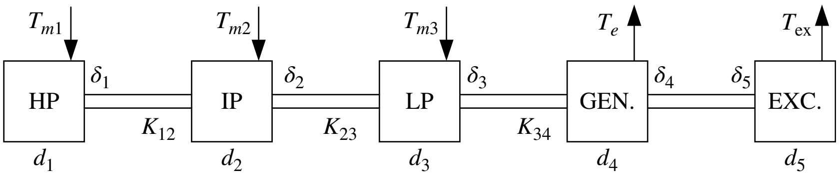

Figure P1.8

T_{mi} = mechanical torque applied to mass i

T_e, T_{ex} = electrical torque of generator and exciter, respectively

K_{ij} = spring constant of shaft between masses i and j

d_i = damping (mechanical) applied to mass i

H_i = inertia constant associated with mass i

δ_i = angular displacement of the shaft at mass i

Write the equations of motion (swing equations) for the various masses of this system in matrix form.

■

REFERENCES

1. Kundur, P., Paserba, J., Ajjarapu, V. et al. (2004). Definition and Classification of Power System Stability. IEEE/CIGRE Joint Task Force on Stability Terms and Definitions Report. *IEEE Trans. Power Syst.* 19 (3): 1387–1401.
2. Kundur, P. (1994). *Power System Stability and Control*. New York: McGraw Hill.