CHAPTER 1

INTRODUCTION

This book provides a tutorial description of the mathematical models and equation formulations that are required for the study of a special class of dynamic power system problems, namely *subsynchronous resonance* (SSR). Systems that experience SSR exhibit dynamic oscillations at frequencies below the normal system base frequency (60 Hz in North America). These problems are of great interest in utilities where this phenomenon is a problem, and the computation of conditions that excite these SSR oscillations are important to those who design and operate these power systems.

This book presents the mathematical modeling of the power system, which is explained in considerable detail. The data that are required to support the mathematical models are discussed, with special emphasis on field testing to determine the needed data. However, the purpose of modeling is to support mathematical analysis of the power system. Here, we are interested in the oscillatory behavior of the system, and the damping of these oscillations. A convenient method of analysis to determine this damping is to compute the eigenvalues of a linear model of the system. Eigenvalues that have negative real parts are damped, but those with positive real parts represent resonant conditions that can lead to catastrophic results. Therefore, the computation of eigenvalues and eigenvectors for the study of SSR is an excellent method of providing crucial information about the nature of the power system. The method for computing eigenvalues and eigenvectors is presented, and the interpretation of the resulting information is described.

1.1 DEFINITION OF SSR

Subsynchronous resonance (SSR) is a dynamic phenomenon of interest in power systems that have certain special characteristics. The formal definition of SSR is provided by the IEEE [1]:

> *Subsynchronous resonance* is an electric power system condition where the electric network exchanges energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system.

The definition includes any system condition that provides the opportunity for an exchange of energy at a given subsynchronous frequency. This includes what might be considered "natural" modes of oscillation that are due to the inherent system characteristics, as well as "forced" modes of oscillation that are driven by a particular device or control system.

The most common example of the natural mode of subsynchronous oscillation is due to networks that include series capacitor compensated transmission lines. These lines, with their series LC combinations, have natural frequencies ω_n that are defined by the equation

$$\omega_n = \sqrt{\frac{1}{LC}} = \omega_B \sqrt{\frac{X_C}{X_L}} \qquad (1.1)$$

where ω_n is the natural frequency associated with a particular line LC product, ω_B is the system base frequency, and X_L and X_C are the inductive and capacitive reactances, respectively. These frequencies appear to the generator rotor as modulations of the base frequency, giving both subsynchronous and supersynchronous rotor frequencies. It is the subsynchronous frequency that may interact with one of the natural torsional modes of the turbine-generator shaft, thereby setting up the conditions for an exchange of energy at a subsynchronous frequency, with possible torsional fatigue damage to the turbine-generator shaft.

The torsional modes (frequencies) of shaft oscillation are usually known, or may be obtained from the turbine-generator manufacturer. The network frequencies depend on many factors, such as the amount of series capacitance in service and the network switching arrangement at a particular time. The engineer needs a method for examining a large number of feasible operating conditions to determine the possibility of SSR interactions. The eigenvalue program provides this tool. Moreover, the eigenvalue computation permits the engineer to track the locus of system eigenvalues as parameters such as the series capacitance are varied to represent equipment outages. If the locus of a particular eigenvalue approaches or crosses the imaginary axis, then a critical condition is identified that will require the application of one or more SSR countermeasures [2].

1.2 POWER SYSTEM MODELING

This section presents an overview of power system modeling and defines the limits of modeling for the analysis of SSR. We are interested here in modeling the power system for the study of dynamic performance. This means that the system is described by a system of differential equations.

Usually, these equations are nonlinear, and the complete description of the power system may require a very large number of equations. For example, consider the interconnected network of the western United States, from the Rockies to the Pacific, and the associated generating sources and loads. This network consists of over 3000 buses and about 400 generating stations, and service is provided to about 800 load points. Let us assume that the network and loads may be defined by algebraic models for the analytical purpose at hand. Moreover, suppose that the generating stations can be modeled by a set of about 20 first order differential equations. Such a specification, which might be typical of a transient stability analysis, would require 8000 differential equations and about 3500 algebraic equations. A very large number of oscillatory modes will be present in the solution. This makes it difficult to understand the effects due to given causes because so many detailed interactions are represented.

Power system models are often conveniently defined in terms of the major subsystems of equipment that are active in determining the system performance. Figure 1.1 shows a broad overview of the bulk power system, including the network, the loads, the generation sources, the system control, the telecommunications, and the interconnections with neighboring utilities. For SSR studies we are interested in the prime mover (turbines) and generators and their primary controls, the speed governors and excitation systems. The network is very important and is represented in detail, but using only algebraic equations and ordinary differential equations (lumped parameters) rather than the exact partial differential equations. This is because we are interested only in the low frequency performance of the network, not in traveling waves. The loads may be important, but are usually represented as constant impedances in SSR modeling. We are not interested in the energy sources, such as boilers or nuclear reactors, nor are we concerned about the system control center, which deals with very low frequency phenomena, such as daily load tracking. These frequencies are too low for concern here.

Clearly, the transient behavior of the system ranges from the dynamics of lightning surges to that of generation dispatch and load following, and covers several decades of the frequency domain, as shown in Figure 1.2. Note that SSR falls largely in the middle of the range depicted, with major emphasis in the subsynchronous range. Usually, we say that the frequencies of oscillation that are of greatest interest are those between about 10 and 50 Hz. We must model frequencies outside of this narrow band, however, since modulations of other interactions may produce frequencies in the band of interest. It is noted, from Figure 1.2, that the.

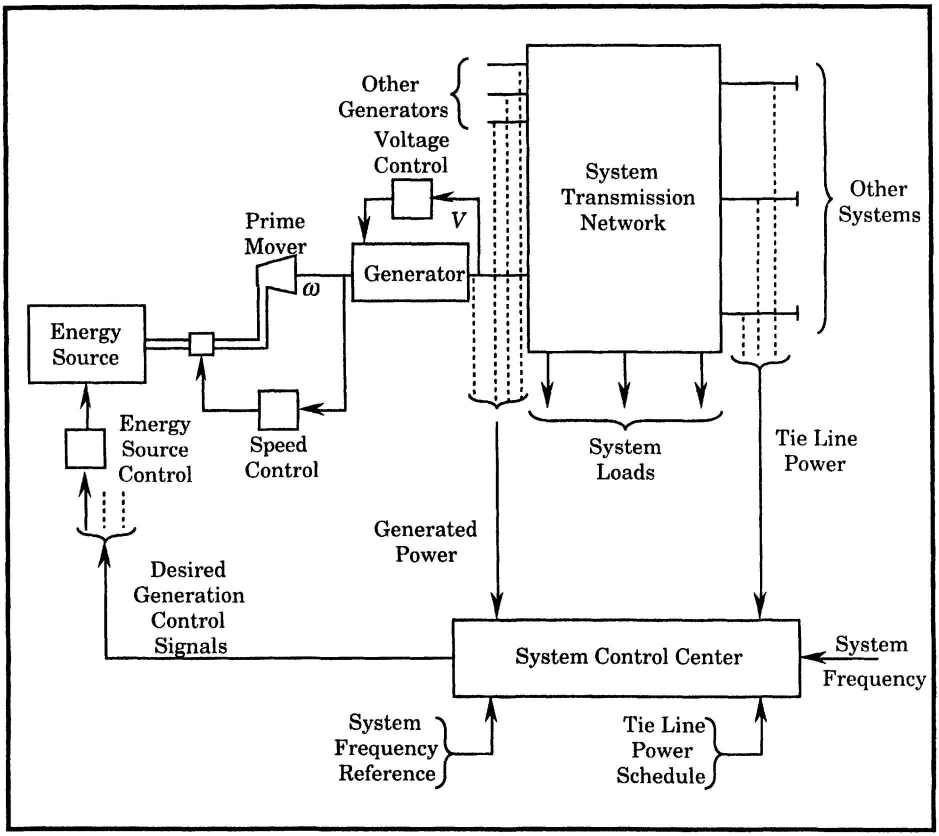

Figure 1.1 Structure of a Power System for Dynamic Analysis

basic range of frequencies of interest is not greatly different from transient stability. Hence, many of the models from transient stability will be appropriate to use.

In modeling the system for analysis, we find it useful to break the entire system up into physical subsystems, as in Figure 1.3, which shows the major subsystems associated with a single generating unit and its interconnection with the network and controls. In SSR analysis, it is necessary to model most, but not all, of these subsystems, and it is necessary to model at least a portion of the network. The subset of the system to be modeled for SSR is labeled in Figure 1.3, where the shaded region is the subset of interest in many studies. Also, it is usually necessary to model several machines for SSR studies, in addition to the interface between each machine and the network.

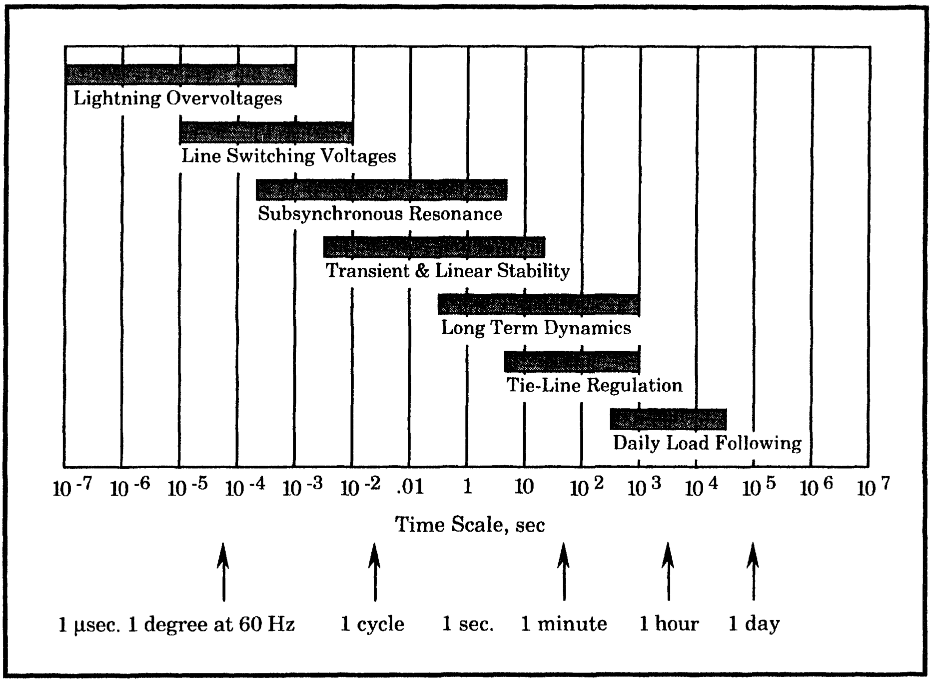

Figure 1.2 Frequency Bands of Different Dynamic Phenomena

Figure 1.3 also shows a convenient definition of the inputs and outputs defined for each subsystem model. The shaded subset defined in this figure is somewhat arbitrary. Some studies may include models of exciters, speed governors, high voltage direct current (HVDC) converter terminals, and other apparatus. It would seldom be necessary to model a boiler or nuclear reactor for SSR studies. The shaded area is that addressed in this book. Extensions of the equations developed for subsystems shown in Figure 1.3 should be straightforward.

In modeling the dynamic system for analysis, one must first define the scope of the analysis to be performed, and from this scope define the modeling limitations. No model is adequate for all possible types of analysis. Thus, for SSR analytical modeling we define the following scope:

> **Scope of SSR Models** The scope of SSR models to be derived in this monograph is limited to the dynamic performance of the interactions between the synchronous machine and the electric network in the subsynchronous frequency range, generally between 0 and 50 Hz. The subsystems defined for modeling are the following:

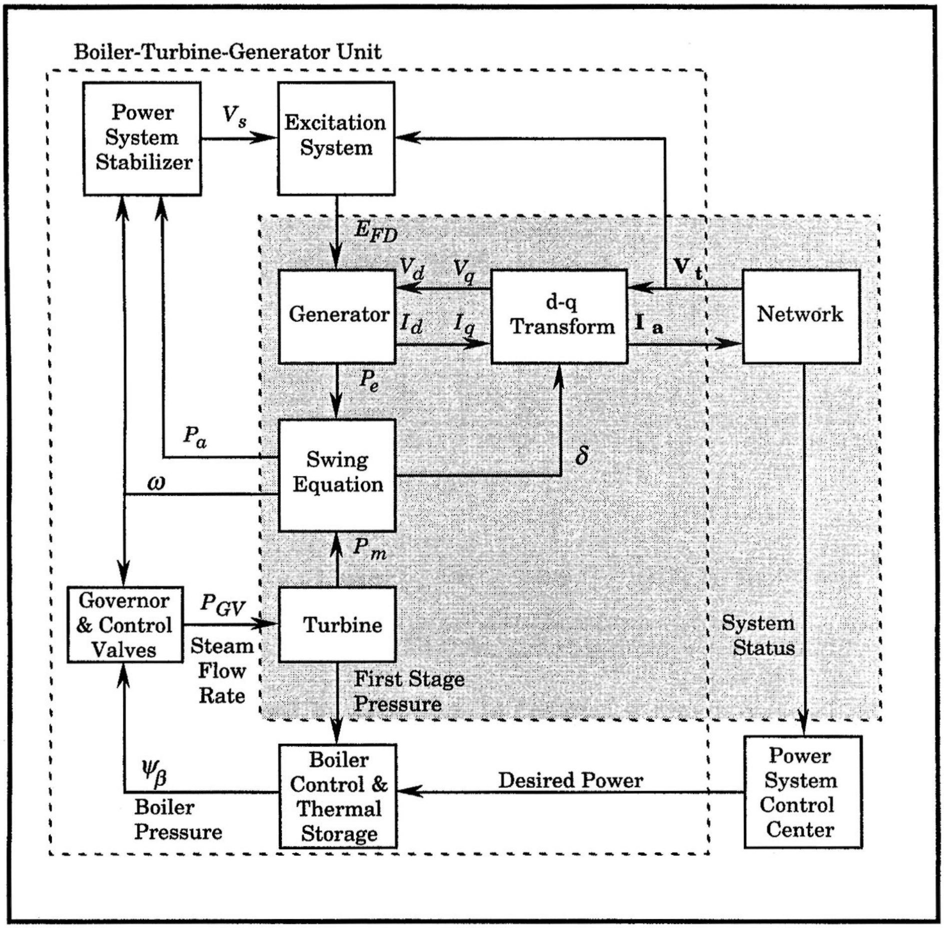

Figure 1.3 Subsystems of Interest at a Generating Station

- Network transmission lines, including series capacitors.
- Network static shunt elements, consisting of R, L, and C branches.
- Synchronous generators.
- Turbine-generator shafts with lumped spring-mass representation and with self and mutual damping.
- Turbine representation in various turbine cylinder configurations.

It is also necessary to define the approximate model bandwidth considered essential for accurate simulated performance of the system under study. For the purpose here, models will be derived that have a bandwidth of about 60 Hz.

1.3 INTRODUCTION TO SSR

Subsynchronous resonance is a condition that can exist on a power system wherein the network has natural frequencies that fall below the nominal 60 hertz of the network applied voltages. Currents flowing in the ac network have two components; one component at the frequency of the driving voltages (60 Hz) and another sinusoidal component at a frequency that depends entirely on the elements of the network. We can write a general expression for the current in a simple series R-L-C network as

$$i(t) = K\left[A\sin(\omega_1 t + \psi_1) + Be^{-\varsigma\omega_2 t}\sin(\omega_2 t + \psi_2)\right] \tag{1.2}$$

where all of the parameters in the equation are functions of the network elements except ω_1, which is the frequency of the driving voltages of all the generators. Note that even ω_2 is a function of the network elements.

Currents similar to (1.2) flow in the stator windings of the generator and are reflected into the generator rotor a physical process that is described mathematically by Park's transformation. This transformation makes the 60 hertz component of current appear, as viewed from the rotor, as a dc current in the steady state, but the currents of frequency ω_2 are transformed into currents of frequencies containing the sum $(\omega_1+\omega_2)$ and difference $(\omega_1-\omega_2)$ of the two frequencies. The difference frequencies are called *subsynchronous* frequencies. These subsynchronous currents produce shaft torques on the turbine-generator rotor that cause the rotor to oscillate at subsynchronous frequencies.

The presence of subsynchronous torques on the rotor causes concern because the turbine-generator shaft itself has natural modes of oscillation that are typical of any spring mass system. It happens that the shaft oscillatory modes are at subsynchronous frequencies. Should the induced subsynchronous torques coincide with one of the shaft natural modes of oscillation, the shaft will oscillate at this natural frequency, sometimes with high amplitude. This is called subsynchronous resonance, which can cause shaft fatigue and possible damage or failure.

1.3.1 Types of SSR Interactions

There are many ways in which the system and the generator may interact with subsynchronous effects. A few of these interactions are basic in concept and have been given special names. We mention three of these that are of particular interest:

Induction Generator Effect
Torsional Interaction Effect
Transient Torque Effect

Induction Generator Effect

Induction generator effect is caused by self excitation of the electrical system. The resistance of the rotor to subsynchronous current, viewed from the armature terminals, is a negative resistance. The network also presents a resistance to these same currents that is positive. However, if the negative resistance of the generator is greater in magnitude than the positive resistance of the network at the system natural frequencies, there will be sustained subsynchronous currents. This is the condition known as the "induction generator effect."

Torsional Interaction

Torsional interaction occurs when the induced subsynchronous torque in the generator is close to one of the torsional natural modes of the turbine-generator shaft. When this happens, generator rotor oscillations will build up and this motion will induce armature voltage components at both subsynchronous and supersynchronous frequencies. Moreover, the induced subsynchronous frequency voltage is phased to sustain the subsynchronous torque. If this torque equals or exceeds the inherent mechanical damping of the rotating system, the system will become self-excited. This phenomenon is called "torsional interaction."

Transient Torques

Transient torques are those that result from system disturbances. System disturbances cause sudden changes in the network, resulting in sudden changes in currents that will tend to oscillate at the natural frequencies of the network. In a transmission system without series capacitors, these transients are always dc transients, which decay to zero with a time constant that depends on the ratio of inductance to resistance. For networks that contain series capacitors, the transient currents will be of a form similar to equation (1.2), and will contain one or more oscillatory frequencies that depend on the network capacitance as well as the inductance and resistance. In a simple radial R-L-C system, there will be only one such natural frequency, which is exactly the situation described in

(1.2), but in a network with many series capacitors there will be many such subsynchronous frequencies. If any of these subsynchronous network frequencies coincide with one of the natural modes of a turbine-generator shaft, there can be peak torques that are quite large since these torques are directly proportional to the magnitude of the oscillating current. Currents due to short circuits, therefore, can produce very large shaft torques both when the fault is applied and also when it is cleared. In a real power system there may be many different subsynchronous frequencies involved and the analysis is quite complex.

Of the three different types of interactions described above, the first two may be considered as small disturbance conditions, at least initially. The third type is definitely not a small disturbance and nonlinearities of the system also enter into the analysis. From the viewpoint of system analysis, it is important to note that the induction generator and torsional interaction effects may be analyzed using linear models, suggesting that eigenvalue analysis is appropriate for the study of these problems.

1.3.2 Analytical Tools

There are several analytical tools that have evolved for the study of SSR. The most common of these tools will be described briefly.

Frequency Scanning

Frequency scanning is a technique that has been widely used in North America for at least a preliminary analysis of SSR problems, and is particularly effective in the study of induction generator effects. The frequency scan technique computes the equivalent resistance and inductance, seen looking into the network from a point behind the stator winding of a particular generator, as a function of frequency. Should there be a frequency at which the inductance is zero and the resistance negative, self sustaining oscillations at that frequency would be expected due to induction generator effect.

The frequency scan method also provides information regarding possible problems with torsional interaction and transient torques. Torsional interaction or transient torque problems might be expected to occur if there is a network series resonance or a reactance minimum that is very close to one of the shaft torsional frequencies.

Figure 1.4 shows the plot of a typical result from a frequency scan of a network [3]. The scan covers the frequency range from 20 to 50 hertz and shows separate plots for the resistance and reactance as a function of

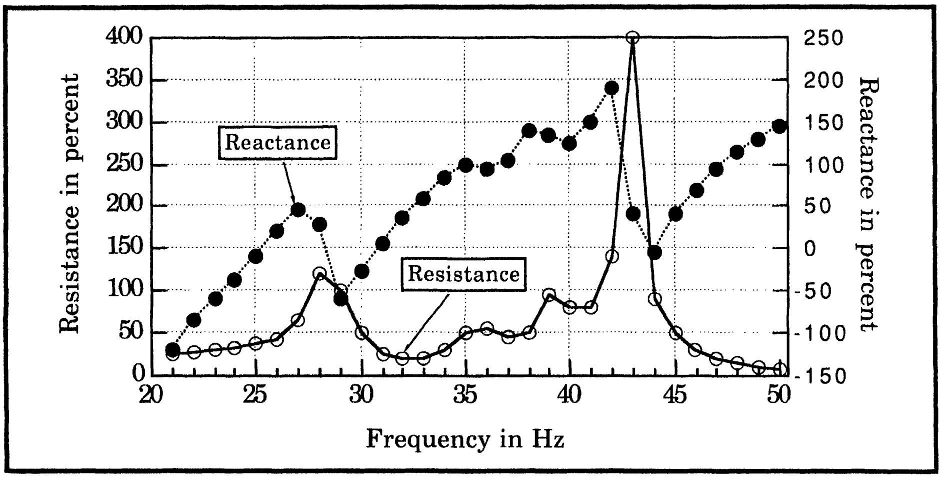

Figure 1.4 Plot from the Frequency Scan of a Network [3]

frequency. The frequency scan shown in the figure was computed for a generator connected to a network with series compensated transmission lines and represents the impedance seen looking into that network from the generator. The computation indicates that there may be a problem with torsional interactions at the first torsional mode, which occurs for this generator at about 44 Hz. At this frequency, the reactance of the network goes to zero, indicating a possible problem. Since the frequency scan results change with different system conditions and with the number of generators on line, many conditions need to be tested. The potential problem noted in the figure was confirmed by other tests and remedial countermeasures were prescribed to alleviate the problem [3].

Frequency scanning is limited to the impedances seen at a particular point in the network, usually behind the stator windings of a generator. The process must be repeated for different system (switching) conditions at the terminals of each generator of interest.

Eigenvalue Analysis

Eigenvalue analysis provides additional information regarding the system performance. This type of analysis is performed with the network and the generators modeled in one linear system of differential equations. The results give both the frequencies of oscillation as well as the damping of each frequency.

Eigenvalues are defined in terms of the system linear equations, that are written in the following standard form.

Table 1.1 Computed Eigenvalues for the First Benchmark Model			
Eigenvalue Number	Real Part, s^{-1}	Imaginary Part, rad/s	Imaginary Part, Hz
1,2	+0.07854636	±127.15560200	±20.2374426
3,4	+0.07818368	±99.70883066	±15.86915327
5,6	+0.04089805	±160.38986053	±25.52683912
7,8	+0.00232994	±202.86306822	±32.28666008
9,10	−0.00000048	±298.17672924	±47.45630037
11	−0.77576318		
12	−0.94796049		
13,14	−1.21804111	±10.59514740	±96.61615878
15,16	−5.54108044	±136.97740321	±21.80063081
17,18	−6.80964255	±616.53245850	±98.12275595
19	−25.41118956		
20	−41.29551248		

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \qquad (1.3)$$

Then the eigenvalues are defined as the solutions to the matrix equation

$$\det[\lambda \mathbf{U} - \mathbf{A}] = 0 \qquad (1.4)$$

where the parameters λ are called the eigenvalues.

An example of eigenvalue analysis is presented using the data from the First Benchmark Model, a one machine system used for SSR program testing [4]. The results of the eigenvalue calculation is shown in Table 1.1. Note that this small system is of 20th order and there are 10 eigenvalues in the range of 15.87 to 47.46 Hz, which is the range where torsional interaction usually occur. Moreover, eight of the eigenvalues have positive real parts, indicating an absence of damping in these modes of response.

Eigenvalue analysis is attractive since it provides the frequencies and the damping at each frequency for the entire system in a single calculation.

EMTP Analysis

The ElectroMagnetic Transients Program (EMTP) is a program for numerical integration of the system differential equations. Unlike a transient stability program, which usually models only positive sequence quantities representing a perfectly balanced system, EMTP is a full three-phase model of the system with much more detailed models of transmission lines, cables, machines, and special devices such as series capacitors with complex bypass switching arrangements. Moreover, the EMTP permits nonlinear modeling of complex system components. It is, therefore, well suited for analyzing the transient torque SSR problems.

The full scope of modeling and simulation of systems using EMTP is beyond the scope of this book. However, to illustrate the type of results that can be obtained using this method, we present one brief example. Figure 1.5 shows the torque at one turbine shaft section for two different levels of series transmission compensation, a small level of compensation for Case A and a larger level for Case B [5]. The disturbance is a three phase fault at time $t = 0$ that persists for 0.06 seconds. It is apparent that the Case B, the higher level of series compensation, results is considerably torque amplification. This type of information would not be available from a frequency scan or from eigenvalue computation, although those methods would indicate the existence of a resonant condition at the indicated frequency of oscillation. EMTP adds important data on the magnitude of the oscillations as well as their damping.

Summary

Three prominent methods of SSR analysis have been briefly described. Frequency scanning provides information regarding the impedance seen, as a function of frequency, looking into the network from the stator of a generator. The method is fast and easy to use. Eigenvalue analysis provides a closed form solution of the entire network including the machines. This gives all of the frequencies of oscillation as well as the damping of each frequency. The method requires more modeling and data than frequency scanning and requires greater computer resources for the computation. EMTP requires still greater modeling effort and computer resources, but allows the full nonlinear modeling of the system machines and other devices, such as capacitor bypass schemes.

In the balance of this book, we concentrate only on the eigenvalue method of SSR analysis. Most of the book is devoted to the mathematical modeling and the determination of accurate model parameters for eigenvalue analysis. First, however, we discuss briefly the types of models used for the SSR

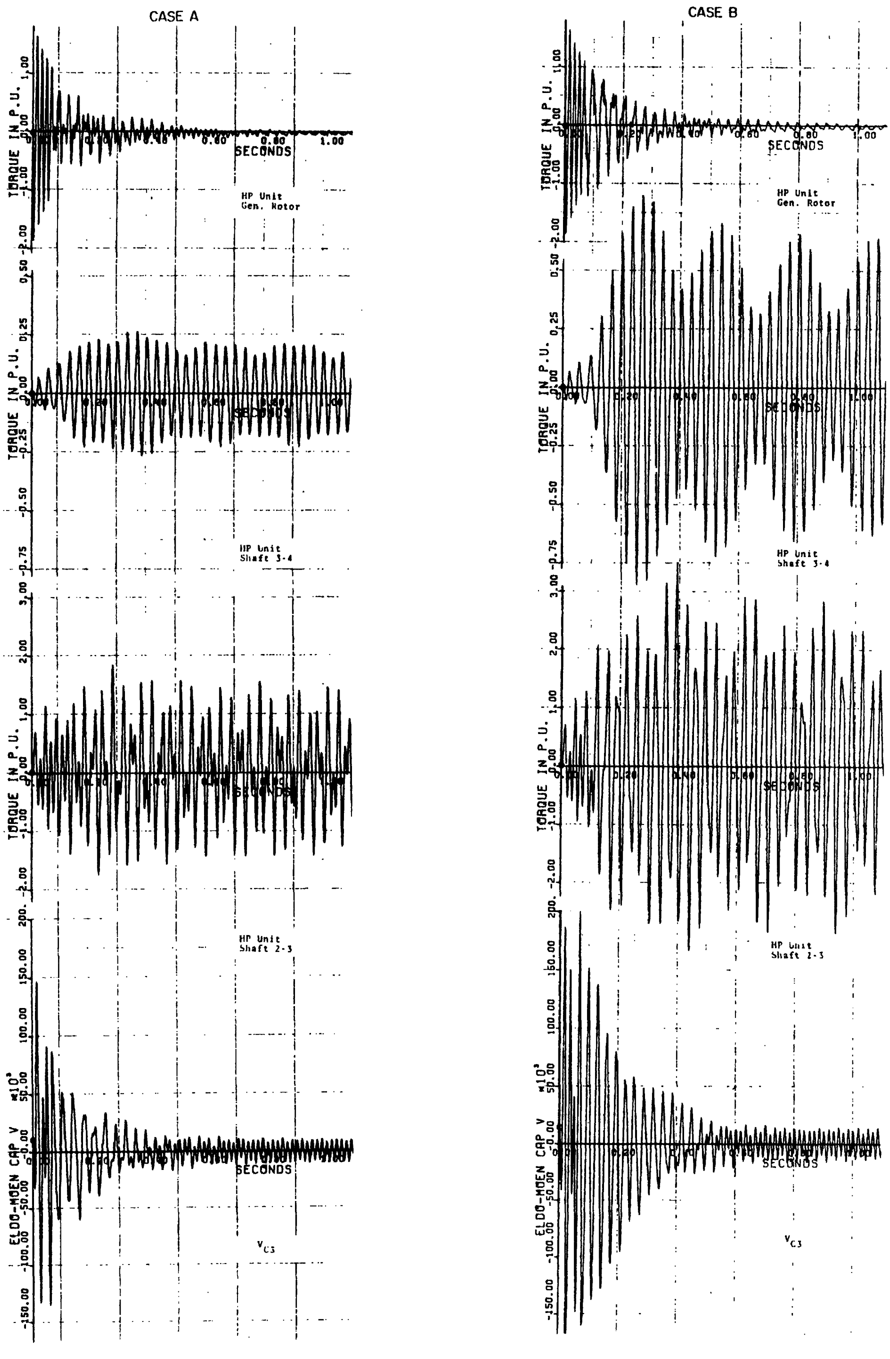

Figure 1.5 Typical Computed Generator Shaft Torques (upper 3 traces) and Voltage Across a Series Capacitor (bottom trace) Using EMTP [5]

analysis. Then we comment briefly on the computed results and their use by the system analyst. Finally, we conclude this chapter with some results from an actual system study to illustrate the way in which eigenvalue calculations may be used.

1.4 EIGENVALUE ANALYSIS

Eigenvalue analysis uses the standard linear, state-space form of system equations and provides an appropriate tool for evaluating system conditions for the study of SSR, particularly for induction generator and torsional interaction effects.

1.4.1 Advantages of Eigenvalue Computation

The advantages of eigenvalue analysis are many. Some of the prominent advantages are:

- Uses the state-space equations, making it possible to utilize many other analytical tools that use this same equation form
- Compute all the exact modes of system oscillation in a single computation
- Can be arranged to perform a convenient parameter variation to study parameter sensitivities
- Can be used to plot root loci of eigenvalue movement in response to many different types of changes

Eigenvalue analysis also includes the computation of *eigenvectors*, which are often not as well understood as eigenvalues, but are very important quantities for analyzing the system. Very briefly, there are two types of eigenvectors, usually called the "right hand" and "left hand" eigenvectors. These quantities are used as follows:

- Right Hand Eigenvectors - show the distribution of modes of response (eigenvalues) through the state variables
- Left Hand Eigenvectors - show the relative effect of different initial conditions of the state variables on the modes of response (eigenvalues)

The right hand eigenvectors are the most useful in SSR analysis. Using these vectors, one can establish the relative magnitude of each mode's response due to each state variable. In this way, one can determine those state variables that have little or no effect on a given mode of response and, conversely, those variables that an play important role is contributing to a given response. This often tells the engineer exactly those variables that need to be controlled in order to damp a subsynchronous oscillation on a given unit.

1.4.2 Disadvantages of Eigenvalue Calculation

Eigenvalue analysis is computationally intensive and is useful only for the linear problem. Moreover, this type of analysis is limited to relatively small systems, say of 500th order or less. Recent work has been done on much larger systems, but most of these methods compute only selected eigenvalues and usually require a skilled and experienced analyst in order to be effective [8,9]. Work is progressing on more general methods of solving large systems, but no breakthroughs have been reported.

Another difficulty of eigenvalue analysis is the general level of difficulty in writing eigenvalue computer programs. Much work has been done in this area, and the SSR analyst can take advantage of this entire realm of effort. Perhaps the most significant work is that performed over the years by the Argonne National Laboratory, which has produced the public domain program known as EISPACK [10]. Another program called PALS has been developed by Van Ness for the Bonneville Power Administration, using some special analytical techniques [11]. Thus, there are complete programs available to those who wish to pursue eigenvalue analysis without the difficult startup task of writing an eigenvalue program.

1.5 CONCLUSIONS

In this chapter, we have reviewed the study of subsynchronous resonance using eigenvalue analysis. From our analysis of the types of SSR interactions, we conclude that eigenvalue analysis is appropriate for the study of induction generator and torsional interaction effects. This will not cover all of the concerns regarding SSR hazards, but it does provide a method of analyzing some of the basic problems.

The system modeling for eigenvalue analysis must be linear. Linear models must be used for the generator, the turbine-generator shaft, and the network. These models are not much different than those used for other types of analysis, except that nonlinearities must be eliminated in the equations. These models are described in Chapters 2, 3, and 4. Another problem related to modeling is the determination of accurate data, either from records of the utility or manufacturer, or from field testing. This important subject is discussed in Chapters 5 and 6.

Eigenvalue and eigenvector computation provide valuable insight into the dynamics of the power system. It is important to identify the possibility of negative damping due to the many system interactions, and the eigenvalue computation does this very clearly. Moreover, eigenvector computation provides a powerful tool to identify those states of the system that lead to various modes of oscillation, giving the engineer a valuable method of designing effective SSR countermeasures. Eigenvalues and eigenvector computations are described more fully in Chapter 7.

Finally, we have illustrated the type of eigenvalue calculation that is performed by showing data from actual system tests to determine damping parameters and the application of these parameters to assure proper damping of various modes of oscillation. The final chapter of the book provides the solution to several "benchmark" problems. These solved cases provide the reader with a convenient way of checking computations made with any eigenvalue program.

1.6 PURPOSE, SCOPE, AND ASSUMPTIONS

The purpose of this monograph is to develop the theory and mathematical modeling of a power system for small disturbance (linear) analysis of subsynchronous resonance phenomena. This theoretical background will provide the necessary linear dynamic equations required for eigenvalue analysis of a power system, with emphasis on the problems associated with SSR. Because the scope is limited to linear analysis of SSR, several important assumptions regarding the application of the system models are necessary. These assumptions are summarized as follows:

1. The turbine-generator initial conditions are computed from a steady-state power flow of the system under study.

2. All system nonlinearities can be initialized and linearized about the initial operating point.

3. The network and loads may be represented as a balanced three-phase system with impedances in each phase equal to the positive sequence impedance.

4. The synchronous generators may be represented by a Park's two-axis model with negligible zero-sequence current.

5. The turbine-generator shaft may be represented as a lumped spring-mass system, with adjacent masses connected by shaft

stiffness and damping elements, and with damping between each mass and the stationary support of the rotating system.

6. Nonlinear controllers may be represented as continuous linear components with appropriately derived linear parameters.

1.7 GUIDELINES FOR USING THIS BOOK

This book is intended as a complete and well documented introduction to the modeling of the major power system elements that are required for SSR analysis. The analytical technique of emphasis is eigenvalue analysis, but many of the principles are equally applicable to other forms of analysis. The major assumption required for eigenvalue analysis is that of linearity, which may make the equations unsuitable for other applications. The nonlinear equations, from which these linear forms are derived, may be necessary for a particular application.

This book does not attempt proofs or extensive derivations of system equations, and the reader must refer to more academic sources for this kind of detailed assistance. Many references to suggested sources of background information are provided. It is assumed that the user of this book is an engineer or scientist with training in the physical and mathematical sciences. These basic study areas are not reviewed or presented in any way, but are used with the assumption that a trained person will be able to follow the developments, probably without referring to other resources.

The major topic of interest here is SSR, and all developments are presented with this objective in mind. We presume that the reader is interested in learning about SSR or wishes to review the background material pertinent to the subject. With this objective foremost, we suggest that the first-time user attempt a straight-through superficial reading of the book in order to obtain an overall grasp of the subject and an understanding of the modeling objectives and interfaces. This understanding should be followed by returning to those sections that require additional study for better understanding or for reinforcing the modeling task at hand.

The second objective of this work is to present a discussion of eigen analysis and to explain the meaning of results that are obtainable from eigenvalue-eigenvector computation. These calculations must be performed by digital computer using very large and complex computer codes. We do not attempt an explanation of these codes or the complex algorithmic development that makes these calculations possible. This area is considered much more detailed than the average engineer would find useful. We do feel, however, that the user should have a sense of what the eigenprogram is used for and should be able to interpret the results of these calculations. In this sense, this document stands as a background reference to the eigenvalue programs [4].

A third objective of this book is to present a discussion of the problems associated with preparing data for use in making SSR eigenvalue-eigenvector calculations. A simulation is of no value whatever if the input data is incorrect or is improperly prepared. Thus it is necessary to understand the modeling and to be able to interpret the data made available by the manufacturers in order to avoid the pitfall of obtaining useless results due to inadequate preparation of study data. This may require the use of judgment, for example, for interpreting the need for a data item that is not immediately available. It may also provide guidance for identifying data that should be obtained by field tests on the actual equipment installed on the system.

1.8 SSR REFERENCES

There are many references on the subjects of concern in this book. This review of prior work is divided into three parts: general references, SSR references, and eigenvalue applications to power systems.

1.8.1 General References

The general references of direct interest in this book are **Power System Control and Stability**, by Anderson and Fouad [14], **Power System Stability, vol 1, 2, and 3**, by Kimbark [15-17], **Stability of Large Electric Power Systems**, by Byerly and Kimbark [18], **The General Theory of Electrical Machines**, by Adkins [19], **The Principles of Synchronous Machines**, by Lewis [20], and **Synchronous Machines**, by Concordia [21].

The material presented in this book is not new and is broadly based on the above references, but with emphasis on the SSR problem.

1.8.2 SSR References

SSR has been the subject of many technical papers, published largely in the past decade. These papers are summarized in three bibliographies [22-24], prepared by the IEEE Working Group on Subsynchronous Resonance (hereafter referred to as the IEEE WG). The IEEE WG has also been responsible for two excellent general references on the subject, which were published as the permanent records of two IEEE Symposia on SSR. The first of these, "Analysis and Control of Subsynchronous Resonance" [25] is largely tutorial and describes the state of the art of the subject. The second document, "Symposium on Countermeasures for Subsynchronous Resonance" [26] describes various approaches used by utilities to analyze and design SSR protective strategies and controls.

In addition to these general references on SSR, the IEEE WG has published six important technical papers on the subject. The first of these, "Proposed Terms and Definitions for Subsynchronous Oscillations" [27] provides an important source for this monograph in clarifying the terminology of the subject area. A later paper, "Terms, Definitions and Symbols for Subsynchronous Oscillations" [28] provides additional definitions and clarifies the original paper. This document is adhered to as a standard in this book. Another IEEE WG report, "First Benchmark Model for Computer Simulation of Subsynchronous Resonance" [4], provides a simple one machine model and test problem for computer program verification and comparison. This was followed by a more complex model described in the paper "Second Benchmark Model for Computer Simulation of Subsynchronous Resonance" [29], which provides a more complex model and test system. A third paper, "Countermeasures to Subsynchronous Resonance Problems" [30], presents a collection of proposed solutions to SSR problems without any attempt at ranking or evaluating the merit of the various approaches. Finally, the IEEE WG published the 1983 prize paper "Series Capacitor Controls and Settings as Countermeasures to Subsynchronous Resonance" [31], which presents the most common system conditions that may lead to large turbine-generator oscillatory torques and describes series capacitor controls and settings that have been successfully applied as countermeasures.

Another publication that contains much information of general importance to the SSR problem is the IEEE document "State-of-the-Art Symposium--Turbine Generator Shaft Torsionals," which describes the problem of stress and fatigue damage in turbine-generator shafts from a variety of causes [32].

1.8.3 Eigenvalue/Eigenvector Analysis References

In the area of eigenvalue analysis there are literally hundreds of papers in the literature. Even those that address power system applications are numerous. We mention here a few references of direct interest. J. H. Wilkinson's book, **The Algebraic Eigenvalue Problem** [12] is a standard reference on the subject. Power system applications can be identified in association with certain authors. We cite particularly the work performed at McMasters University [34-39], that performed at Northwestern University [11, 40-45], the excellent work done at MIT [46], that performed at

Westinghouse[47-49], and the work performed by engineers at Ontario Hydro [50-53]. Also of direct interest is the significant work performed on eigenvalue numerical methods, which resulted in the computer programs known as EISPACK, summarized in [10] and [54].

1.9 REFERENCES FOR CHAPTER 1

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