chapter 1

Power System Stability

1.1 Introduction

Since the industrial revolution man's 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 ever-increasing supply of electrical power, and the demand on the North American continent has been doubling every ten years. Very complex power systems have been built to satisfy this increasing demand. 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 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.

1.2 Requirements of a Reliable Electrical Power Service

Successful operation of a power system depends largely on the engineer's ability to provide reliable and uninterrupted service to the loads. The reliability of the power supply implies much more than merely being available. Ideally, the loads must be fed at constant voltage and frequency at all times. In practical terms this means that both voltage and frequency must be held within close tolerances so that the consumer's equipment may operate satisfactorily. For example, a drop in voltage of 10–15% or a reduction of the system frequency of only a few hertz may lead to stalling of the motor loads on the system. Thus it can be accurately stated that the power system operator must maintain a very high standard of continuous electrical service.

The first requirement of reliable service is to keep the synchronous generators running in parallel and with adequate capacity to meet the load demand. If at any time a generator loses synchronism with the rest of the system, significant voltage and current fluctuations may occur and transmission lines may be automatically tripped by their relays at undesired locations. If a generator is separated from the system, it must be resynchronized and then loaded, assuming it has not been damaged and its prime mover has not been shut down due to the disturbance that caused the loss of synchronism.

Synchronous machines do not easily fall out of step under normal conditions. If a machine tends to speed up or slow down, synchronizing forces tend to keep it in step. Conditions do arise, however, in which operation is such that the synchronizing forces for one or more machines may not be adequate, and small impacts in the system may cause these machines to lose synchronism. A major shock to the system may also lead to a loss of synchronism for one or more machines.

A second requirement of reliable electrical service is to maintain the integrity of the power network. The high-voltage transmisssion system connects the generating stations and the load centers. Interruptions in this network may hinder the flow of power to the load. This usually requires a study of large geographical areas since almost all power systems are interconnected with neighboring systems. Economic power as well as emergency power may flow over interconnecting tie lines to help maintain continuity of service. Therefore, successful operation of the system means that these lines must remain in service if firm power is to be exchanged between the areas of the system.

While it is frequently convenient to talk about the power system in the "steady state," such a state never exists in the true sense. Random changes in load are taking place at all times, with subsequent adjustments of generation. Furthermore, major changes do take place at times, e.g., a fault on the network, failure in a piece of equipment, sudden application of a major load such as a steel mill, or loss of a line or generating unit. We may look at any of these as a change from one equilibrium state to another. It might be tempting to say that successful operation requires only that the new state be a "stable" state (whatever that means). For example, if a generator is lost, the remaining connected generators must be capable of meeting the load demand; or if a line is lost, the power it was carrying must be obtainable from another source. Unfortunately, this view is erroneous in one important aspect: it neglects the dynamics of the transition from one equilibrium state to another. Synchronism frequently may be lost in that transition period, or growing oscillations may occur over a transmission line, eventually leading to its tripping. These problems must be studied by the power system engineer and fall under the heading "power system stability."

1.3 Statement of the Problem

The stability problem is concerned with the behavior of the synchronous machines after they have been perturbed. If the perturbation does not involve any net change in power, the machines should return to their original state. If an unbalance between the supply and demand is created by a change in load, in generation, or in network conditions, a new operating state is necessary. In any case *all* interconnected synchronous machines should remain in synchronism if the system is stable; i.e., they should all remain operating in parallel and at the same speed.

The transient following a system perturbation is oscillatory in nature; but if the system is stable, these oscillations will be damped toward a new quiescent operating condition. These oscillations, however, are reflected as fluctuations in the power flow over the transmission lines. If a certain line connecting two groups of machines undergoes excessive power fluctuations, it may be tripped out by its protective equipment thereby disconnecting the two groups of machines. This problem is termed the stability of the tie line, even though in reality it reflects the stability of the two groups of machines.

A statement declaring a power system to be "stable" is rather ambiguous unless the conditions under which this stability has been examined are clearly stated. This includes the operating conditions as well as the type of perturbation given to the system. The same thing can be said about tie-line stability. Since we are concerned here with the tripping of the line, the power fluctuation that can be tolerated depends on the initial operating condition of the system, including the line loading and the nature of the impacts to which it is subjected. These questions have become vitally important with the advent of large-scale interconnections. In fact, a severe (but improbable) disturbance can always be found that will cause instability. Therefore, the disturbances for which the system should be designed to maintain stability must be deliberately selected.

1.3.1 Primitive definition of stability

Having introduced the term "stability," we now propose a simple nonmathematical definition of the term that will be satisfactory for elementary problems. Later, we will provide a more rigorous mathematical definition.

The problem of interest is one where a power system operating under a steady load condition is perturbed, causing the readjustment of the voltage angles of the synchronous machines. If such an occurrence creates an unbalance between the system generation and load, it results in the establishment of a new steady-state operating condition, with the subsequent adjustment of the voltage angles. The perturbation could be a major disturbance such as the loss of a generator, a fault or the loss of a line, or a combination of such events. It could also be a small load or random load changes occurring under normal operating conditions.

Adjustment to the new operating condition is called the transient period. The system behavior during this time is called the dynamic system performance, which is of concern in defining system stability. The main criterion for stability is that the synchronous machines maintain synchronism at the end of the transient period.

Definition: If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, we say the system is stable. If the system is not stable, it is considered unstable.

This primitive definition of stability requires that the system oscillations be damped. This condition is sometimes called asymptotic stability and means that the system contains inherent forces that tend to reduce oscillations. This is a desirable feature in many systems and is considered necessary for power systems.

The definition also excludes continuous oscillation from the family of stable systems, although oscillators are stable in a mathematical sense. The reason is practical since a continually oscillating system would be undesirable for both the supplier and the user of electric power. Hence the definition describes a practical specification for an acceptable operating condition.

1.3.2 Other stability problems

While the stability of synchronous machines and tie lines is the most important and common problem, other stability problems may exist, particularly in power systems having appreciable capacitances. In such cases arrangements must be made to avoid excessive voltages during light load conditions, to avoid damage to equipment, and to prevent self-excitation of machines.

Some of these problems are discussed in Part III, while others are beyond the scope of this book.

1.3.3 Stability of synchronous machines

Distinction should be made between sudden and major changes, which we shall call large impacts, and smaller and more normal random impacts. A fault on the high-voltage transmission network or the loss of a major generating unit are examples of large impacts. If one of these large impacts occurs, the synchronous machines may lose synchronism. This problem is referred to in the literature as the transient stability problem. Without detailed discussion, some general comments are in order. First, these impacts have a finite probability of occurring. Those that the system should be designed to withstand must therefore be selected a priori. Second, the ability of the system to survive a certain disturbance depends on its precise operating condition at the time of the occurrence. A change in the system loading, generation schedule, network interconnections, or type of circuit protection may give completely different results in a stability study for the same disturbance. Thus the transient stability study is a very specific one, from which the engineer concludes that under given system conditions and for a given impact the synchronous machines will or will not remain in synchronism. Stability depends strongly upon the magnitude and location of the disturbance and to a lesser extent upon the initial state or operating condition of the system.

Let us now consider a situation where there are no major shocks or impacts, but rather a random occurrence of small changes in system loading. Here we would expect the system operator to have scheduled enough machine capacity to handle the load. We would also expect each synchronous machine to be operating on the stable portion of its power-angle curve, i.e., the portion in which the power increases with increased angle. In the dynamics of the transition from one operating point to another, to adjust for load changes, the stability of the machines will be determined by many factors, including the power-angle curve. It is sometimes incorrect to consider a single power-angle curve, since modern exciters will change the operating curve during the period under study. The problem of studying the stability of synchronous machines under the condition of small load changes has been called "steady-state" stability. A more recent and certainly more appropriate name is dynamic stability. In contrast to transient stability, dynamic stability tends to be a property of the state of the system.

Transient stability and dynamic stability are both questions that must be answered to the satisfaction of the engineer for successful planning and operation of the system. This attitude is adopted in spite of the fact that an artificial separation between the two problems has been made in the past. This was simply a convenience to accommodate the different approximations and assumptions made in the mathematical treat-

1. In the United States the regional committees of the National Electric Reliability Council (NERC) specify the contingencies against which the system must be proven stable.

ments of the two problems. In support of this viewpoint the following points are pertinent.

First, the availability of high-speed digital computers and modern modeling techniques makes it possible to represent any component of the power system in almost any degree of complexity required or desired. Thus questionable simplifications or assumptions are no longer needed and are often not justified.

Second, and perhaps more important, in a large interconnected system the full effect of a disturbance is felt at the remote parts some time after its occurrence, perhaps a few seconds. Thus different parts of the interconnected system will respond to localized disturbances at different times. Whether they will act to aid stability is difficult to predict beforehand. The problem is aggravated if the initial disturbance causes other disturbances in neighboring areas due to power swings. As these conditions spread, a chain reaction may result and large-scale interruptions of service may occur. However, in a large interconnected system, the effect of an impact must be studied over a relatively long period, usually several seconds and in some cases a few minutes. Performance of dynamic stability studies for such long periods will require the simulation of system components often neglected in the so-called transient stability studies.

1.3.4 Tie-line oscillations

As random power impacts occur during the normal operation of a system, this added power must be supplied by the generators. The portion supplied by the different generators under different conditions depends upon electrical proximity to the position of impact, energy stored in the rotating masses, governor characteristics, and other factors. The machines therefore are never truly at steady state except when at standstill. Each machine is in continuous oscillation with respect to the others due to the effect of these random stimuli. These oscillations are reflected in the flow of power in the transmission lines. If the power in *any* line is monitored, periodic oscillations are observed to be superimposed on the steady flow. Normally, these oscillations are not large and hence not objectionable.

The situation in a tie line is different in one sense since it connects one group of machines to another. These two groups are in continuous oscillation with respect to each other, and this is reflected in the power flow over the tie line. The situation may be further complicated by the fact that each machine group in turn is connected to other groups. Thus the tie line under study may in effect be connecting two huge systems. In this case the smallest oscillatory adjustments in the large systems are reflected as sizable power oscillations in the tie line. The question then becomes, To what degree can these oscillations be tolerated?

The above problem is entirely different from that of maintaining a scheduled power interchange over the tie line; control equipment can be provided to perform this function. These controllers are usually too slow to interfere with the dynamic oscillations mentioned above. To alter these oscillations, the dynamic response of the components of the overall interconnected system must be considered. The problem is not only in the tie line itself but also in the two systems it connects and in the sensitivity of control in these systems. The electrical strength (admittance) or capacity of the tie cannot be divorced from this problem. For example, a 40-MW oscillation on a 400-MW tie is a much less serious problem than the same oscillation on a 100-MW tie. The oscillation frequency has an effect on the damping characteristics of prime movers, exciters, etc. Therefore, there is a minimum size of tie that can be effectively made from the viewpoint of stability.

1.4 Effect of an Impact upon 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.

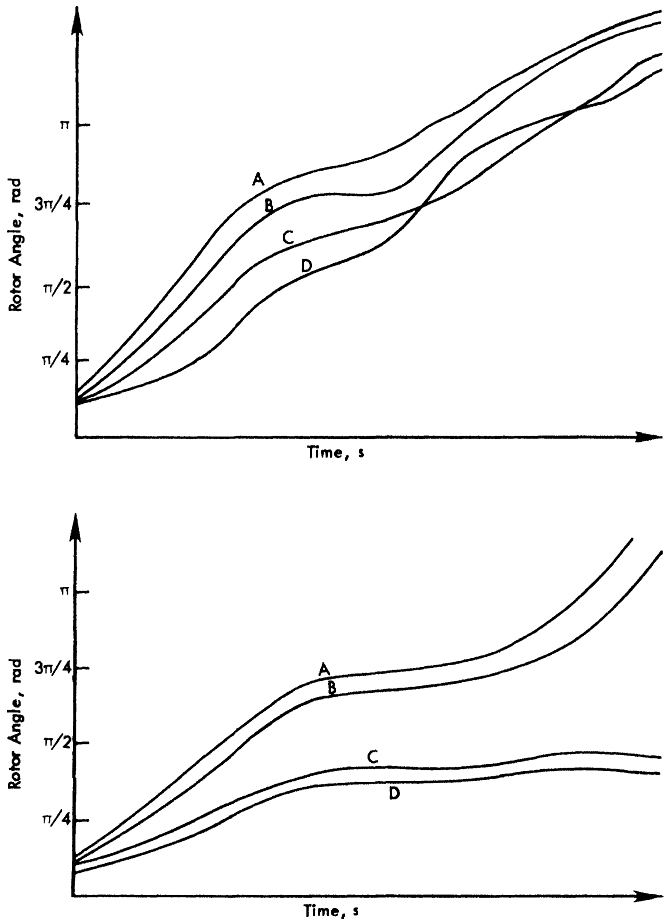

Fig. 1.1. Response of a four-machine system during a transient: (a) stable system, (b) unstable system.

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 these net torques are sufficiently large to cause some of the rotors to swing far enough so that one or more machines "slip a pole," 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 happen 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 1.1 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 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 also may 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 also that the behavior discussed above depends upon 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 the rotor position in addition to any changes in the impedance "seen" by the machine terminals. However, 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. Thus 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 of 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 make 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 upon 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. Other supplementary controls, such as tie-line controls, deemed necessary in the mathematical description of the system.

Thus the basic ingredients for solution are 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 upon many factors. In general, however, differential equations are used to describe the various components. Study of the dynamic behavior of the system depends upon 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 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, and this is the method usually 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 still in the research stage and not in common use. Both linear and nonlinear equations will be developed in following chapters.

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.

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.

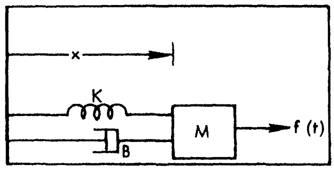

Fig. P1.5.

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