



IEEE Power & Energy Society

IEEE Tutorial Course Power System Stabilization Via Excitation Control

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**IEEE TUTORIAL COURSE
POWER SYSTEM STABILIZATION
VIA EXCITATION CONTROL**

**Sponsored by
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and the
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of the
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FOREWORD

In 1981 the first IEEE tutorial course on power system stabilization via excitation control was presented by Ken Bollinger, Joe Hurley, Frederick Keay, Einar Larsen and David Lee and the notes from that tutorial became a widely used reference for generation engineers working to improve power system stability.

Ideas for power system stabilization using excitation control originated as a result of electric power oscillations occurring on interties between large power pools and stability problems associated with single generators, or banks of generators connected to large power systems. Before the 1981 tutorial increasing use of high gain excitation systems and increased use of transmission systems had been leading to decreased stability margins and power system stability problems. A considerable amount of effort had been spent on research projects, sitework and the development of control electronics to stabilize multi-machine systems.

Since the 1981 tutorial, research work and product development has continued. Electronic control units now utilize digital technology to provide repeatability, more features and easier use, and control algorithms have been improved to eliminate some earlier shortcomings.

The development of the integral of accelerating power type stabilizer (PSS2B type as described in IEEE Standard 421.5 2005) allowed stabilizers to operate successfully with minimal terminal voltage fluctuation even during very rapid loading and unloading of generators. This type has now become the de-facto standard and this type of stabilizer is now a requirement in many parts of North America.

Increasing numbers of power system stabilizers have been installed as grid codes around the world and North American requirements such as the WECC guidelines have demanded that generators be equipped with stabilizers. In addition the power system disturbances in Western North America during July and August 1996 caused increased effort to be focused on testing and validating of generating units including their excitation control systems and associated stabilizers. These factors have resulted in many more engineers being introduced to power system stabilizers for the first time.

Whilst excellent papers are available on many aspects of power system stabilizer design, implementation and testing, this tutorial is intended to provide engineers and technicians with a set of key insights into problems related to power system oscillations and the currently available solutions.

It is expected that the course participants will have a basic understanding of power system analysis and control concepts. The tutorial includes introductory material to provide a basis for understanding of the terminology used in the latter part of the course.

This tutorial includes contributions from present day experts in the field of power system stability in addition to material from the authors of the original tutorial. The first two chapters review feedback control and power system stability concepts. Following chapters describe more detail on performance criteria, tuning techniques, accelerating power type stabilizers, field testing techniques and application considerations. The last chapter describes some future directions in stabilizer design.

The authors and presenters of this tutorial are grateful to the authors of original tutorial and to the experts in this industry who have written many excellent papers referenced here.

Robert Thornton-Jones
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IEEE Tutorial Course Power System Stabilization Via Excitation Control

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Abstract—The document comprises chapters supporting a tutorial course on power system stabilization via excitation control to be presented at the IEEE PES general meeting in June 2007. Feedback control and power system stability theory is presented to explain the foundation concepts of power system stabilization by excitation control. Tuning and testing techniques and application considerations are described. Both present day stabilizer types and future directions in stabilizer design are explained.

Index Terms - Control, Excitation, Generator, Regulator, Stabilizer.

CHAPTER 1**REVIEW OF FEEDBACK CONTROL CONCEPTS**

Arjun Godhwani

I. INTRODUCTION

Study of feedback control requires knowledge of various mathematical tools that consist of Laplace transforms, Bode plots, Nyquist plots, and Root locus. These tools apply to single-input-single-output systems (SISO) that are linear and time invariant - LTI. The state space approach is used to analyze not only (SISO) systems but also multiple-input-multiple-output (MIMO) systems. Some of the systems tend to be nonlinear and are linearized around an operating point for small excursions of the signals before applying these tools. Knowledge of these tools is critical to understanding power system control and stability. Therefore a review of these tools is presented in the following.

It will be impossible to cover all relevant mathematics in the brief period available yet the Tutorial Course organizers felt that some review was needed. This section of the course will survey those areas of mathematics that are part of the repertoire of analysts who are working in the power system control area.

There are two approaches to handling power system control problems and, in particular, power system stabilization problems.

- The analyst can use a combination of intuition and common sense to deduce proper control strategy and settings.
- The problem may be approached from the theoretical viewpoint and computer techniques employed to synthesize the controller.

Most engineers involved in tuning controllers will tend to agree that the best approach lies somewhere between 'a' and 'b'. If one relies too heavily on intuition, situations will arise when the process, or system, does not respond according to plan and there is nothing to fall back on as an alternate control strategy. On the other hand, theoretical studies often lead to elegant solutions with no practical way of implementing the solution. This latter approach does not yield a feel for the physical system and sometimes masks an obvious solution.

A compromise between intuition, or common sense, and theory is usually the best approach. In many situations Engineering judgment must be used to cull out second-order effects and reduce the problem to the point where mathematical concepts will yield practical solutions. A simple power system model will be used to illustrate this compromise and to highlight certain analytical techniques. Analyzing plant (or process) stability can be done simply by observing the mechanical linkage, or gauges, in a control loop or doing an in depth study on a mathematical model of the system. Synthesizing, or tuning controllers can involve everything from "tweaking" the knobs with an "experienced" hand to applying computerized algorithms to calculate

controller parameters in offline studies on a mathematical model of the system.

The subsequent sections of this chapter will attempt to concentrate on those aspects of feedback control theory that are pertinent to power system stabilizer (PSS) tuning. Emphasis will be placed on concepts that have been used in offline studies and subsequently used for tuning hardware that is now in place at power plants. This should not imply that other methods are not equally applicable but it was felt that a comprehensive survey of all controller synthesis techniques would be outside the scope of this tutorial. In many situations advanced controller synthesis concepts must be applied when design constraints on the controller are quite stringent.

The next section describes basic concepts relating time, frequency, and Complex-S-Plane Parameters. This is followed by a brief review of basic control concepts with emphasis on stability of feedback control systems. State space techniques are discussed next followed by introductory concepts related to simulation techniques.

II. LAPLACE TRANSFORMS

Fourier analysis is extremely useful in analyzing many practical problems involving signals and LTI systems. Fourier series can represent periodic signals, while aperiodic signals can be represented by Fourier transforms. In each case the signals are represented by an infinite set of complex exponentials e^{st} with $s = j\omega$. In addition when a complex exponential passes through an LTI system the output is also a complex exponential of same frequency with a change in amplitude and change in phase. This concept is one of the reasons for usefulness of frequency response techniques such as Bode plots and Nyquist plots. The above-mentioned property of complex exponentials not only applies to pure imaginary values of s but also arbitrary values of s . This leads to generalization of Fourier transform to Laplace transform. Laplace transforms have many of the same properties that make Fourier transforms useful. But usefulness of Laplace transforms goes beyond that of Fourier transforms. For example Laplace transforms can be used to investigate stability. Using Laplace transforms we will develop the concepts of transfer function, natural and forced modes of response, poles and zeros etc. In addition block-diagram reduction will allow us to manipulate systems that possess one or more feedback loops.

The starting point for studying a control system is to represent it by its differential and algebraic equations. The study is usually done to answer one or both of the following questions:

- How stable is the system?
- What has to be added, or changed, to achieve a desired level of stability?

One approach to answering these questions is to derive a compact model of the process (system) relating the input of the process to the output. This is shown in "block diagram" form in Fig.1.1. The output $y(t)$ is a function of the input $u(t)$.

and the system model.

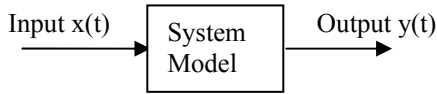


Figure 1.1 Block Diagram Of Input Output Model

A convenient way to represent the system model is to use Laplace Transforms [1]. The Laplace transform model is usually derived as a special case of general transform theory, but an intuitive approach will be used for expediency.

A periodic signal can be represented by a series of sinusoidal signals. The analysis for calculating the amplitudes of the sine and cosine terms of the series is referred to as Fourier series [2]. The Fourier series for periodic functions, and Fourier transform for aperiodic functions, transform a time domain signal into its frequency components.

An extension of this transform concept to the more general case allows the analyst to transform functions of time into the "Complex Frequency" domain.

Laplace transform of a time function $f(t)$ is denoted as $F(s)$ and is defined as follows:

$$F(s) = \int_0^{\infty} f(t)e^{-st} dt \quad (1.1)$$

The set of commonly used Laplace transform pairs and properties are listed in Table I. Laplace transforms for commonly used time functions are rational functions i.e. ratio of two polynomials.

One of the important applications of the Laplace transform is in the analysis of systems. The system transfer function is defined as the ratio of the output transform and the input transform, assuming all initial conditions as 0.

$$H(s) = \frac{Y(s)}{X(s)} \quad (1.2)$$

The roots of the numerator of the transfer function are called the zeros of the system and the roots of the denominator of the transfer function are called the poles of the system. An example of a transfer function and how we display poles and zeros on the s-plane is shown in Fig.1.2. In this example K is the gain, and the system has a zero at $s = -2$, and poles at $s = 0$ and $s = -10$.

$$H(s) = \frac{K(s+2)}{s(s+10)} \quad (1.3)$$

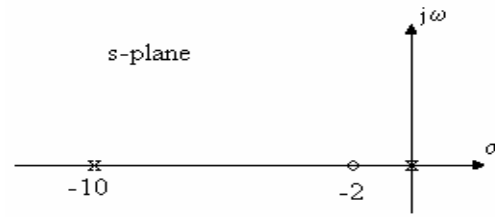


Figure 1.2 Pole-Zero Plot

Differential equations (D.E.) can be transformed into algebraic equations using Laplace transforms. The resulting Laplace expression can then be manipulated algebraically to obtain stability information and other relevant information about the physical system described by the D.E. In some cases the Laplace transform is used to obtain the time domain solution of the D.E. but in most cases it is used to obtain stability information about a process.

Table I contains the Laplace transform of relevant time domain expressions including differential and integration operations. The entries in Table I are determined using (1). Table I also includes initial value and final value properties.

TABLE I
LAPLACE TRANSFORM PAIRS AND PROPERTIES

$f(t)$	$F(s)$
$\delta(t)$	1
$u(t)$	$\frac{1}{s}$
t	$\frac{1}{s^2}$
e^{-at}	$\frac{1}{s+a}$
$\cos(\omega t)$	$\frac{s}{\omega^2 + s^2}$
$\sin(\omega t)$	$\frac{\omega}{\omega^2 + s^2}$
$e^{-at} \cos(\omega t)$	$\frac{s+a}{\omega^2 + (s+a)^2}$
$e^{-at} \sin(\omega t)$	$\frac{\omega}{\omega^2 + (s+a)^2}$
$\frac{df(t)}{dt}$	$sF(s) - f(0)$
$\frac{d^2f(t)}{dt^2}$	$s^2F(s) - sf(0) - \frac{df(0)}{dt}$
$\int_0^t f(t)dt$	$\frac{F(s)}{s}$
$\lim_{t \rightarrow \infty} f(t)$	$\lim_{s \rightarrow 0} sF(s)$
$\lim_{t \rightarrow 0} f(t)$	$\lim_{s \rightarrow \infty} sF(s)$

III. TRANSFER FUNCTIONS AND BLOCK DIAGRAMS

A D.E. can be solved using Laplace transforms as shown below. A general D.E. is shown in (1.4).

$$\frac{d^2 y(t)}{dt^2} + 3 \frac{dy(t)}{dt} + 2y(t) = \frac{df(t)}{dt} + 3f(t) \quad (1.4)$$

The Laplace Transform of (1.4) yields

$$(s^2 + 3s + 2) Y(s) = (s + 3) F(s) + I(s) \quad (1.5)$$

where, $F(s)$ = Laplace Transform of $f(t)$, and $I(s)$ = Laplace term associated with initial conditions.

Equation (1.5) can be written as

$$Y(s) = \frac{N(s)}{D(s)} F(s) + \frac{I(s)}{D(s)} \quad (1.6)$$

Where

$$N(s) = (s + 3) \quad (1.7)$$

and

$$D(s) = (s^2 + 3s + 2) \quad (1.8)$$

It is readily seen that the polynomial $D(s)$ appears both in the denominator of the "forcing function" term and also the "initial condition" term. It is further seen that if $f(t)$ is specified, the time domain solution for $y(t)$ can be obtained by factoring (finding the roots of) $D(s)$ and using partial fractions.

Then each of the roots of $D(s)$ contributes a term to the time domain response with the roots having a direct relationship with the time constants and frequency of oscillation of the time domain terms. The polynomial $D(s)$ is called the characteristic polynomial of the system.

Since the forcing function term contains the characteristic polynomial (and thus all information pertaining to stability and the form of the time domain transients), the initial condition term is dropped and (1.6) reduces to

$$Y(s) = \frac{N(s)}{D(s)} F(s) \quad (1.9)$$

The term $N(s)/D(s)$ as discussed before is referred to as the "Transfer Function" of the system.

A. Transfer Function Example

Determine the transfer function, $Y(s)/F(s)$ of the following mechanical system.

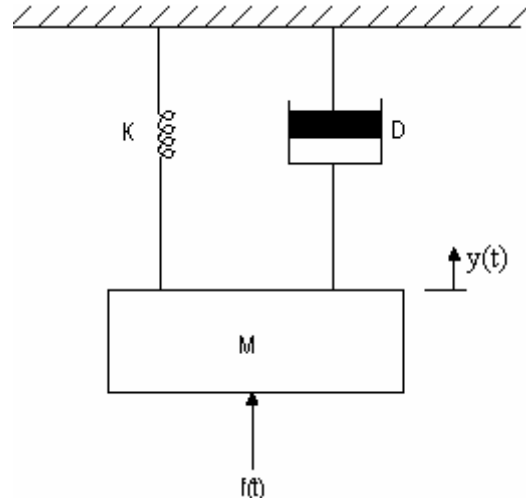


Figure 1.3 Mechanical System

The Differential Equation that describes this system is

$$M \frac{d^2 y(t)}{dt^2} + D \frac{dy(t)}{dt} + K y(t) = f(t) \quad (1.10)$$

Using entries of Laplace Transform Table I, with initial conditions set to zero,

$$M s^2 Y(s) + D s Y(s) + K Y(s) = F(s) \quad (1.11)$$

or

$$\frac{Y(s)}{F(s)} = \frac{1}{M s^2 + D s + K} \quad (1.12)$$

The main advantage of deriving a transfer function relating system output to system input is that it enables the analyst to assess system stability from the roots of the characteristic equation of the system.

One of the main problems with using Laplace transforms to assess system stability is that it usually requires a considerable amount of algebra to obtain the transfer function (T.F.) and the corresponding characteristic equation. This is partly expedited by using block diagrams to represent the system and then manipulating the block diagram to obtain the characteristic equation. This concept is discussed in the next section.

B. Block Diagrams

Block diagram representation of a physical system enables the analyst to obtain overall input/output relationships by using "block-diagram" manipulation rather than apply matrix methods or other reduction techniques [3] on the set of Laplace equations describing the physical system. Of greater significance is the fact that block diagram representation of the physical system indicates a cause and effect, or signal flow pattern, of the physical system. When set up properly, the block diagram (B.D.) is a one-to-one representation of the

elements of the physical system and the blocks of the Laplace B.D.

The basic element of B.D. representation is the transfer function. The input/output relation,

$$Y(s) = G_1(s) F(s) \quad (1.13)$$

is represented by the block diagram shown in Fig.1.4 with Model represented by the transfer function $G_1(s)$.

C. Interconnection Of Systems

Many real systems are built as interconnection of subsystems. Fig.1.4 below shows a series (also called cascade) and a parallel interconnection. In addition to the transfer function blocks, parallel connection uses the summing block.

The series connection is represented by the following equations,

$$Y(s) = G_2(s) X(s) \quad (1.14)$$

And

$$X(s) = G_1(s) F(s) \quad (1.15)$$

(1.14) and (1.15) can be combined as

$$Y(s) = G_1(s) G_2(s) F(s) \quad (1.16)$$

Thus the series connection can be equivalently represented by a single block with transfer function $G_1(s) G_2(s)$. Similarly the parallel connection can be represented by a single block with transfer function $G_1(s) + G_2(s)$.

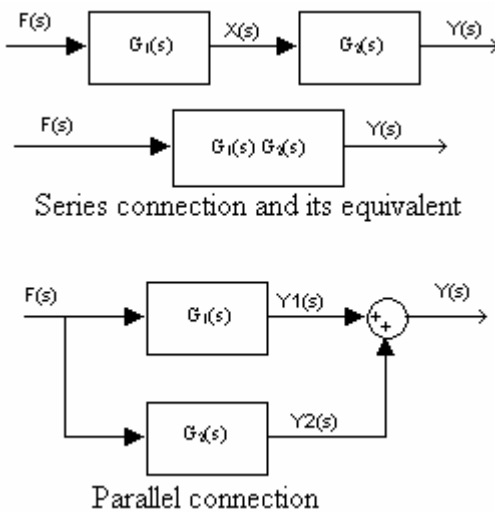


Figure 1.4 Series And Parallel Connections

It is possible to manipulate block diagram models using the elementary operations described previously. An example of the application of B.D. manipulation to obtain a system transfer function is shown below.

D. B.D. Manipulation Example

Derive the T.F., $C(s)/R(s)$, for the feedback system shown below in Fig.1.5.

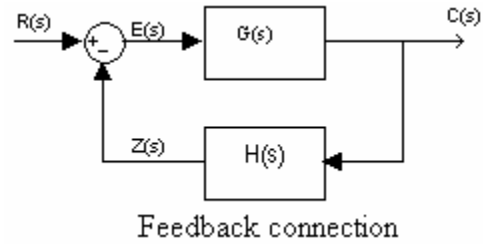


Figure 1.5 Feedback Control System

From the B.D.

$$E(s) = R(s) - Z(s) \quad (1.17)$$

$$C(s) = G(s) E(s) \quad (1.18)$$

$$Z(s) = H(s) C(s) \quad (1.19)$$

Substituting for E from (1.17) and Z from (1.19) in (1.18), and simplifying gives

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1 + G(s)H(s)} \quad (1.20)$$

Where $1 + GH = 0$ is the Characteristic Equation of this system.

E. Transfer Function Example

Derive the T.F. $E(s)/R(s)$ for the system shown in the previous example.

$$E(s) = R(s) - G(s)H(s) E(s) \quad (1.21)$$

Therefore

$$\frac{E(s)}{R(s)} = \frac{1}{1 + G(s)H(s)} \quad (1.22)$$

It can be readily seen from the previous two examples that both transfer functions have identical characteristic equations but that they have different numerator terms in the transfer functions. The roots of characteristic equation dictate the types of modes of response, and the numerator terms affect the magnitudes of the response terms. This basic concept is worth noting as it explains why system transients have different characteristics when viewed from different points on a system even though the T.F.s have identical characteristic equations and the same input signal is applied in both instances.

IV. FREQUENCY RESPONSE MODELS

By definition, the frequency response of a system is the ratio of the output over the input when the input to a system is a sinusoidal forcing function of radian frequency ω and steady state conditions have been reached.

We are already familiar with sinusoidal steady-state methods of analysis from circuit analysis.

Theoretically, the frequency response of a system can be obtained from the transfer function by setting $s = j\omega$ in the transfer function. The result is,

$$\frac{Y(j\omega)}{X(j\omega)} = G(j\omega) \quad (1.23)$$

Let us consider a general frequency response function that includes all types of terms as follows:

$$G(j\omega) = \frac{K(1 + T_z j\omega)(1 + 2\zeta(\frac{j\omega}{\omega_{nz}}) + (\frac{j\omega}{\omega_{nz}})^2)}{(j\omega)^n(1 + T_p j\omega)(1 + 2\zeta(\frac{j\omega}{\omega_{np}}) + (\frac{j\omega}{\omega_{np}})^2)} \quad (1.24)$$

The term $G(j\omega)$ can be completely represented graphically by plotting the magnitude $|G|$ and the angle $\angle G$ against ω on two separate graphs. It is customary to plot gain in dB given by $20 \log |G|$ versus $\log(\omega)$. Hence the general frequency expression in decibels can be obtained from (1.24).

$$\begin{aligned} 20 \log |G| = & 20 \log K - n \cdot 20 \log \omega - 20 \log |1 + T_p j\omega| \\ & + 20 \log |1 + T_z j\omega| \\ & + 20 \log |(1 + 2\zeta(\frac{j\omega}{\omega_{nz}}) + (\frac{j\omega}{\omega_{nz}})^2)| \\ & - 20 \log |(1 + 2\zeta(\frac{j\omega}{\omega_{np}}) + (\frac{j\omega}{\omega_{np}})^2)| \end{aligned} \quad (1.25)$$

The expression for the angle of the frequency response is given by

$$\begin{aligned} \angle G = & \sum \text{Angles of numerator terms} \\ & - \sum \text{Angles of denominator terms} \end{aligned} \quad (1.26)$$

Where angles of numerator and denominator terms are determined by specifying a particular value of ω and algebraically summing the angles of the terms in the numerator and denominator of (1.24).

Each of the terms in (1.25) contribute to the magnitude plot (Bode Plot) of the total magnitude plot of $20 \log |G|$ (this is written in shorthand as $|G|$ dB). Fig.1.6 illustrates the contribution of each term to the Bode Plot.

When the transfer function is given, a complete Bode plot

of the transfer function can be obtained by summing up the contribution to the Bode plot of each term as seen in Fig.1.6. It can further be noted from Fig.1.6 that the complex pair can give very sharp attenuation or magnification in the magnitude plot at frequencies in the vicinity of the "resonant humps" of these terms. This feature is important in the design of "pass" and "stop" band filters; a concept that is used in the design of filters to block generator shaft "torsional" frequencies from feeding back into the AVR through the PSS.

Bode diagrams are also used to plot experimental frequency response data when measurements have been made using a sinusoidal generator and recording equipment. In these cases a transfer function can be obtained from the frequency response data by doing a "manual" or "computerized" analysis to best fit the data. In some situations frequency response data is used directly to obtain data for assessing stability of existing systems or for designing controllers to enhance the stability of the control loop. These concepts will be discussed later.

It will be seen in the next section that transfer functions and frequency response concepts form a vital basis for assessing stability of certain types of control systems.

V. STABILITY CRITERIA FOR FEEDBACK CONTROL SYSTEMS

A. General Comments

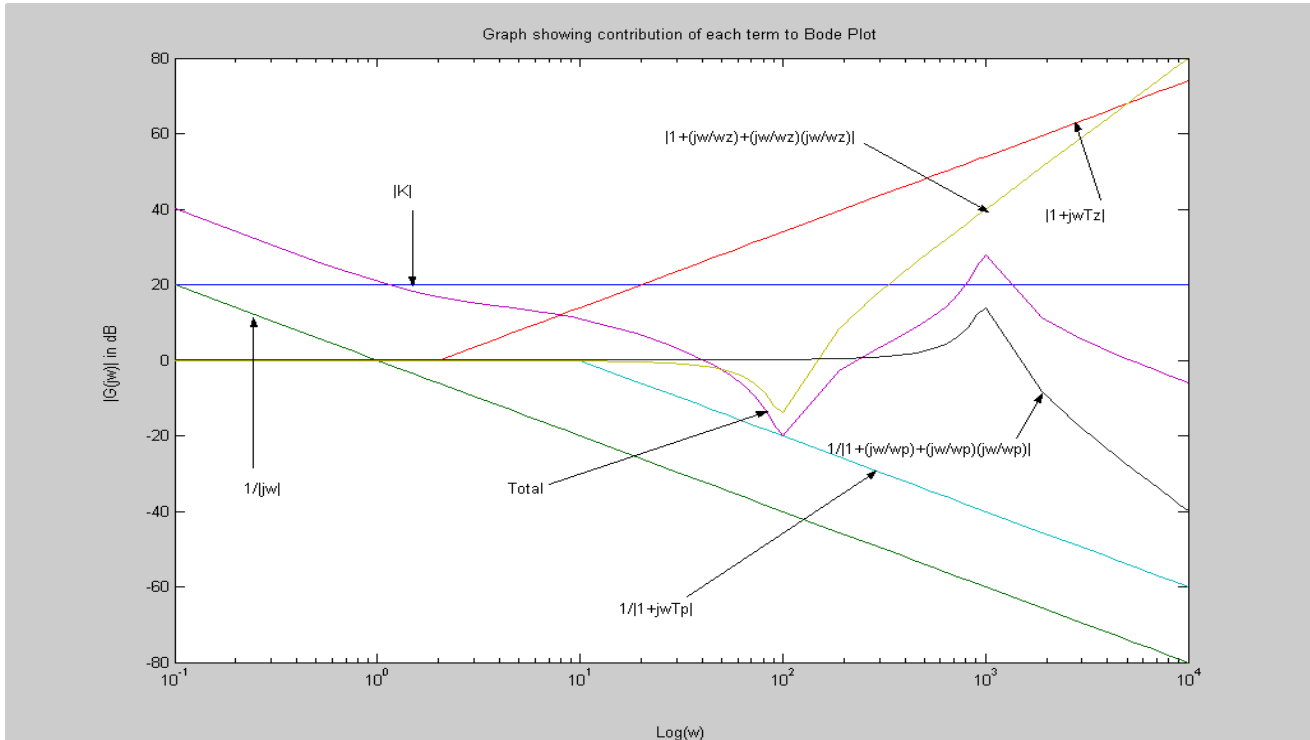
Classical control theory is based on single-input-single-output (SISO) control systems [4] [5]. Stability of these systems is assessed by investigating the effect of adjustable parameters on the roots of the characteristic equations. The characteristic equation is obtained by manipulating the set of equations describing the dynamic system, or the system block diagram.

Once an expression for the characteristic equation is obtained, several techniques can be applied to this equation to assess stability. These so-called classical tools for stability assessment include [6] - [8]:

- Routh-Hurwitz Criterion
- Nyquist Criterion
- Bode Plots
- Root Locus Technique

The latter two will be described here as they relate directly to techniques that are used for PSS tuning.

Many feedback control systems have adjustable gain K either in the forward or feedback path. The locations of closed-loop poles change as the gain K is varied. The closed loop pole locations decide key control system performance characteristics such as stability, transient response, and closed-loop bandwidth.

Figure 1.6 Graph Showing Contribution Of Each Term Of (1.24) To Bode Plot $|G|$

The root-locus method is a graphical technique for plotting closed-loop poles as a function of some system parameter commonly the gain K .

In contrast to the root-locus method, the Nyquist criterion gives information on the stability of a feedback system. The Nyquist method can be applied not only to systems for which mathematical description is available but also to systems for which experimental frequency response information is available. The Nyquist criterion gives relative stability information in the form of gain and phase margins. The Nyquist criterion uses a polar plot of the open-loop transfer function.

Another frequency response method that is widely used is the Bode diagram. In the Bode gain plot, gain in decibels - dB is plotted against ω on logarithmic scale. In the Bode phase plot the phase in degrees is plotted against ω on logarithmic scale. The stability information of Nyquist criterion is easily transferred to the Bode plots. In addition magnitude Bode curve can be easily plotted using asymptotic approximation. Since Bode plots are much more widely used than the Nyquist plots, we will discuss Bode plots in more detail.

Reader should note that Root-locus and Bode plots complement each other. While root-locus gives the exact closed loop pole locations, the Bode plots give relative stability information in the form of gain and phase margins. The root-locus approach gives information about the stability and the transient characteristics of the system. The frequency response approach can be used to design systems to minimize

the effects of noise. The correlation between the transient and frequency responses is indirect, except for the case of second-order systems.

There are many other sophisticated computerized tuning techniques described in the literature that have been applied to simulated power system models or Scaled-down laboratory systems. These include optimal control, optimal output feedback control [9] - [11], pole placement techniques [12], minimum variance methods [13], [14] and frequency domain techniques [15]. The need for imposing additional design constraints (such as minimizing complex performance indices related to system transient swings) on the controller does not appear to be of prime concern to Utilities. Presently most common method for tuning PSS consists of improving damping (i.e. moving characteristic roots).

B. Nyquist Criterion (Gain And Phase Margins)

The Nyquist criterion utilizes either the transfer function or experimentally obtained frequency response data and gives a measure of the relative stability of the roots of the characteristic equation.

Consider the closed-loop system shown in Fig.1.7. If a sinusoidal signal, $R(s)$, is applied it will be modified and phase-shifted by $G(j\omega)$ and $H(j\omega)$ so that the feedback signal $Z(j\omega)$ will subtract vectorially from the input $R(j\omega)$.

$$E(j\omega) = R(j\omega) - Z(j\omega) \quad (1.27)$$

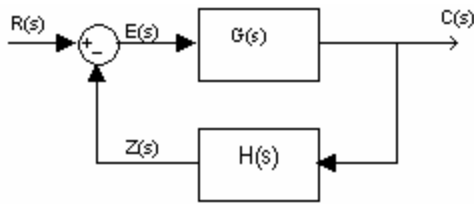


Figure 1.7 Feedback Block Diagram

If GH phase shifts the input sinusoid by 180° and amplifies it by an amount greater than unity, the feedback signal will enhance the original input sinusoid and instability will result. This same intuitive argument can be applied to a wide range of sinusoidal signals applied to the input. It is apparent that if GH has frequency response characteristics such that,

$$|GH| < 1 \text{ when } \angle GH = -180^\circ \quad (1.28)$$

And

$$|\angle GH| < 180^\circ \text{ when } |GH| = 1 \quad (1.29)$$

Over a range of frequencies then the system should be stable. There are exceptions to this rule for some systems and in those cases the generalized "Nyquist criterion" must be applied. The relative stability of a feedback system follows

directly from (1.28) and (1.29). Phase margin, PM, is defined as the phase angle of GH relative to 180° when $|GH| = 1$ or,

$$PM = \angle GH - 180^\circ \quad (1.30)$$

when $|GH| = 1$ and Gain Margin, G.M., is the relative magnitude of GH when the angle of GH is 180° , or,

$$GM = \frac{1}{|GH|} \quad (1.31)$$

when $\angle GH = -180^\circ$.

The gain and phase margin stability parameters are shown in the Bode plot of Fig. 1.8.

Gain and phase margins are used to assess the stability of power systems control loops. This can be illustrated by considering the following power system application. The Bode plot contains the same information as the polar plot and the former is normally used as gain and phase margin for the AVR system can be more readily extracted from the Bode plot.

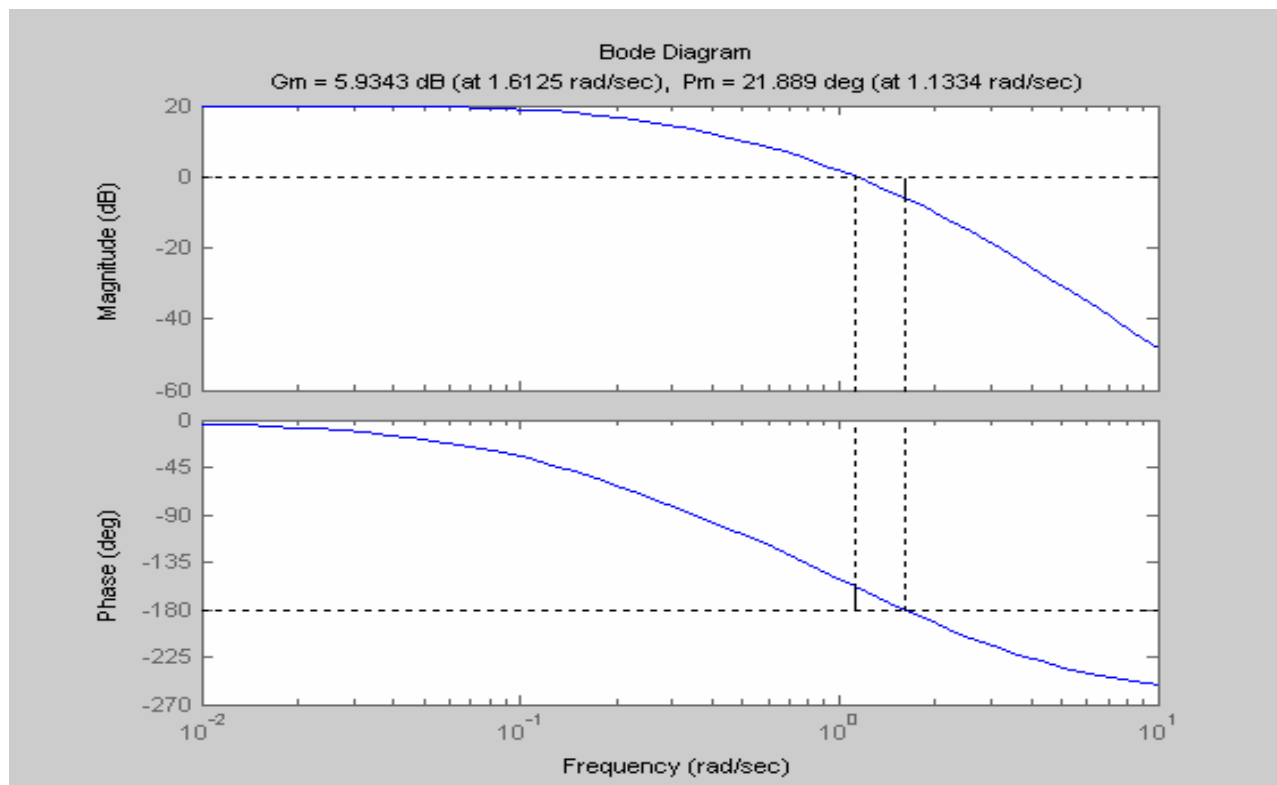


Figure 1.8 Bode Plots Illustrating Gain And Phase Margins

C. Example

A block diagram is shown below for a hypothetical terminal voltage control loop for a synchronous generator operating at rated speed on open circuit.

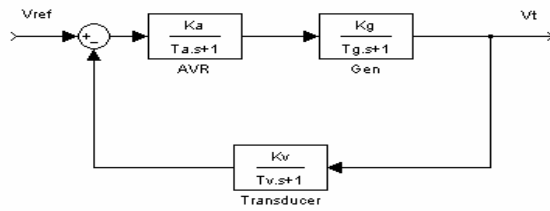


Figure 1.9 Voltage Control Loop

A typical problem would be to assess the stability of this control loop for varying AVR gains.

For this case $GH = \text{AVR} \times \text{Gen} \times \text{Transducer}$

$$GH = \frac{K_a}{1 + T_a s} \times \frac{K_g}{1 + T_g s} \times \frac{K_v}{1 + T_v s} \quad (1.32)$$

The corresponding Bode plot of GH is shown below in Fig.1.10 for three different values of AVR gain. It is assumed that all other gains and time constants are known.

Bode Plot of $GH(j\omega)$ shows the magnitude and phase of $GH(j\omega)$ for 3 values of AVR gain. The gain and phase

margin information is readily available from the Bode plots.

Root-Locus Theory

The root-locus method involves a graphical approach to evaluating the excursion of system roots (loci) as a function of the change in magnitude of one or more of the coefficients of the characteristic equation. This graphical technique yields the approximate root locations of the characteristic equation and hence gives information about the "form" of time domain transients of the system for a particular combination of controller and plant parameters.

Most single-input-single-output (SISO) control systems can be manipulated into the standard form shown in Fig.1.7. For our application the transfer function $G(s)$ can be related to the power system transfer function and the feedback transfer function $H(s)$ to the power system stabilizer.

The closed loop transfer function for the system is given by,

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1 + H(s)G(s)} \quad (1.33)$$

$$1 + G(s)H(s) \quad (1.34)$$

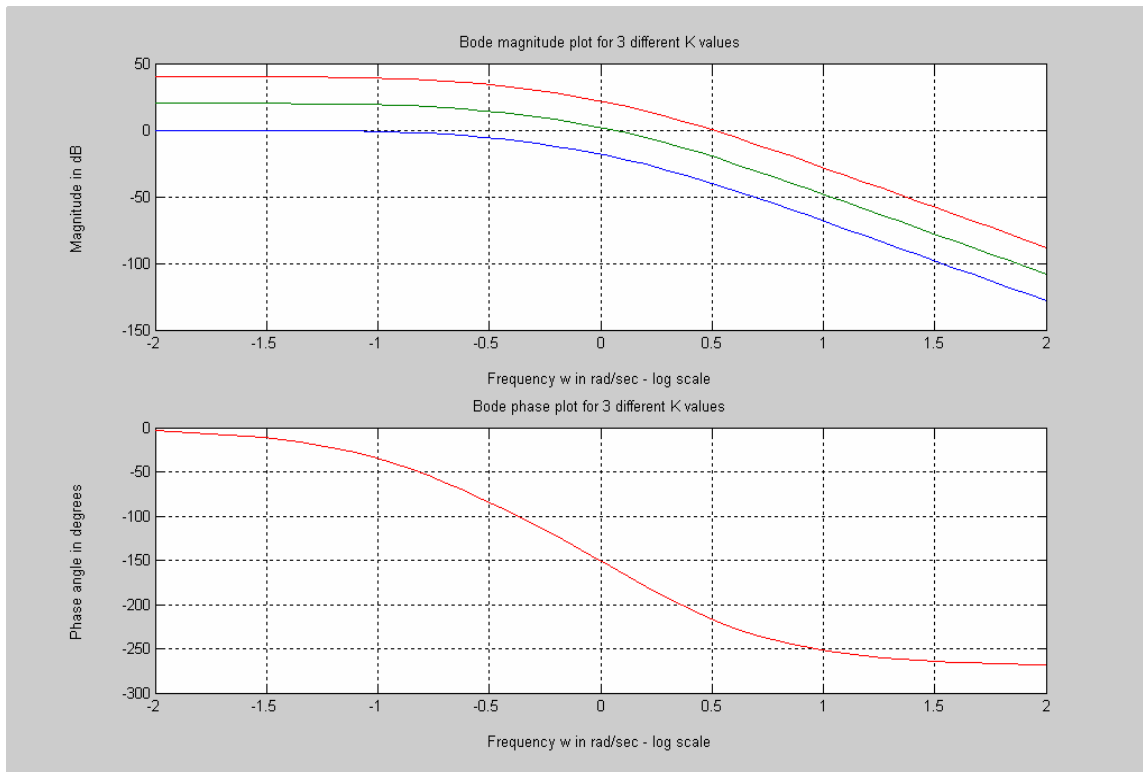


Figure 1.10. Bode Plot For 3 Different Values Of AVR Gain

The characteristic equation is,

$$1 + G(s) H(s) = 0 \quad (1.35)$$

Recall that the roots of the characteristic equation give a direct indication of the frequency modes and time constants of the time domain transients. This can be deduced by first finding the roots of (1.35). After finding the roots, (1.35) can be written as

$$\Pi_n(s + p_n) \Pi_m(s + P_m \pm jQ_m) = 0 \quad (1.36)$$

where $-p_n$ are the real roots of (1.35) and $-P_m \pm jQ_m$ are the complex conjugate roots of (1.35).

$$C(s) = \frac{\text{Numerator}(s)}{\Pi_n(s + p_n) \Pi_m(s + P_m \pm jQ_m)} \quad (1.37)$$

The natural modes of response of the closed loop system are shown below,

$$\sum_n k_n e^{-p_n t} + \sum_m k_m e^{-P_m t} \sin(Q_m t \pm \theta_m) \quad (1.38)$$

Where it is apparent that the time constant in the exponential terms of (1.38) are identical to the real parts of the roots shown in (1.36). It should also be noted that the imaginary part of the roots shown in (1.36) give a direct indication of the damped radian frequency of the decaying sinusoids as represented in the second set of terms in (1.38).

The root-locus method provides a graphical approach to finding the roots of a characteristic equation. Consider a slightly modified form of (1.35) given by,

$$H(s)G(s) = -1 \quad (1.39)$$

It follows that any value of s , say s_i , which satisfies

$$|G(s_i)H(s_i)| = 1 \quad (1.40)$$

and

$$\angle G(s_i)H(s_i) = 180^\circ \text{ or } 360^\circ \quad (1.41)$$

is a root of the characteristic equation. The transfer function $G(s) H(s)$ (commonly referred to as the "open loop" transfer function) can be written as,

$$\frac{K \Pi(s + Z_i)}{\Pi(s + P_j)} = -1 \quad (1.42)$$

Where $-Z_i$ and $-P_j$ are referred to as the zeros and poles of GH . It follows that the roots of the characteristic equation must satisfy,

$$\frac{K \Pi(s + Z_i)}{\Pi(s + P_j)} = 1 \quad (1.43)$$

and

$$\sum \angle(s + Z_i) - \sum \angle(s + P_j) = 180^\circ \text{ or } 360^\circ \quad (1.44)$$

For $K = 0$ to ∞

By initially locating the zeros and poles on a graph with an imaginary vertical axis and a real horizontal axis (referred to as the complex s -plane), it is possible to establish some rules using (1.43), and (1.44) to sketch the characteristic root excursions (referred to as root loci) while varying K from zero to infinity.

For the Characteristic Equation,

$$1 + KGH(s) = 0 \quad (1.45)$$

TABLE 2
RULES FOR ROOT-LOCUS CONSTRUCTION FOR $K > 0$

1. Loci originate on poles of $GH(s)$ and terminate on the zeros of $GH(s)$
2. The root locus on the real axis always lies in a section of the real axis to the left of an odd number of poles and zeros.
3. The root locus is symmetrical with respect to the real axis.
4. The number of asymptotes n_a is equal to the number of poles of $GH(s)$, n_p , minus the number of zeros of $GH(s)$, n_z , with angles given by $[(2m+1)180^\circ] / (n_p - n_z)$, where m is an integer between 0 and $(n_a - 1)$.
5. The asymptotes intersect the real axis at σ where $\sigma = (\sum \text{poles of } GH - \sum \text{zeros of } GH) / (n_p - n_z)$
6. The breakaway points are given by the roots of $\frac{dK}{ds} = 0$ Where $K' = \frac{K_a K_g K_v}{T_g T_a T_v}$ (1.46) If all parameters are specified except the AVR gain K_a , then a root locus plot for varying K_a would be constructed as shown in Fig.1.11.

D. Root Locus Example

Consider the voltage regulator loop of the previous example shown in Fig.1.9. A typical application for applying root locus techniques would be to study the effects of K_a on the roots of the characteristic equation.

For this case the characteristic equation is given by

$$1 + \frac{K_a}{1 + T_a s} \times \frac{K_g}{1 + T_g s} \times \frac{K_v}{1 + T_v s} = 0 \quad (1.47)$$

This can be written as

$$\frac{K'}{(s + \frac{1}{T_a})(s + \frac{1}{T_g})(s + \frac{1}{T_v})} = -1 \quad (1.48)$$

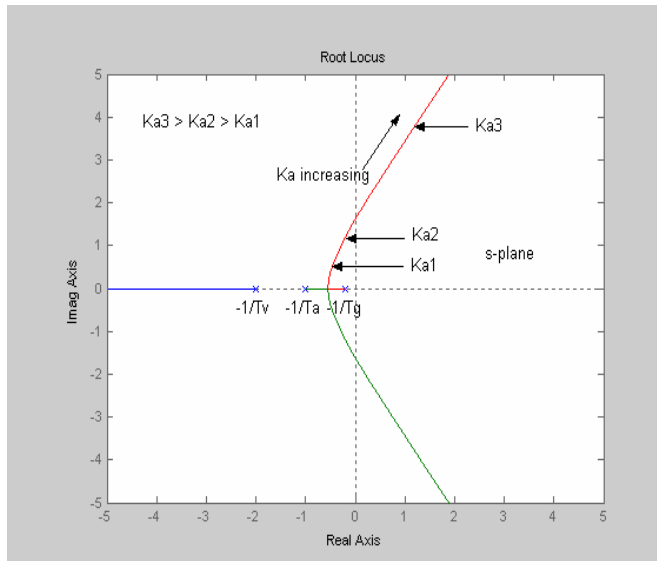


Figure 1.11 Root Locus Plot Of The System

The open-loop poles and zeros of the system are shown on the s-plane. As the AVR gain increases two of the roots of the characteristic equation move towards the right half-plane (unstable side of the s-plane). Typical time domain characteristics for three values of gain K_a are shown in Fig. 1.12. For instance the roots of the characteristic equation for gain K_{a1} where the AVR is at a low gain, give rise to reasonably damped oscillations.

This is compared with the root locations for a gain K_{a2} where the system is oscillatory and those for gain K_{a3} where the system is unstable.

The next section describes the State-Space approach to modeling and assessing stability of linearized systems. This technique allows the analyst to formulate the system model using first order differential equations and then use computer programs to assess stability and synthesize controllers.

VI. STATE-SPACE TECHNIQUES

A. General Comments

Root-locus and frequency-response methods are quite useful for dealing with single-input single-output systems. For example, by means of open-loop frequency-response tests, we can predict the dynamic behavior of the closed-loop system. If necessary, the dynamic behavior of

a complex system may be improved by inserting a simple lead or lag compensator. The techniques of conventional control theory are conceptually simple and require only a reasonable amount of computation.

In conventional control theory, only the input, output, and error signals are considered important; the analysis and design of control systems are carried out using transfer functions, together with a variety of graphical techniques such as root-locus plots and Bode plots. The unique characteristic of conventional control theory is that it is based on the input-output (transfer function) relationship of the system.

The main disadvantage of conventional control theory is that, generally speaking, it is applicable only to low order linear time-invariant systems having a single input and a single output. It is cumbersome for time-varying, nonlinear larger systems with multiple-inputs multiple-outputs (MIMO).

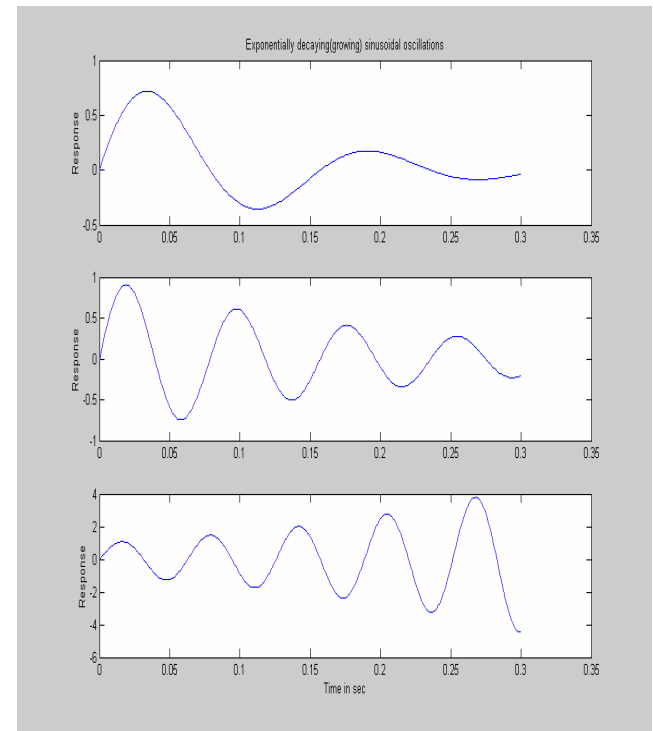


Figure 1.12 Time Domain Sketches For 3 Values Of K_a

Because of the necessity of meeting increasingly stringent requirements on the performance of complex control systems, modern control theory is gaining in popularity. Modern control theory is based on the concept of state [7], [9]. The concept of state by itself is not new since it has been in existence for a long time in the field of classical dynamics and other fields.

System design using modern control theory enables the engineer to design optimal control systems with respect to given performance indices.

The state-space approach can be used to study various aspects of control systems. These include:

- obtaining root contours, or root loci, or eigenvalue plots using digital computer programming techniques,
- optimal controller design for large systems,
- system reduction and equivalent models of large systems,
- sensitivity studies to ascertain the influence of system parameters on roots and time domain transients.

We will be mostly dealing with the eigenvalue plots.

A physical system described by a set of differential equations of any order can be transformed into a set of first order D.E.'s using simple substitutions. The variables of the new set of D.E.'s define the "state" of the system at any instant of time "t".

The transformed set in matrix form is given by,

$$\dot{X}(t) = AX(t) + BF(t) \quad (1.49)$$

$$Y(t) = C X(t) \quad (1.50)$$

Where,

X is an $n \times 1$ vector containing the state variables

$\dot{X}$ is an $n \times 1$ vector containing the first derivative of X

F is an $m \times 1$ vector containing the independent forcing functions to the system

A is an $n \times n$ characteristic matrix

B is an $n \times m$ coupling matrix

Y is an $r \times 1$ output vector

C is an $r \times n$ coupling matrix

B. State-Space Models

It is possible to derive the standard state-space form,

$\dot{X} = A X + BF(t)$ of a physical system from any of the different mathematical models of the system.

State space equations can be written from a block diagram of a system as illustrated by considering the power system "inertia" model shown below. In this model, the turbo-generator inertia is denoted "H"; sources of damping are represented by the term "D"; and the synchronizing coefficient is denoted " K_1 ". States ω and δ are the generator speed and rotor angle, respectively.

C. State Space model Example

Determine the state-space model and the eigenvalues for the system shown in Fig.1.13.

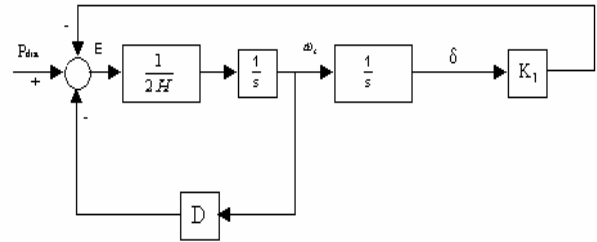


Figure1.13 Inertia Model

The steps used in finding the state space model are described below.

- Assign a state variable x_i to the output of each integrator block ($1/s$).
- Since the input to each integrator block must be $\dot{x}_i$, the state space equations can be written directly.

For this example,

$$\dot{x}_1 = \frac{1}{2H}(-Dx_1 - K_1x_2) + \frac{1}{2H}P_{dist} \quad (1.51)$$

$$x_2 = x_1 \quad (1.52)$$

The matrix form of these two equations is,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -\frac{D}{2H} & -\frac{K_1}{2H} \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{2H} \\ 0 \end{bmatrix} P_{dist} \quad (1.53)$$

which is of the form,

$$\dot{X} = AX + BF(t) \quad (1.54)$$

The output equation is

$$y = x_1 \quad (1.55)$$

The matrix form of this equation is,

$$Y = [1 \quad 0] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad (1.56)$$

We next show the connection between roots of characteristic equation and of the characteristic matrix $[A]$.

In this example the transfer function linking shaft speed, ω_s , to power disturbance, P_{dist} , is derived as follows,

$$\omega_s = \frac{1}{2Hs} E \quad (1.57)$$

$$E = P_{dist} - D\omega_s - \frac{K_1}{s} \omega_s \quad (1.58)$$

Substituting (1.58) into (1.57) and simplifying yields

$$\frac{\omega_s}{P_{dist}} = \frac{\frac{1}{2H}s}{s^2 + \frac{D}{2H}s + \frac{K_1}{2H}} \quad (1.59)$$

Where the roots of the characteristic equation are given by

$$s_1, s_2 = \frac{-D}{4H} \pm \left[\left(\frac{D}{4H} \right)^2 - \frac{K_1}{2H} \right]^{1/2} \quad (1.60)$$

The eigenvalues, λ , of matrix $[A]$ of the corresponding state space model are given by the solution to,

$$\text{Det}[\lambda I - A] = 0 \quad (1.61)$$

Where, Det is the determinant of the matrix, and

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (1.62)$$

It follows that

$$\lambda I = \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix} \quad (1.63)$$

For this example,

$$A = \begin{bmatrix} -\frac{D}{2H} & -\frac{K_1}{2H} \\ 1 & 0 \end{bmatrix} \quad (1.64)$$

Equation (1.61) applied to this example yields the following,

$$\begin{bmatrix} \lambda + \frac{D}{2H} & \frac{K_1}{2H} \\ -1 & \lambda \end{bmatrix} \quad (1.65)$$

Expanding the determinant expression of (1.65) yields,

$$\lambda^2 + \frac{D}{2H} \lambda + \frac{K_1}{2H} = 0 \quad (1.66)$$

It can be noted that (1.66) is identical to the Characteristic Equation shown in (1.59).

Several powerful digital computer subroutines are available for calculating eigenvalues (characteristic roots) directly from the matrix $[A]$. This allows the analyst to obtain roots of very large systems by generating the $[A]$ matrix and inserting the elements of $[A]$ directly into a computer program.

It is useful to compare classical methods for assessing system stability with the state-space eigenvalue approach. For classical methods a considerable amount of algebra is required in order to get the equations in a form that will allow approximate graphical methods or root-finding algorithms to be applied. In other words, the dynamic equations have to be compressed down to an input-output expression. With the state-space approach, the state-space model is formulated directly from the separate blocks or equations describing the physical system. Computer techniques are applied directly to the $[A]$ matrix and thus manual algebra is virtually eliminated.

VII. SYSTEM SIMULATION

An important part of investigating system stability and designing controllers is to simulate the complete system with nonlinearities. State-space and classical methods for assessing stability are applicable to linearized representation of the physical plant and to low order nonlinear models.

If one is concerned about the operation of the system under large signal operation, then the nonlinear equations could be simulated on the digital computer and plots of time domain transients obtained for pre-selected parameters and disturbances to the system. Transient stability programs are used extensively for this purpose in the electric power industry. Although these nonlinear simulation programs are needed for large-signal investigations they are very inefficient when used for trial-and-error investigations in the design of controllers for linear systems. The Matlab/Simulink [16] package is very widely used for this purpose. The next chapter outlines basic power system dynamics and identifies factors contributing to negative damping of synchronous generator rotor oscillations.

CHAPTER 2

OVERVIEW OF POWER SYSTEM

STABILITY CONCEPTS

Arjun Godhwani, Jose Taborda, Les Hajagos

I. INTRODUCTION

Power system stability is considered by first presenting the definition followed by the classification of stability in to Voltage, Frequency and Rotor angle stability. It is then argued that the subject of this tutorial is ‘Power System Stabilization via Excitation Control’ and the rotor angle stability is the one that plays the critical role. We consider a synchronous machine connected to infinite bus and develop an expression for electric power as it is related to rotor angle. We go on to discuss the transient (large signal) and oscillatory rotor angle (small signal) stability and their dependence on synchronizing and damping torques. It is established that the synchronizing torque governs the transient stability whereas the oscillatory stability is affected by the damping torque. We next show that a fast acting, high gain AVR improves the synchronizing coefficient but may reduce the damping coefficient. The reduction in damping can be compensated by power system stabilizer (PSS), acting through the voltage regulator, to provide a supplementary signal to increase the damping and thus stabilize the system against oscillatory instability. We conclude the paper by briefly discussing different kinds of PSS in use and their basic structure.

The overview of power system stability concepts was part of the IEEE tutorial of 1981 [17]. An IEEE committee report [18] just preceded the tutorial. Although the basic concepts of the power system stability have not changed that much, the technology of power system stabilizers has gone through significant evolution. In this paper we present the status of power system stability concepts at present and discuss the status of some issues such as stability classification, new types of power system stabilizers etc. We start with stability classification.

II. POWER SYSTEM STABILITY CLASSIFICATION

A. Definition

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 system variables bounded so that system integrity is preserved. Integrity of the system is preserved when practically the entire power system remains intact with no tripping of generators or loads, except for those disconnected by the isolation of the faulted elements or intentionally tripped to preserve the continuity of operation of the rest of the system.

B. Categories Of Stability

Analysis of stability, including identifying key factors

that contribute to instability and devising methods of improving stable operation, is greatly facilitated by classification of stability into appropriate categories. There are mainly three categories of stability: voltage [19], frequency [20], and rotor angle stability. The following are descriptions of the corresponding forms of stability phenomena.

1) Voltage Stability

Voltage stability is concerned with the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. Instability that may result occurs in the form of a progressive fall or rise of voltages of some buses. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and other elements by their protection equipment leading to cascading outages.

2) Frequency Stability

Frequency stability is concerned with the ability of a power system to maintain steady frequency within a nominal range following a severe system upset resulting in a significant imbalance between generation and load. It depends on the ability to restore balance between system generation and load, with minimum loss of load. Instability that may result occurs in the form of sustained frequency swings leading to tripping of generating units and/or loads.

3) Rotor Angle Stability

Rotor angle stability is concerned with the ability of interconnected synchronous machines of a power system to remain in synchronism after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system. Instability that may result occurs in the form of increasing angular swings of some generators leading to their loss of synchronism with other generators.

Note: The subject of this tutorial is ‘Power System Stabilization via Excitation Control’. While Frequency stability and Voltage stability are important in the overall power system stability problem, it is the rotor angle stability that has a critical role to play in ‘Power System Stabilization via Excitation Control’. Therefore we have limited ourselves to a short description of the Frequency and Voltage stabilities.

We next discuss basic issues involved in the power system stability. We begin with the consideration of a generator connected to infinite bus configuration and develop the concepts of transient and oscillatory stability.

III. BACKGROUND - GENERATOR CONNECTED TO INFINITE BUS

Since power systems rely on synchronous machines for the generation of electrical power, a necessary condition for the transmission and exchange of power is that all generators rotate in synchronism. Consider a remote generator connected radially to a major substation of a very large system, as shown in Fig. 2.1. The transmission system feeds into the large system or infinite bus, which assumes that its voltage is so strongly influenced by large nearby generation that it is independent of events at the remote generator.

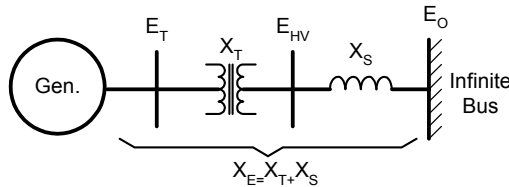


Figure 2.1 Single-Machine Power System Configuration

A phasor diagram of the voltages on such a system is shown in Fig.2.2. These voltages are:

- E_o infinite bus voltage
- E_T generator terminal voltage
- E'_q generator internal voltage behind transient reactance
- E_q generator internal voltage behind synchronous reactance

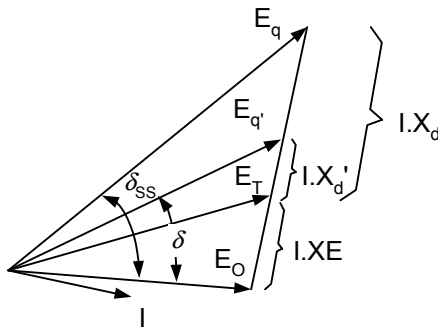


Figure 2.2 Generator/ Infinite Bus Phasor Diagram

The angle difference in the phasors indicates a real power flow from the generator into the infinite bus.

In the analysis of classical steady-state stability, the voltage E_q and the power angle δ_{ss} are used in the characteristic electrical power flow equation. However, for simple transient and dynamic stability analyses, it is more appropriate to use the voltage E behind transient reactance and the angle δ between this voltage and the infinite bus voltage. In this way, the generator electrical power can be expressed as:

$$P_E = \frac{E_q E_o}{X_d + X_e} \sin \delta \quad (2.1)$$

This power-angle characteristic is shown as the sine function plotted in Fig. 2.3.

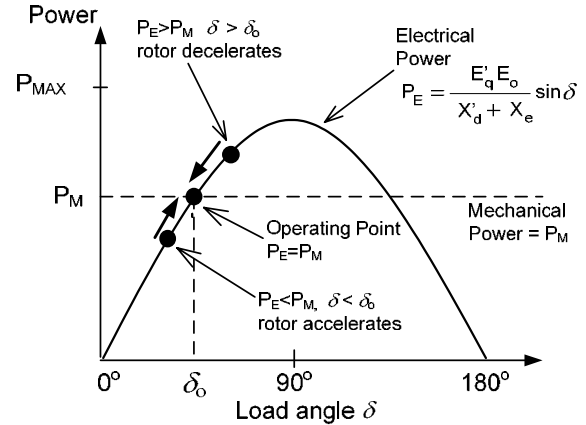


Figure 2.3 Power-Angle Curve

IV. TRANSIENT STABILITY

Transient stability analysis is primarily concerned with the immediate effects of transmission line disturbances on generator synchronism. Fig.2.4 illustrates the typical behavior of a generator in response to a fault condition. Starting from the initial operating condition (point 1), a close-in transmission line fault causes the generator electrical output power P_E to be drastically reduced. The resultant difference between electrical power and mechanical turbine power causes the generator rotor to accelerate with respect to the system, increasing the power angle (point 2). When the fault is cleared, the electrical power is restored to a level corresponding to the appropriate point on the power-angle curve (point 3). Clearing the fault necessarily removes one or more transmission elements from service and at least temporarily weakens the transmission system. For simplicity, this effect is not shown in Fig.2.4.

After clearing the fault, the electrical power out of the generator becomes greater than the turbine power. This causes the unit to decelerate (point 4), reducing the momentum the rotor gained during the fault. If there is enough retarding torque after fault clearing to make up for the acceleration during the fault, the generator will be transiently stable on the first swing and will move back toward its operating point in approximately 0.5 second from the inception of the fault. If the retarding torque is insufficient, the power angle will continue to increase until synchronism with the power system is lost.

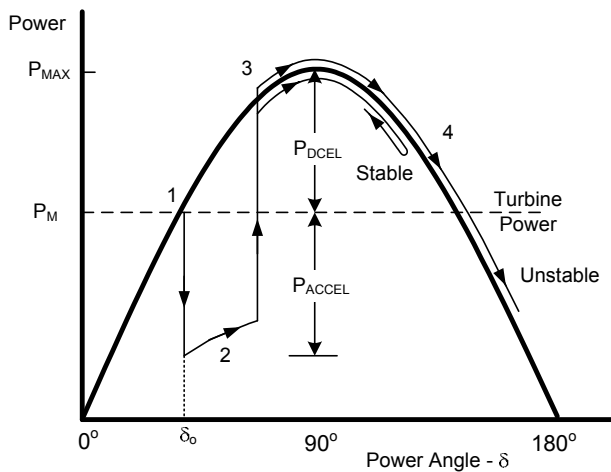


Figure 2.4 Power-Angle Curve Illustrating Transient Stability.

Excitation system forcing during and following the fault attempts to increase the electrical power output by raising the generator internal voltage E_q , thus increasing P_{MAX} . Fast and powerful excitation systems can improve transient stability, although the effect is limited due mainly to the large field inductance of the generator which prevents a sudden change in E'_q for a sudden increase in exciter output voltage.

The steady-state stability refers to the ability of a power system to maintain synchronism at all points for incremental slow-moving changes in power output of units or power transmission facilities. Steady-state stability a small signal phenomenon is governed by the synchronizing coefficient. Transient stability a large signal phenomenon is also governed by the synchronizing coefficient. A fast acting, high gain AVR in general increases the synchronizing coefficient but may decrease the damping coefficient. Thus a high gain AVR helps the steady state and transient stabilities but may reduce the oscillatory stability.

V. TRANSIENT VS. OSCILLATORY STABILITY

In present-day systems, a machine being transiently stable on the first swing does not guarantee that it will return to its steady-state operating point in a well-damped manner and thus be stable in an oscillatory mode. Significant improvement in transient stability has been achieved through very rapid fault detection and circuit breaker operation. System effects such as sudden changes in load, short circuits, and transmission line switching not only introduce transient disturbances on machines, but also may give rise to less stable operating conditions. For example, if a transmission line must be tripped due to a fault, the resulting system may be much weaker than that existing prior to the fault and oscillatory instability may result.

One solution to improve the dynamic performance of this system and large scale systems in general could be to

add more parallel transmission lines in order to lower the reactance between the generator and the load center. Such a solution may be quite costly as well as unfeasible to implement. In the presence of a weak transmission system, control means, such as a power system stabilizer (PSS), acting through the voltage regulator, can provide significant stabilization of such oscillations if properly implemented.

VI. OSCILLATORY STABILITY

A. Characteristic Dynamic Equation

Following a system disturbance, whether it is a large disturbance or just a minimal load change on the system, a generating unit will characteristically tend to oscillate around its operating point until it again reaches steady state. The characteristics of these oscillations are analogous to the motion of the spring mass systems.

For a synchronous machine under constant field excitation, an approximation of its dynamic motion is obtained by relating the angular acceleration of the generator rotor to the torques imposed on the rotor, in the same manner that linear acceleration relates to force in a spring mass system. This relationship for a synchronous machine is:

$$(\text{Inertia}) (\text{Angular Acceleration}) + (\text{Damping Torque}) + (\text{Electrical Torque} - \text{Turbine Torque}) = 0.$$

For small changes, the behavior is described by a characteristic equation having the same structure as that of the mechanical spring mass system. This is the "swing" equation:

$$\frac{2H}{\omega_s} \frac{d^2\delta}{dt^2} + \frac{D}{\omega_s} \frac{d\delta}{dt} + K_1 \Delta\delta = 0 \quad (2.2)$$

Where the parameters are defined as:

$\Delta\delta$ (radians)	rotor angle deviation from the steady state operating point
H (kW sec/kVA)	inertia constant of the rotor of the generating unit (or group of units)
D (p.u. power/p.u. freq. change)	damping coefficient representing friction and windage, prime mover and load damping, etc.
ω_s (radians/sec)	synchronous frequency = 377 r/s on 60 Hz systems
K_1 (p.u. ΔP /radian)	synchronizing coefficient.

Acting like the restoring force of the spring in the mechanical spring mass system, the term $K_1 \Delta\delta$ called the synchronizing power, acts to accelerate or decelerate the rotating inertia back toward the synchronous operating point. For small deviations from the operating point, the synchronizing coefficient K_1 is the slope of the transfer