THE APPLICATION OF POWER SYSTEM STABILIZERS IN A MULTIMACHINE GENERATING PLANT

A Thesis

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Electrical Engineering Abstract 86A268

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ABSTRACT

This thesis illustrates the effectiveness of speed-input, conventional power system stabilizers in a multimachine system. The particular real power system concerned was comprised of six generating units and an infinite bus. This is a reduced order model of part of the Saskatchewan Power Corporation System.

The oscillation of the system as a result of an infinite bus fault is shown to have several poorly damped frequency modes. These frequency modes were studied by using the eigen-value and eigen-vector method. The units which would give the maximum damping effects were determined using this method.

Two stabilizer design methods are described in this thesis, the Root Locus Method(RLM) and the Phase Compensation Method(PCM). The RLM approach requires a system transfer function in factored form. A method of determining this from time-domain test data is described in detail in the thesis. The PCM approach, which is significantly simpler to apply than the RLM approach, is demonstrated also. This method is based on the approach of compensating the phase shift between the air gap flux deviation($\Delta E_q'$) and the rotor speed deviation($\Delta\omega$) to achieve positive damping torque to damp the system oscillation. This thesis shows that the Phase Compensation Method as compared with the Root Locus Method requires less computational work, has lower sensitivity to the precision of the models or the calculations and higher accuracy due to its use of actual system test data.

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LIST OF PRINCIPAL SYMBOLS

$C(S)$	Output function for a system in Laplace form
$C'(S)$	The preliminary output function for the system
$\Delta E_q'$	Air gap flux deviation
ΔE_{ref}	Voltage reference deviation
Δf	Ac bus frequency deviation
$G(j\omega)$	Frequency response function of a system
$G(S)$	Transfer function of a system in Laplace form
$G'(S)$	The preliminary transfer function of the system
$H(S)$	Transfer function of the stabilizer
K_s	Gain of power system stabilizer
ΔP	Electrical power deviation
P_m	Mechanical power
R_{ref}	Input reference
$R(S)$	Input function of a system in Laplace form
T_2, T_3, T_4	The stabilizer time constants
V_f	Field voltage
V_r	Output voltage of the voltage regulator amplifier
V_s	Stabilizer output voltage
$\Delta\omega$	Generator rotor speed deviation
$\Delta\delta$	Electrical power angle(deviation)
ω	Frequency radians/second
ω_n	Natural frequency of a system
μ	Frequency ratio ω/ω_n
ζ	Damping ratio

1. INTRODUCTION

1.1 The Power System and Steady-state Stability

Electricity is one of the most important elements in industrial, agricultural, educational and everyday lives. The need for electricity is increasing with the development of economy and standard of living. The number and locations of electrical generating plants must be chosen by considering the costs, the alternative sources of energy, load locations, system reliability, technical feasibility, etc. To meet the requirements for power over a widespread area, the transmission of electricity is needed. In general terms, to supply a large system reliably, it requires that several individual plants must work together to form an integrated electrical power system. This co-operation is developing between plants, regions and countries resulting in the large electrical power systems seen today.

In the operation of large dynamic systems, such as power systems, a requirement of fundamental importance is that the system must be stable. In power system operation an important aspect of stability of synchronous machines is the mode of small perturbation stability, referred to as "steady-state dynamic stability". This thesis deals with a particular aspect of this stability problem.

To place the problem of dynamic stability and the work presented in this thesis in context, the basic concepts of steady-state stability of an individual generator synchronized to a large system are reviewed briefly here. Figure 1.1a shows a simple system model in which V is the generator voltage, E is the infinite bus voltage which is considered to be constant and X_c is the sum of the impedances between the generator and the infinite bus. P_m is the mechanical power supplied to the generator.

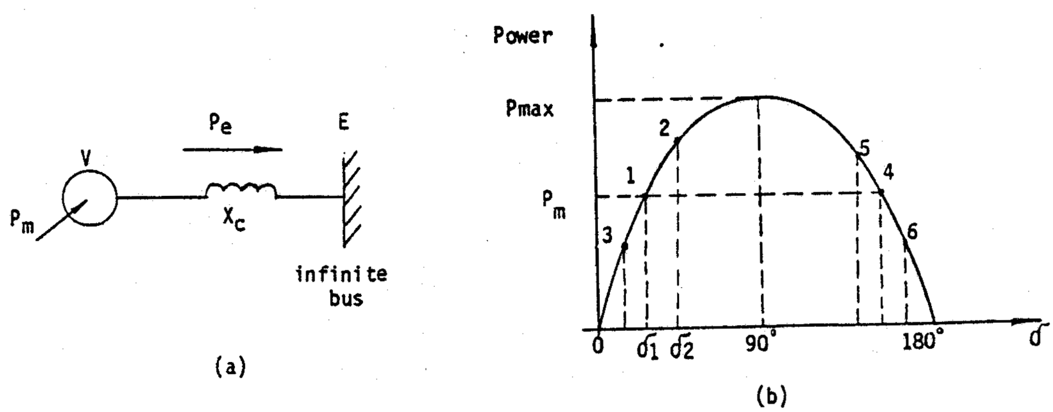


Figure 1.1 (a)A simple system model. (b)Power angle curve

The unbalanced torque on the rotor is:

$$T = T_m - T_e = \frac{P_m}{\omega} - \frac{P_e}{\omega} = T_j \frac{d\omega}{dt} \qquad (1.1)$$

where: T_m is the mechanical torque, T_e is the electrical torque and T_j is an inertia constant.

The transmitted electric power is:

$$P_e = \frac{EV}{X_c} \sin\delta$$

where δ is the angle of the generator rotor with respect to the infinite bus.

The corresponding power angle curve for this is shown in Figure 1.1b. When the system is stable, it works at point 1 in Figure 1.1b. The unbalanced torque T equals zero or in other words, the mechanical power input to the generator is equal to the electrical power the generator is generating and transferring to the infinite bus. The electrical power will go up(down) to the point 2(3) if a small disturbance causes a increase(decrease) in δ. Then the electrical power P_e will be increased(decreased) and the rotor speed will be decreased(increased) according to the equation (1.1). The rotor angle will be decreased(increased). Eventually the mechanical and electrical power will be rebalanced and the system will be back to point 1 after a certain time of oscillation. In this case, the system is said to be steady-state stable.

If the system is working at point 4 initially, the disturbance causes the δ to increase(decrease) and the electrical power goes down(up) to point 6(5). This will make the rotor speed increase and the electrical power even lower. In this case, the system is steady-state unstable.

1.2 Power System Stabilizer (PSS)

The Power System Stabilizer assists with the former(stable) case mentioned above. After the disturbance, a system oscillation occurs before it goes back to the steady-state again. This is caused by negative damping via modulation of the generator excitation. To reduce the oscillation in terms of its magnitude and duration is the main purpose of the PSS. This is also called the supplementary excitation control.

1.2.1 The principle of Power System Stabilizer

The Power System Stabilizer is used to introduce a supplementary stabilizing signal into the excitation system to increase the damping torque of the synchronous machine at the troublesome frequency. A functional block diagram of a synchronous machine with an exciter and stabilizer is shown in Figure 1.2. The major elements of power system stabilizer are shown in Figure 1.3[1].

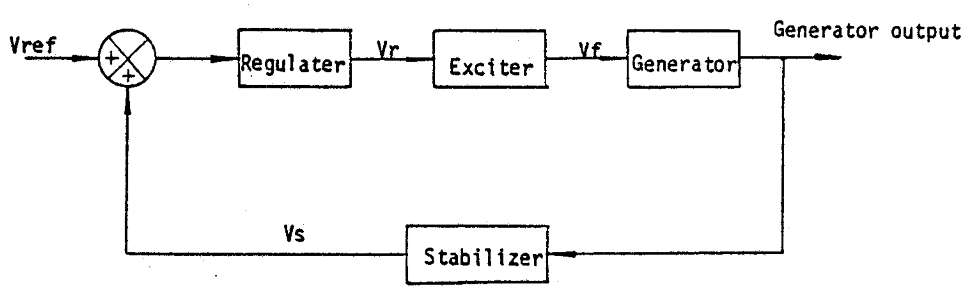


Figure 1.2 Functional block diagram of a synchronous machine with an exciter and stabilizer

The PSS acts as a feedback from the generator terminal to the input of the excitation system as shown in Figure 1.2 and 1.3. The overall effect of the PSS is to force the air gap flux of the generator to change in phase with rotor speed oscillation so that positive damping of speed oscillations occurs. The input of the PSS is the signal from

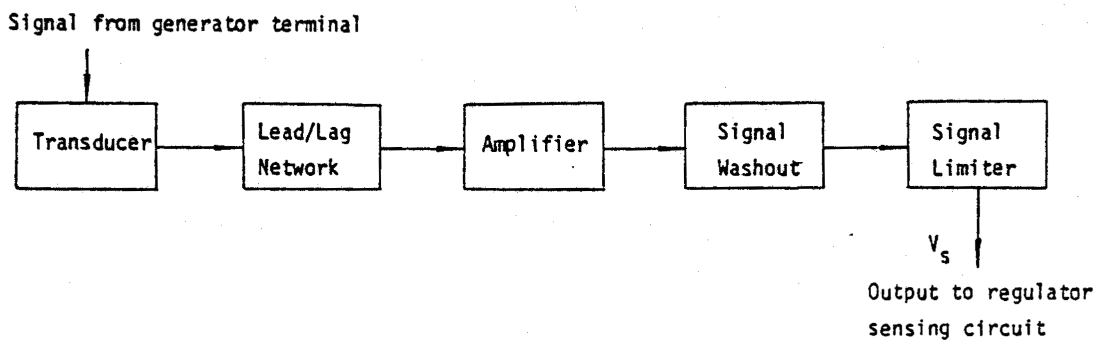


Figure 1.3 The major elements of PSS

the generator terminal. It can be shaft speed deviation($\Delta\omega$), ac bus frequency deviation(Δf) or accelerating power(ΔP). The transducer converts the signal to a control voltage. The transducer output is then phase-shifted by an adjustable lead-lag network which acts to compensate for time delays in the generator and excitation system thereby achieving the appropriate timing of the output for damping. The resulting signal is amplified to a desired level and sent through a signal wash-out module which acts as a high-pass filter to wash out the DC component and very low frequencies. It thus prevents the PSS from biasing the generator voltage for prolonged frequency or power excursions. The output limiter serves to prevent the stabilizer output signal from causing excessive voltage changes upon load rejection and to retain beneficial action of regulator forcing during severe system disturbances.

1.2.2 Variety of PSS's

For the purposes described above, there is a variety of power system stabilizers which have been studied in various systems. There are conventional, single input single output stabilizers, linear optimal and variable or optimal variable stabilizers. For various reasons, only the simpler, conventional single input single output types have been used in practice. The input of a power system stabilizer may be deviations in shaft speed($\Delta\omega$), generator electrical frequency(Δf), electrical power(ΔP_e), power angle($\Delta\delta$) or accelerating power(ΔP_a).

Although linear optimal and variable controller methods are very powerful mathematical techniques, they have not been justified in practical PSS applications because the successful application to power system stabilizers requires that constraints be imposed by power system nonlinearities and a limited number of practical feedback signals be included. So far, this has not been done successfully in units which have been proposed. The requirement of high reliability also emphasizes the need for simple controllers.

Now, the variety of power system stabilizers will be discussed briefly.

1.2.2.1 Linear optimal stabilizer

The design of the linear optimal stabilizer uses a time-domain technique which is based on the theory of the linear optimal regulator[6].

Optimal design techniques for stabilizers have been studied for more than ten years. The difficulties arise from the fact that dynamic stability depends upon the properties of the nonlinearized system at a given operating point. The necessary optimal parameter values of a stabilizer change in the course of a transient swing so that the control needed to optimally stabilize the system is disturbance dependent. For short circuits, for example, the location and duration of the fault will affect the control. It has been demonstrated that the type of fault matters and in certain cases, the optimal control designed for a three phase fault has an adverse effect for unbalanced faults.

A paper by Hsu Yuan-yin & Chan Wah-chun[6] describes a technique that has the potential of taking all the above difficulties into account: after a structure and approximate parameter values for the stabilizers have been obtained from a preliminary analysis of the linearized system. The literature does not indicate that this has been used in practice.

1.2.2.2 Optimal variable stabilizer

The optimal variable stabilizer is based on the variable structure system theory[6]. It is based on the development of linear optimal control theory. It is in the sense of minimizing a quadratic performance index as the operating state of the electrical power system changes. It has some advantages compared with the linear optimal stabilizer because it can operate at different operating points. It has not been applied practically because of its complexities.

1.2.2.3 Multivariable stabilizer

It is also demonstrated [20] that a multivariable stabilizer can be designed to provide auxiliary excitation damping for a multimachine plant. It is a centralized controller instead of the individual stabilizer for each machine. For each machine a number of terminal quantities (power, voltage, speed frequency, etc.) can be measured and fed back to the controller that calculates the control signals for all machines. By properly selecting the controller settings, all the modes of electromechanical oscillation can be made uniformly damped with the control effort shared in a predetermined way among the machines. The use of more than one measurement for each machine reduces or eliminates the undesirable effects of using only one signal. Again, in this case, this method has not yet been applied in practice.

1.2.2.4 Conventional stabilizer

As mentioned in Section 1.2, there are three possible PSS inputs which can be used in a conventional stabilizer(i.e. shaft speed, ac bus frequency and accelerating power). Each of these alteratives is considered in turn.

A power system stabilizer utilizing shaft speed as an input must compensate for the lags in the excitation system through which the PSS must operate to produce a component of torque in phase with speed changes. The stabilizer gain is very high for strong ac systems and decreases as the ac system becomes weaker. So without adaptive gain control, the speed input stabilizer gain can not be as high as designed under weak ac system conditions where the PSS contribution is needed most. Also the speed input signal may be affected by the choice of the position on the turbine/generator shaft where the measurement is made. This is due to shaft torsional effects.

The primary difference between a speed input PSS and a frequency input PSS is that in the former the sensitivity of the frequency signal to rotor oscillation increases as the external transmission system becomes weaker. In addition, the frequency signal is more sensitive to modes of oscillation between power plants or large areas than to modes involving only individual units; including those between units within a power plant. Consequently, it appears to be possible to obtain greater damping contribution for modes of oscillation between plants or areas than would be obtainable with the speed input stabilizer.

The use of accelerating power as an input signal to the power system stabilizer has received considerable attention due to its inherent low level of torsional interaction[14]. However, it must be recognized that a practical power stabilizer requires some compensating device for mechanical power variations(e.q. a heavily filtered speed signal). The most common approach to analyzing the power input PSS is to treat its input as the derivative of speed and apply the same concepts utilized in analyzing the speed input PSS.

1.3 Outline of the Thesis

This thesis deals with the application of a conventional power system stabilizer to an individual machine in a multimachine plant.

The Boundary Dam Plant of the Saskatchewan Power Corporation System was used as a working example to illustrate the various techniques employed. This system was simulated on the VAX computer using the PSDS[18] simulation program. Identification procedures were shown on the simulation to determine reduced order models of the system suitable for design of the PSS. Then the PSS units were designed to provide enhanced damping for troublesome oscillation frequencies in the system. The PSS designs were tested in the simulation for suitability.

In Chapter 1 of the thesis, the stability concept of the electrical power system is briefly reviewed and the principle of the Power System Stabilizer is described.

Chapter 2 presents the models of the Saskatchewan Power Corporation and particular the Boundary Dam Plant which was used in these studies.

In Chapter 3, the test method for determining the transfer function of the system is described in detail again by using the Boundary Dam Plant as an example. This is needed for designing the stabilizer(s) using the Root Locus method.

Chapter 4 represents respectively the design of stabilizer(s) by using two design methods, the Root Locus Method and the Phase Compensation Method.

Chapter 5 presents the conclusions for the thesis and Chapter 6 is the list of references. The last chapter(Chapter 7) is appendices which includes the Table

7.1(the system time response data for the input of U(t)=0.1) and two subroutine programs for the static exciter with transient gain reduction and the static exciter with auxiliary stabilizer which were developed by the author.

The most significant contributions of the work reported in this thesis is the demonstration of the use of the eigen-value and eigen-vector methods to show how different machines in a multimachine power plant interact at different oscillation frequency modes when an external system fault occurs. Also it is shown how to design the stabilizer(s) to damp the particular oscillating frequency within the plant. The design process is shown by using the Root Locus and Phase Compensation methods respectively.

2. SIMULATION OF THE BOUNDARY DAM POWER PLANT

2.1 Introduction

The main object of this project was to study the effects of putting a power system stabilizer on machines of a multi-machine plant. For this reason, it was necessary to use detailed models for the machines within the plant but less detailed or simpler models for parts of the system external to that plant.

For the purposes of this study, data for the Boundary Dam Power Plant and other parts of the Saskatchewan Power Corporation System were used.

In this chapter, the specific mathematical models(in block diagram form) are presented for the various components of the system studied. The block diagram form of presentation is convenient because information in this form is needed in the Power System Dynamic Simulation Program(PSDS) which was employed in the studies.

2.2 Description of the System

The single line diagram of a 30-bus model of the Saskatchewan Power Corporation(SPC) system is shown in Figure 2.1[16]. The system shown in Figure 2.1 shows nine generators and one synchronous condenser. Each generator shown in this figure actually represents a multi-machine group. Of particular importance in this study is the Boundary Dam Plant which is encircled by dotted lines in Figure 2.1.

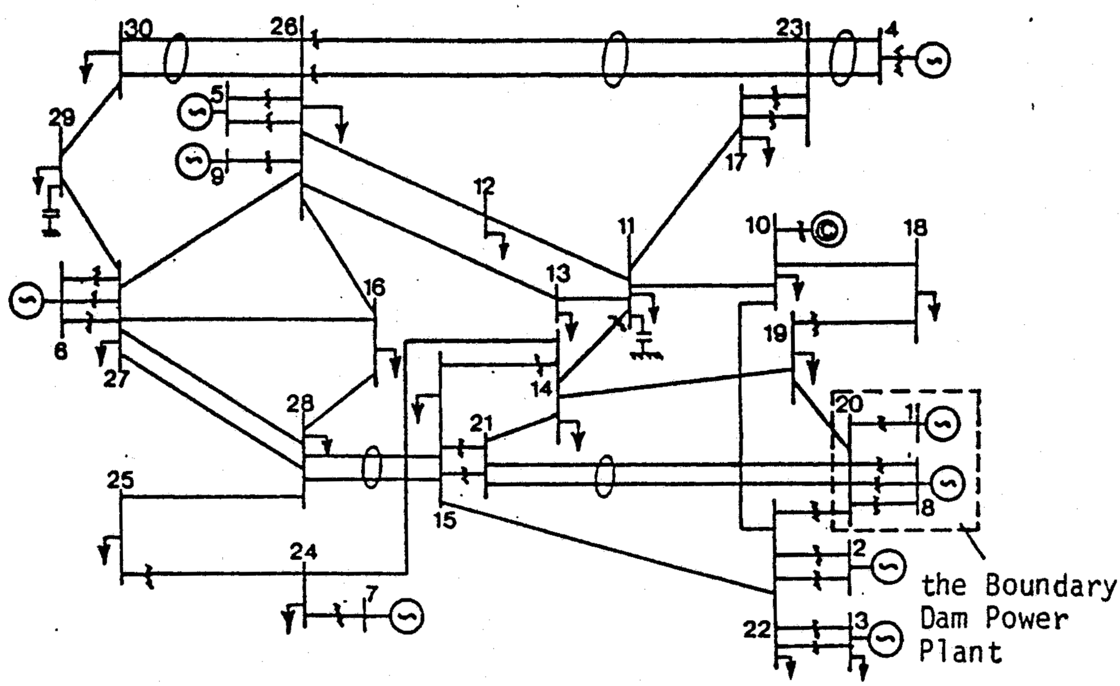


Figure 2.1 Single line diagram of a 30-bus model of the SPC system

The Boundary Dam Power Plant has six generators with a maximum total capacity of about 980 MVA at PF .85. Since the Boundary Dam Plant was of prime concern, it was represented in detail as shown in Figure 2.2. The remainder of the SPC system, external to the Boundary Dam Plant, was represented simply as an infinite bus identified as BD#7 in Figure 2.2. The values of external impedances Z_1 and Z_2 shown in Figure 2.2 were estimated from fault current levels supplied by SPC.

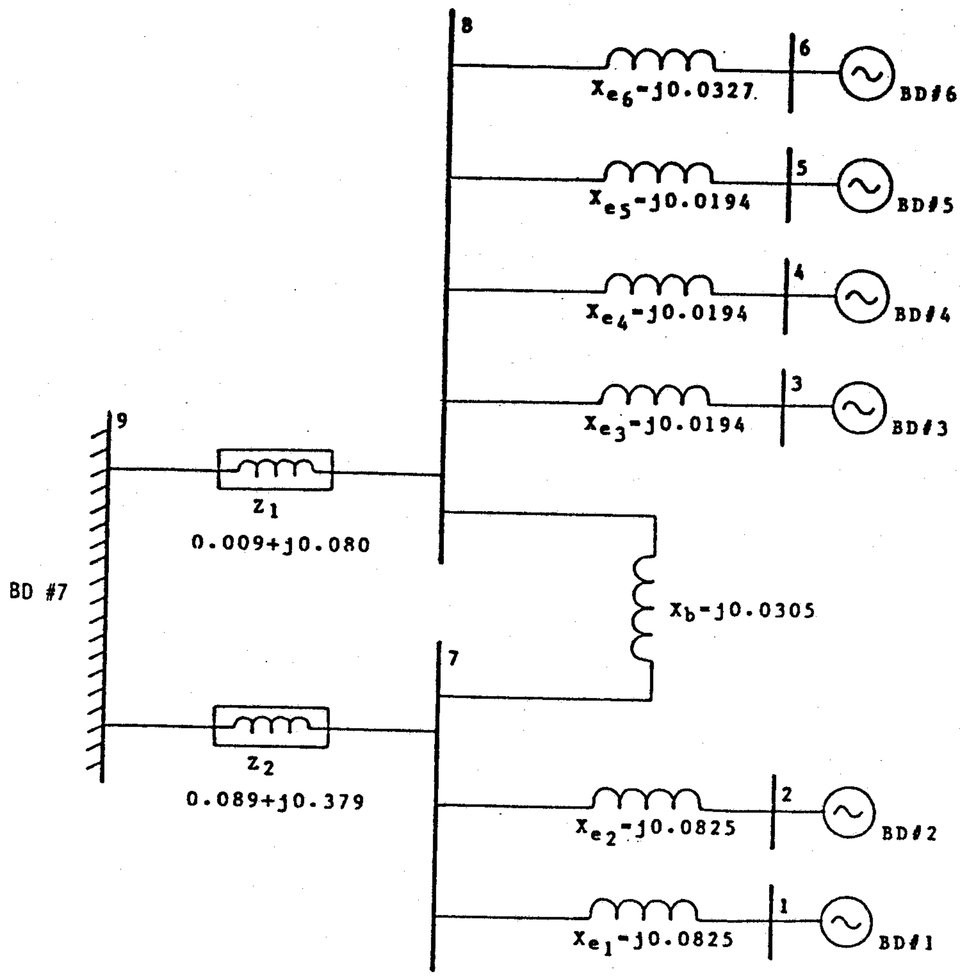


Figure 2.2 Plant infinite bus system

(Bus number 9 is the infinite bus)

2.3 Models of the Machines and Controllers

The block diagram form was used to represent the machines and controllers of the system. Analog-computer type diagrams were used to generate the digital computer statements to solve the model equations in the PSDS Program. In the following sections, these models are presented and described briefly. All of the models except that shown in Figure 2.7 were taken from the PSDS Program Manual[18]. The model in Figure 2.7 for a static exciter with an auxiliary stabilizer was developed by this author.

2.3.1 Models of generators

The synchronous generator model which was used in the simulation was based on the two-axis representation[18] of a machine with one d-axis field winding and a q-axis damper on the rotor. It has been shown[18] that such a machine model is sufficiently accurate for the study of power system stabilizer problems. The block diagram of the synchronous generator model is shown in Figure 2.3[18] and the values of the generator parameters are given in Table 2.1[16][18]. The inputs to this model are kE_f and P_m which are produced by excitation system and prime mover models, respectively. The output electrical variables V_{real} and Vimag go to the network part of the simulation.

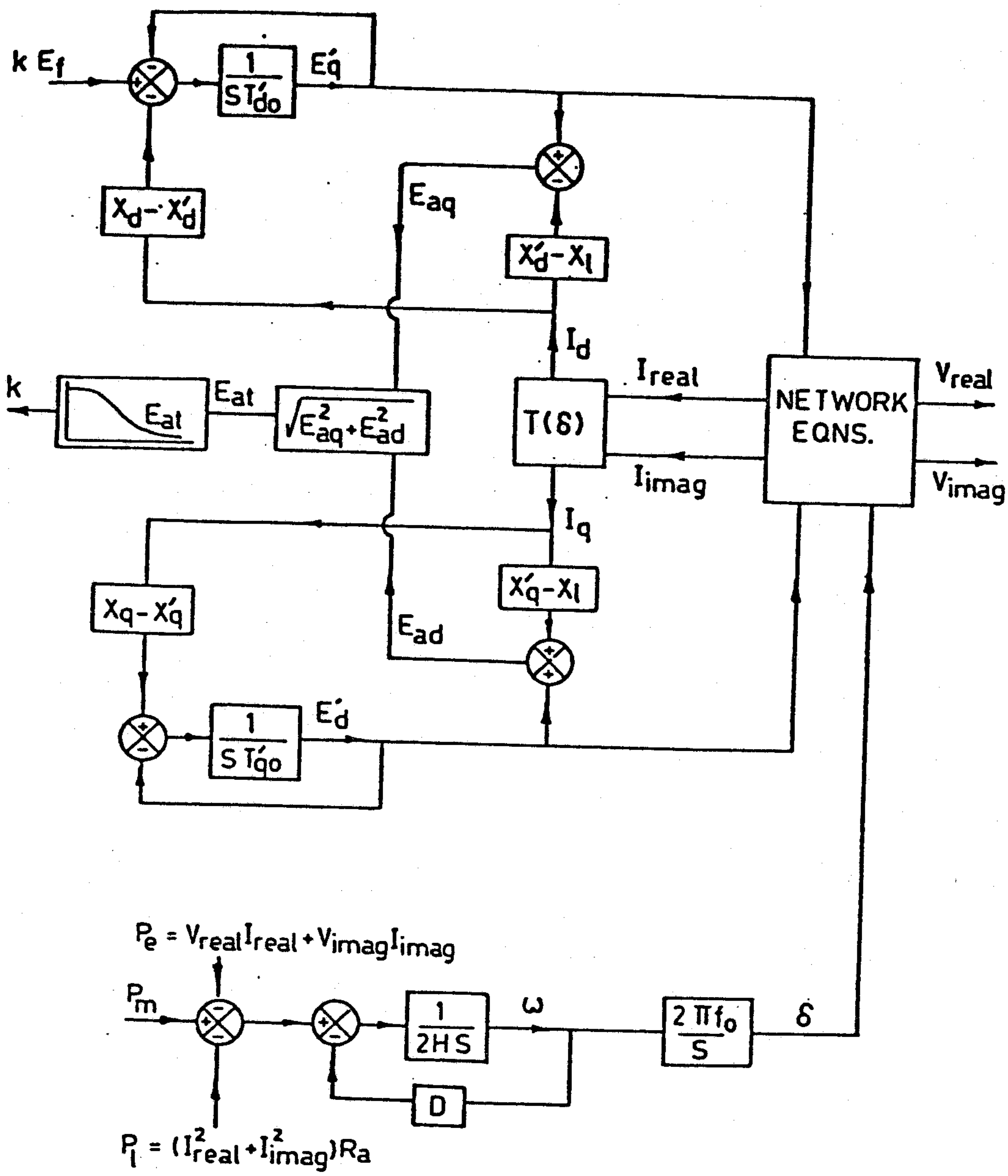


Figure 2.3 Synchronous generator model

Table 2.1

The generator parameters for the Boundary Dam Plant

	BD #1	BD #2	BD #3	BD #4	BD #5	BD #6	INF(#7)
P_{BASE}	100.0	100.0	100.0	100.0	100.0	100.0	100.0
H	4.28	4.28	4.30	4.30	4.30	10.35	1000.
R_A	.0015	.002	.002	.002	.002	.002	0.0
X_B	.0773	.0387	.066	.066	.064	.035	
X_1	.172	.141	.116	.116	.103	.063	0.0
X_2	.270	.297	.097	.097	.107	.076	
X_D	1.72	1.42	1.164	1.164	1.029	.625	.0001
X_Q	1.72	1.42	1.164	1.164	1.029	.625	.0001
X_D'	.296	.309	.146	.146	.124	.084	.0001
X_Q'	.296	.309	.146	.146	.124	.084	.0001
X_D''	.232	.245	.097	.097	.098	.073	
X_Q''	.232	.245	.1095		.093	.063	
T_{DO}'	5.70	5.00	3.84	3.84	3.84	6.86	1000.0
T_{QO}'	1.43	1.43	0.96	0.96	2.35	1.72	1000.0
T_{DO}''	0.03	0.03	.034	.034	0.02	.063	
T_{QO}''	0.03	0.03	.034	.034	0.02	.063	
D	4.0	4.0	8.0	8.0	8.0	10.0	0.0

2.3.2 Models of excitation system

In the Boundary Dam Power Plant several different types of excitation systems are used because the generators were supplied by different manufacturers at different times. The excitation systems of units #1 and #2 were represented as

IEEE Type 1 Rotating Excitation Systems. The block diagram and its equivalent analog diagram are shown in Figure 2.4[18]. The parameters for these units are given in Table 2.2[16].

The excitation systems of units #3, #4 and #6 are static exciters and are represented as IEEE Type 1s Static Excitation System Models as shown in Figure 2.5[18] with the parameters as given in Table 2.3[16].

The excitation system of unit #5 is a different type of static exciter and it is represented as an IEEE Type 1s excitation system model with transient gain reduction. This type is shown in Figure 2.6 with its parameters given in Table 2.4[16].

A new model of a static excitation system with an auxiliary stabilizer was developed by this author for the study of stabilization of the system. The block diagram and analog diagram of this exciter are shown in Figure 2.7 and its parameters are listed in Table 2.5.

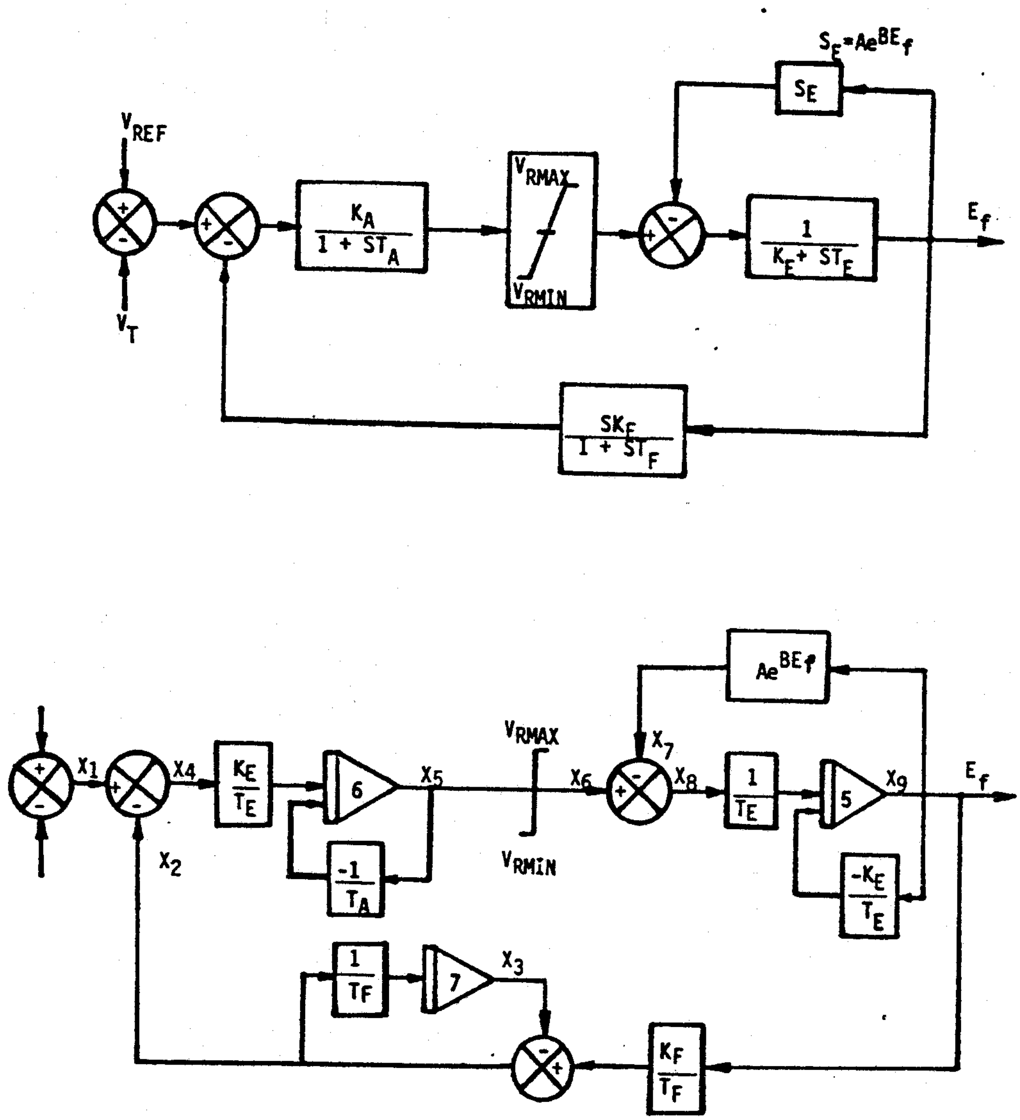


Figure 2.4 Block and analog diagram of IEEE type 1 rotating excitation system model

Table 2.2

The parameters of IEEE type 1 rotating excitation system model

	BD #1	BD #2
K_A	50	50
K_E	0.026	0.026
K_F	0.035	0.035
T_A	0.06	0.06
T_E	0.217	0.217
T_F	1.00	1.00
V_{RMIN}	-1.00	-1.00
V_{RMAX}	1.00	1.00
A	0.00007	0.00007
B	2.021	2.021

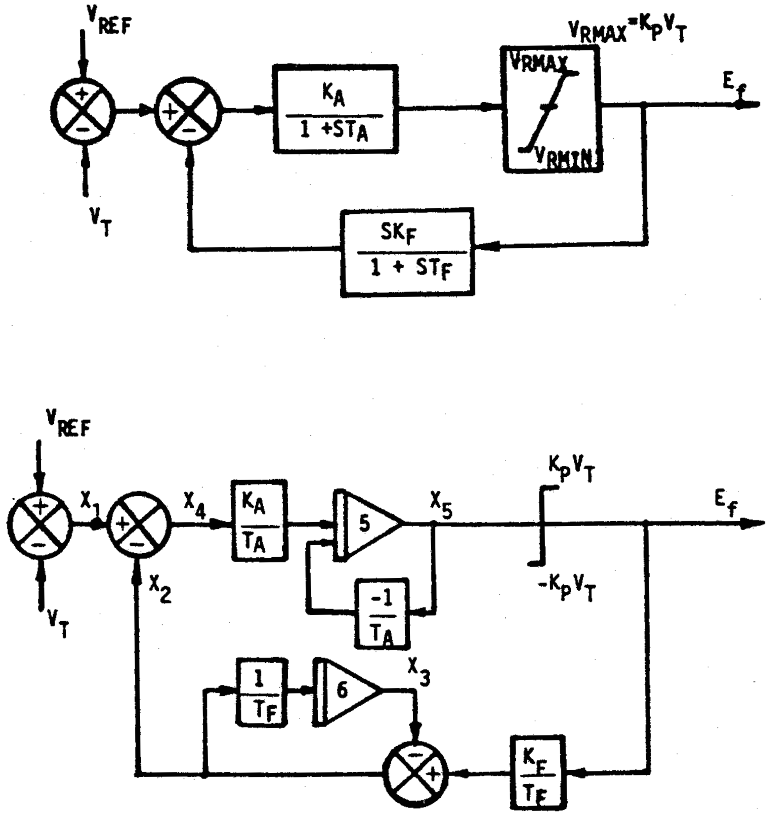


Figure 2.5 Block and analog diagram of IEEE type 1s static excitation system model

Table 2.3

The parameters of IEEE type 1s static excitation system model

	BD # 3	BD # 4	BD # 6
K_A	69.50	135.3	324.0
K_F	0.0	0.0	0.0
T_A	0.02	0.02	0.02
T_F	100000.	100000.	100000.
K_P	5.0	5.0	5.0

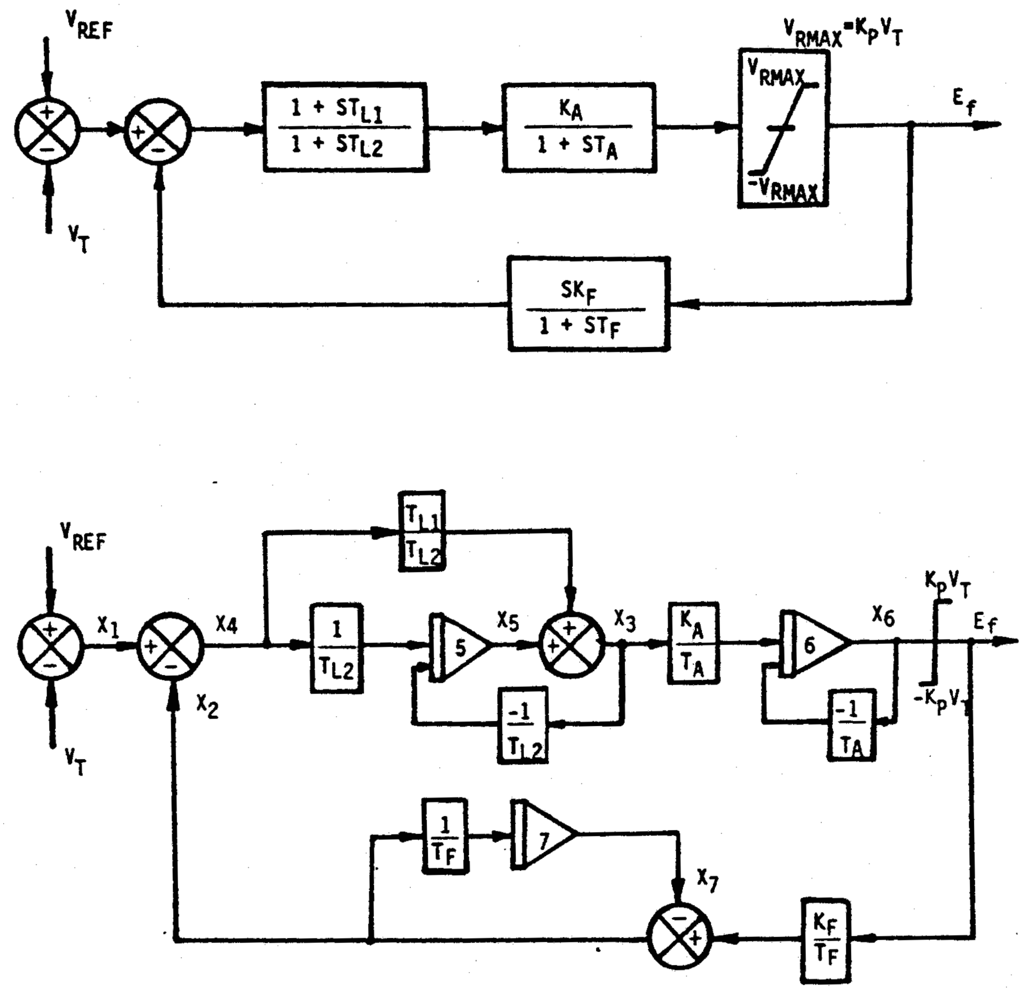


Figure 2.6 Block and analog diagram of IEEE type 1s static excitation system model with transient gain reduction

Table 2.4

The parameters of IEEE type 1s static excitation system model with transient gain reduction

	K_A	K_F	T_A	T_F	K_P	T_{L1}	T_{L2}
BD#5	921.1	0.0	0.05	100000.	5.0	0.415	1.33

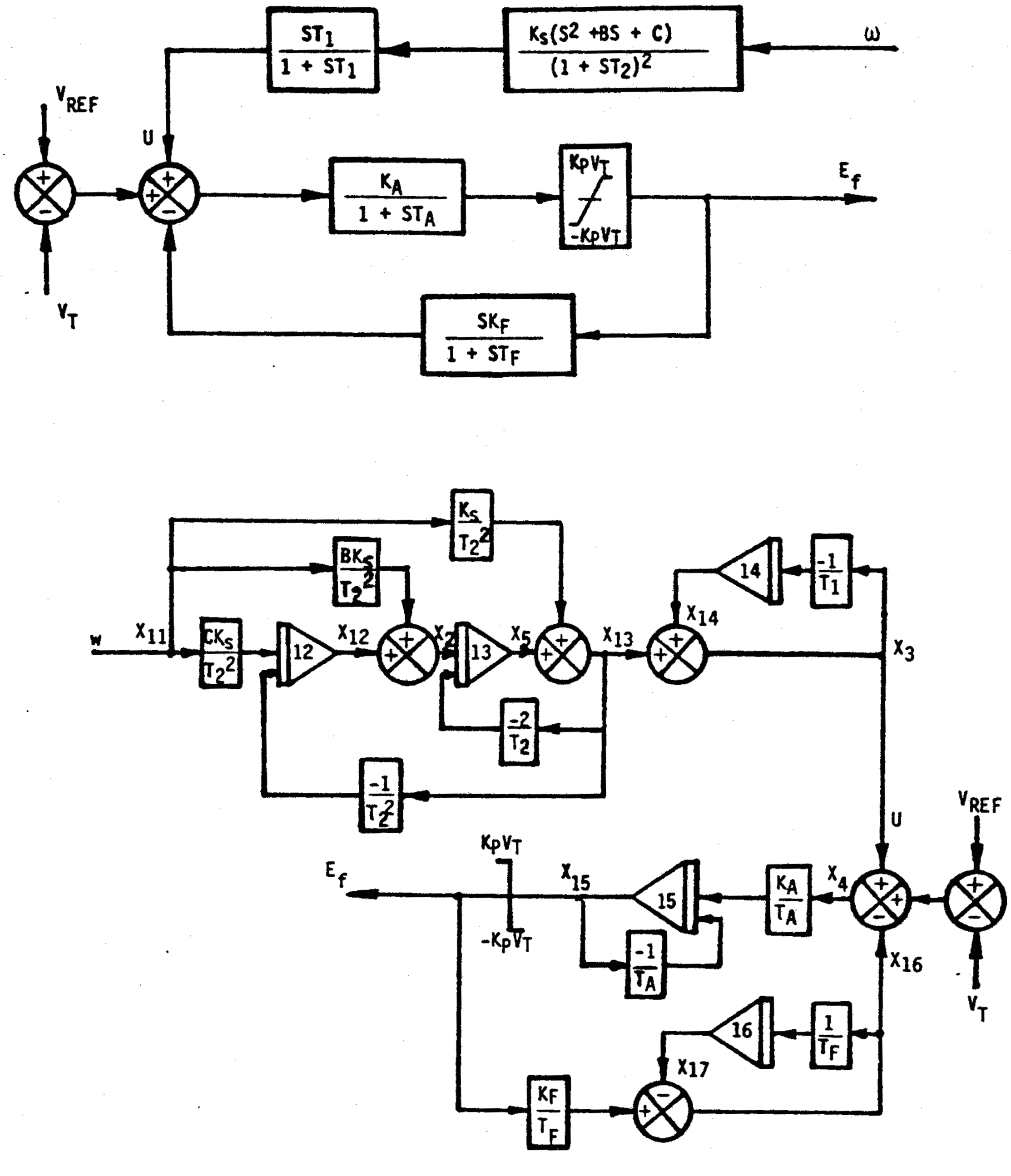


Figure 2.7 IEEE type 1s static excitation system with an auxiliary stabilizer model (block and analog diagram)

Table 2.5

	Value (BD #6)
K_A	324.0
K_F	0.0
T_A	0.02
T_F	100000.0
K_p	5.0
T_1	0.05
K_S	0.128
B	37.16
C	1.87
T_2	0.05

The parameters of IEEE type 1S static excitation system with an auxiliary stabilizer model

The numerical values of the excitation system parameters were determined by ADEC(Advanced Digital Engineering Corporation) from field tests on the Boundary Dam Plant units in June 1980[20].

The computer simulation subroutine programs which were developed by the author for the IEEE type 1s excitation system model with transient gain reduction and the static excitation system with an auxiliary stabilizer model are shown in appendices.

2.4 Conclusion

In this chapter a single line diagram of the Boundary Dam Power Plant is shown along with a 30-bus model of the SPC system. For the study of the damping in the Boundary Dam Plant, the SPC system external to the plant is represented as an infinite bus. The block diagrams and analog-computer type diagrams of the generator and its controllers with their parameters are also given in this chapter. These system diagrams and models of machine with their controllers were used in the studies described in the next and later chapters of this thesis.

3. TEST METHOD FOR OBTAINING TRANSFER FUNCTION OF THE SYSTEM

3.1 Introduction

One of the most important tasks in the system control design problem is to specify the transfer function of the system to be dealt with. In this chapter, the basic concepts of system identification are reviewed briefly and then it is shown how these methods were used in the specific problem of the Boundary Dam Power Plant.

There are basicly two ways of identifying a specific transfer function of a system, these are:

(1) the calculation method, which is to find the system transfer function by combining the models of all elements and the network of the system, provided these are all known. This method will become extremely difficult if the system is large, and

(2) the more practical method for many real large systems where the models of all components are not known, is the test method[15]. This is to derive the transfer function of the system from measured test data. This method is drawn from feedback control theory, and was chosen as the method of identifying the system for designing the power system stabilizer in this project. This method is not affected unduly by changing the system in complexity and size and can

be used in the actual system in the field and in a computer simulation of the system.

3.2 General Background

In this section, the general concepts of frequency response and impulse response techniques are reviewed briefly. These particular concepts are related to the methods employed in these studies, so they are presented here for reference.

3.2.1 Frequency response plots and Bode plot

The frequency response method uses the steady-state response of the system to a sinusoidal input signal. This response function plays a very important role in system control theory and practice.

A frequency response plot is a plot of the absolute magnitude and phase of the frequency response function versus the logarithm of the frequency. The Bode plot is a plot of the logarithm of magnitude versus the logarithm of the frequency(ω).

The transfer function G(S) of a system can be described in the frequency domain by replacing S with $j\omega$, and the frequency response function can be represented by a magnitude $G(j\omega)$ and a phase $ANG(j\omega)$ as:

$$G(j\omega)=|G(j\omega)|\ \underline{/ANG(j\omega)}$$

The logarithm of the magnitude is usually expressed in decibels (db) which is:

$$db=20\log_{10}|G(j\omega)|$$

In a Bode diagram, the plot of logarithmic gain in db versus $\log(\omega)$ is normally plotted on one axis and the phase $ANG(j\omega)$ versus $\log(\omega)$ on another axis, as shown in the following example.

Example: Consider the second order system:

$$G(S) = \frac{\omega_n^2}{S^2 + 2\zeta\omega_n S + \omega_n^2}$$

The Bode diagram for the second order system is shown in Figure 3.1. Note that at low frequency ($\mu < 0.1$), the amplitude approaches 0 db while the phase lag approaches 0^o. At high frequency($\mu > 10$), the amplitude decreases with a slope of -40db/decade while the phase approaches -180^o.

Bode diagrams of the type shown in Figure 3.1 were used in this study as a means of identifying unknown transfer functions from frequency response data. The frequency response data were determined from time response measurements taken on a simulation of the system under study.

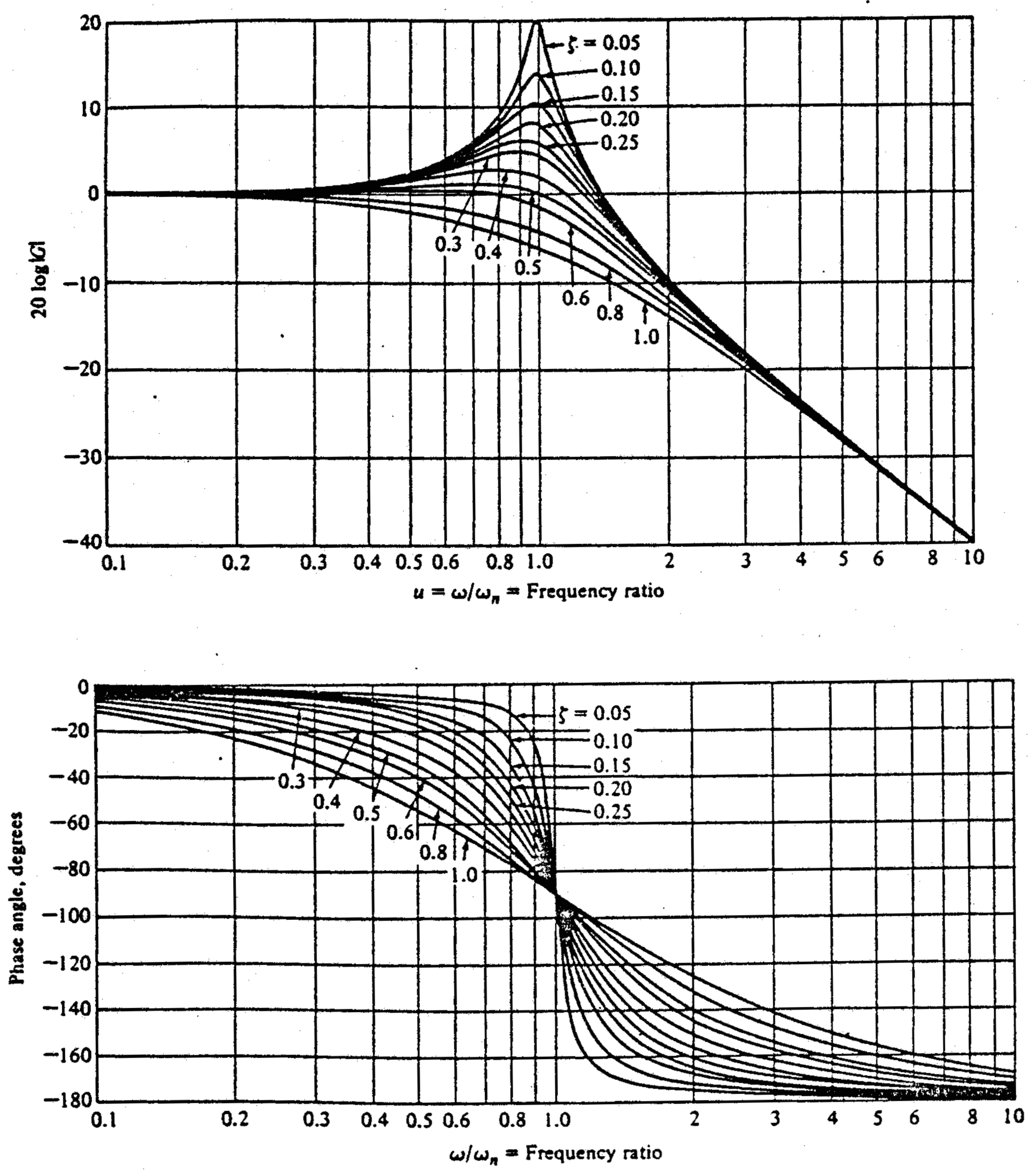


Figure 3.1 Bode diagram for a second order system

3.2.2 Impulse and sampling technique

The impulse function is a function which has a non-zero value only at a specific time instant. A unit impulse which occurs at time t_n in the time domain is written as $\delta(t-t_n)$. This is shown in Figure 3.2, where t_n means the placement in time of the impulse. In the figure, the impulse at t=0 is $\delta(t)$, at t=0.1 is $\delta(t-0.1)$, at t=0.2 is 0.66 $\delta(t-0.2)$, at t=0.3 is 0.5$\delta(t-0.3)$,etc.

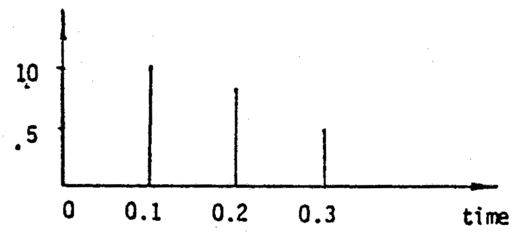


Figure 3.2 Arbitrary impulse train

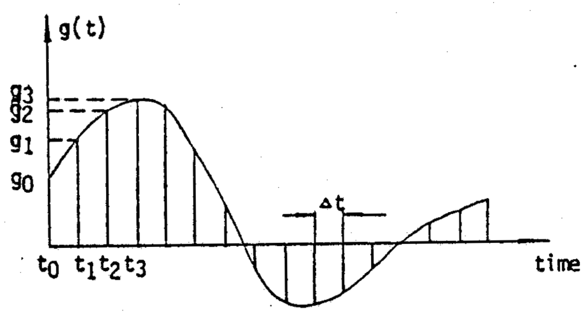


Figure 3.3 Approximation of a time function with impulses

A time function can be sampled and approximated with impulses as shown in Figure 3.3, where t is the sample time interval.

The function for the time response shown in Figure 3.3 in terms of impulse functions is:

$$g(t)=g_0\,\delta(t_0)+g_1\,\delta(t-t_1)+g_2\,\delta(t-t_2)+g_3\,\delta(t-t_3)+\ldots+g_n\,\delta(t-t_n) \quad (3.1)$$

The Laplace transformation of Equation 3.1 as

$$G(S)=g_0e^{-s}+g_1e^{-t_1s}+g_2e^{-t_2s}+g_3e^{-t_3s}+\ldots+g_ne^{-t_ns} . \qquad (3.2)$$

The Equation 3.2 can be written in compact form as:

$$G(S) = \sum_{n=0}^{k} g(t_n)e^{-t_nS} \qquad (3.3)$$

Where $n=0,1,2,3,\ldots,k$

It is to be noted that[15] a minimum sample rate of twice the highest frequency component is the theoretical limit for the representation of a particular frequency component in a signal. Practically, to recover the frequency components accurately, the sampling rate must be several times greater, 10 to 20 or more of the highest frequency component samples per cycle. This means that a great many samples must be taken which results in a large number of terms in the impulse function equation and excessive labor in calculation using such a function.

The triangular approximation method[19] is a modification of the impulse approximation method which is mentioned above. This method approximates the time function with a series of triangular pulses as shown in Figure 3.4. In the interval t_1 to t_2, the sum of two nonzero triangles is a straight line connecting the points on the time response function $g(t)$ at t_1 and t_2. Thus, a series of triangles can approximate the time function $g(t)$. The transform for the whole time function is the sum of the transforms for all of the triangular pulses used.

The Fourier transform for a single triangular pulse centered at t=0 as shown in Figure 3.5 is $g(t_n)\Delta t[\frac{\sin(\omega t/2)}{\omega t/2}]^2$. Therefore, the general expression for

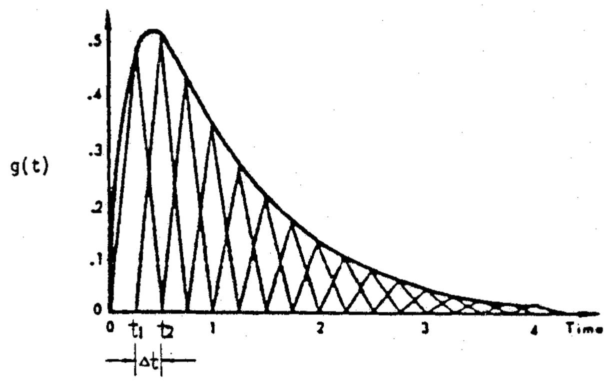


Figure 3.4 Triangular approximation of a time function

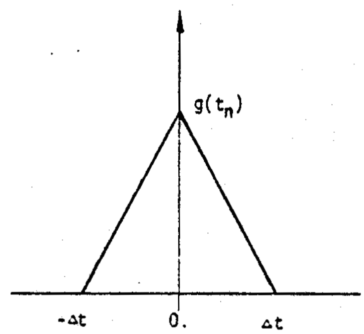


Figure 3.5 A single triangular pulse centered at t=0.

the triangular approximation for a time response function g(t) can be obtained by substituting $g(t_n)\Delta t[\frac{\sin(\omega t/2)}{\omega t/2}]^2$ for $g(t_n)$ in equation (3.3) giving:

$$G(S) = \sum_{n=0}^{k} g(t_n)\Delta t[\frac{\sin(\omega t/2)}{\omega t/2}]^2 e^{-t_n S} \qquad (3.4)$$

Where: n=0,1,2,3,...,k

This expression was used for this project to obtain the Bode diagrams from time functions obtained from the system simulation.

Comparing the triangular approximation method with the impulse approximation method, it was found that the former is more satisfactory for the purpose of this study. The triangular approximation method improves the accuracy with fewer terms in the resulting equations. Figure 3.6a shows the effective approximation of a time function with triangles, and Figure 3.6b shows the effective approximation of a time function by impulses. This shows the improvement of using triangular approximation.

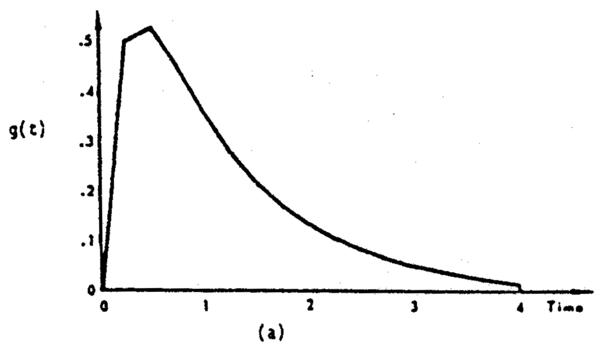


Figure 3.6a The effective approximation of g(t) with triangles

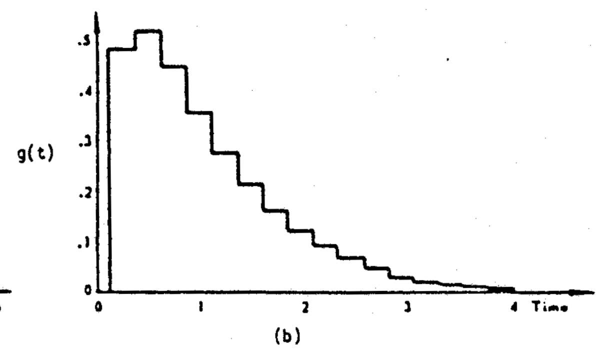


Figure 3.6b The effective approximation of g(t) by impulses

3.2.3 Determination of transfer function from frequency response data

In section 3.2.2 it was indicated how to get a Laplace transform from a time equation, i.e. from equation (3.1) find equation (3.2). The frequency function can be obtained by simply substituting $S=j\omega$. The frequency response function corresponding t_0 the Laplace function in equation (3.2) is given by:

$$G(j\omega)=g_0e^{-j\omega}+g_1e^{-t_1j\omega}+g_2e^{-t_2j\omega}+g_3e^{-t_3j\omega}+\ldots+g_ne^{-t_nj\omega} \qquad (3.5)$$

The Fourier transform for (3.5) is given by:

$$G(j\omega) = \sum_{n=0}^{k} g(t_n)e^{-t_nj\omega} \qquad (3.6)$$

Where: $n=0,1,2,3,\ldots,k$

For plotting purposes, it is more convenient to use the rectangular form of the equation. This can be obtained using:

$$e^{-jn\omega\Delta t} = \cos(n\omega\Delta t) - j\sin(n\omega\Delta t)$$

The general form of the Fourier transfer function $G(j\omega)$ in rectangular form is then:

$$G(j\omega) = \sum_{n=0}^{k} g(t_n)[\cos(n\omega\Delta t) - j\sin(n\omega\Delta t)] \qquad (3.7)$$

Where: $n=0,1,2,3,\ldots,k$

$g(t_n)$ is the amplitude of $g(t)$ at $t=t_n=n\Delta t$

The Fourier transform for the triangular pulses which is expressed by equation 3.4 is given by:

$$G(j\omega) = \sum_{n=0}^{k} g(t_n)\ t\left[\frac{\sin(\omega\Delta t/2)}{\omega\Delta t/2}\right]^2 [\cos(n\omega\Delta t) - j\sin(n\omega\Delta t)] \quad (3.8)$$

The Bode diagram can be obtained by calculating the different values of the equation (3.8) over a range of frequencies of interest. Using the Bode diagram and doing the inverse work of approximating the plot with straight lines one obtains the transfer function in Laplace form[15]. After a sufficiently close approximation is obtained, the transfer function equation can be written in factored form.

It should be noted that the Bode straight line approximation is only applicable to linear, minimum phase systems. Fortunately this is the case for the systems studied in this project.

3.2.4 Determination of transfer function from time domain data

Unlike the frequency response method for the determination of a transfer function, the time domain method is not straight forward and there is no general method to follow. In fact, the time domain method is to use the impulse and sampling technique to find the frequency response Bode diagram, i.e. translate from time domain to frequency domain for identification and design, then back to the time domain for checking specific results.

3.3 Steps for Determination of Transfer Function of the Boundary Dam Plant

The Boundary Dam Power Plant of the Saskatchewan Power Corporation was used as an example for study in this specific project. As it was described in Chapter 2, the Boundary Dam Power Plant was modeled as a six-machine plant connected with an infinite bus(external system). A computer simulation of the system was used for this project study.

The actual steps involved in the determination of the transfer function of a system from time response data are listed here.

Step I, obtaining test data for system identification.

Step II, obtaining the system Bode diagram from the test data.

Step III, determining the approximate output function C'(S) from Bode plot.

Step IV, checking C'(S) in the frequency-domain and determining a more accurate system output function C(S) to be used in subsequent calculations.

Step V, obtaining the approximate transfer function G'(S) for the system.

Step VI, checking the G'(S) in time-domain and determining a more accurate system transfer function G(S)

These steps are explained in detail in the following section.

3.3.1 Obtaining test data for system identification

In this section, the methods used to identify the system transfer function are explained. The simulation of the specific situation at the Boundary Dam Plant of the Saskatchewan Power Corporation is used as an example to illustrate this method. The details of the situation are presented in Chapter 4.

It is assumed for the purpose of this study that a PSS is required on the Boundary Dam Unit #6 to overcome an oscillation of about 8 radians/second. A speed input stabilizer is assumed.

To identify the actual transfer function upon which the PSS will act, it is necessary to test the simulated system by putting an input disturbance into the exciter of Unit #6 and measuring the output speed changes($\Delta\omega$) of that unit. Any input disturbance function could be used but a step is the most convenient in the PSDS simulation and that was used. Figure 3.7 shows the output($\Delta\omega$) response of Unit #6 for a U(t)=0.1 step in the input of the exciter of that unit. For this simulation the digital step sign used was .001 seconds.

It can be seen from Figure 3.7 that the highest frequency of the output function is about 1.3 HZ(8 r/s). To meet the accuracy required for identification purposes, 31 samples/per cycle was chosen(i.e. 40 samples/sec. or Δt=0.025 sec.) for the sampling rate of the problem. 12.8 seconds of record was sampled.

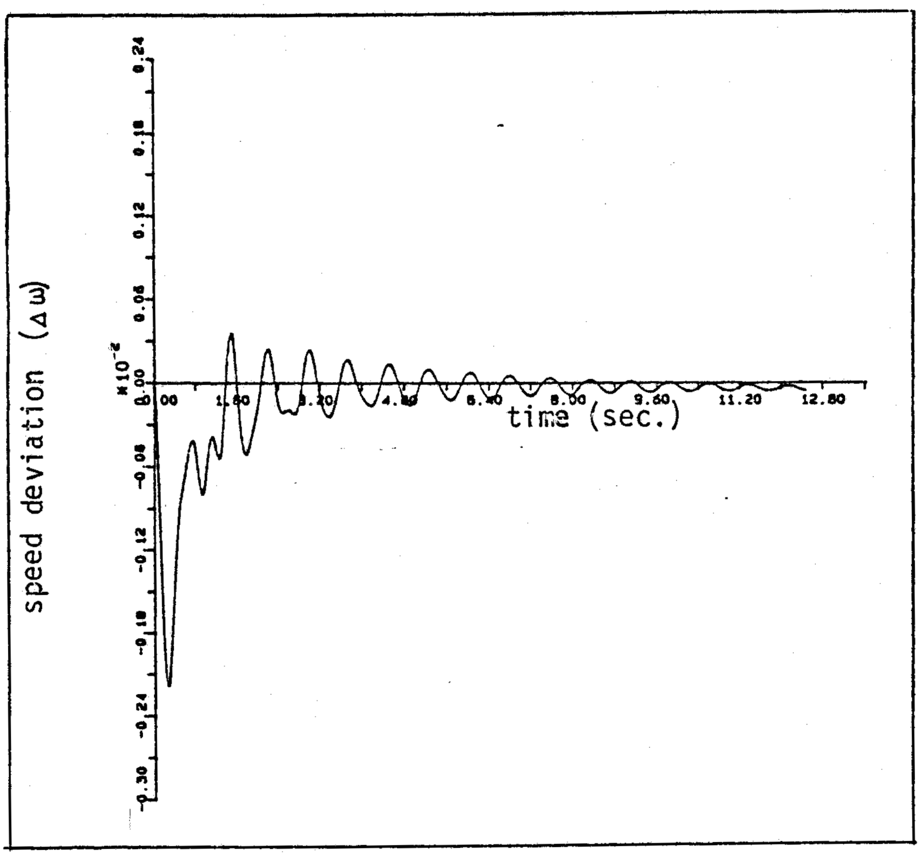


Figure 3.7 System time response for the input of U(t)=0.1

After the sampling, it was necessary to go to the next step of obtaining the Bode diagram of the tested system. This is described in the following section.

3.3.2 Obtaining the system Bode diagram from the test data

This step, in fact, is the process of translating from time domain to frequency domain for design(see 3.2.4).

The output(Figure 3.7) in general Laplace form:

$$C(S) = \sum_{n=0}^{400} g(t_n)e^{-t_n s}$$

The discrete values of $g(t_n)$ are given in Table 3.1.

This function written in Fourier transform form by substituting $S=j\omega$, is given by (3.9):

$$C(j\omega)=\sum_{n=0}^{400} g(t_n)\Delta t\left[\frac{\sin(\omega\Delta t/2)}{\omega\Delta t/2}\right]^2[\cos(n\omega\Delta t) - j\sin(n\omega\Delta t)] \quad (3.9)$$

The frequency was varied from 0.01 HZ to 1000 HZ in equation (3.9) to get the Bode diagram of the system output function corresponding to the step function input $U(t)=0.1$. The Bode diagram so obtained is shown in Figure 3.8. The data for discrete frequency values are shown in Table 3.2. It is to be noted that the sampling frequency used to obtain data from the time response(Figure 3.7) was 40 samples/second; therefore the frequency data shown in Figure 3.8 is actually meaningless above 20 HZ(or 125 rads/sec).

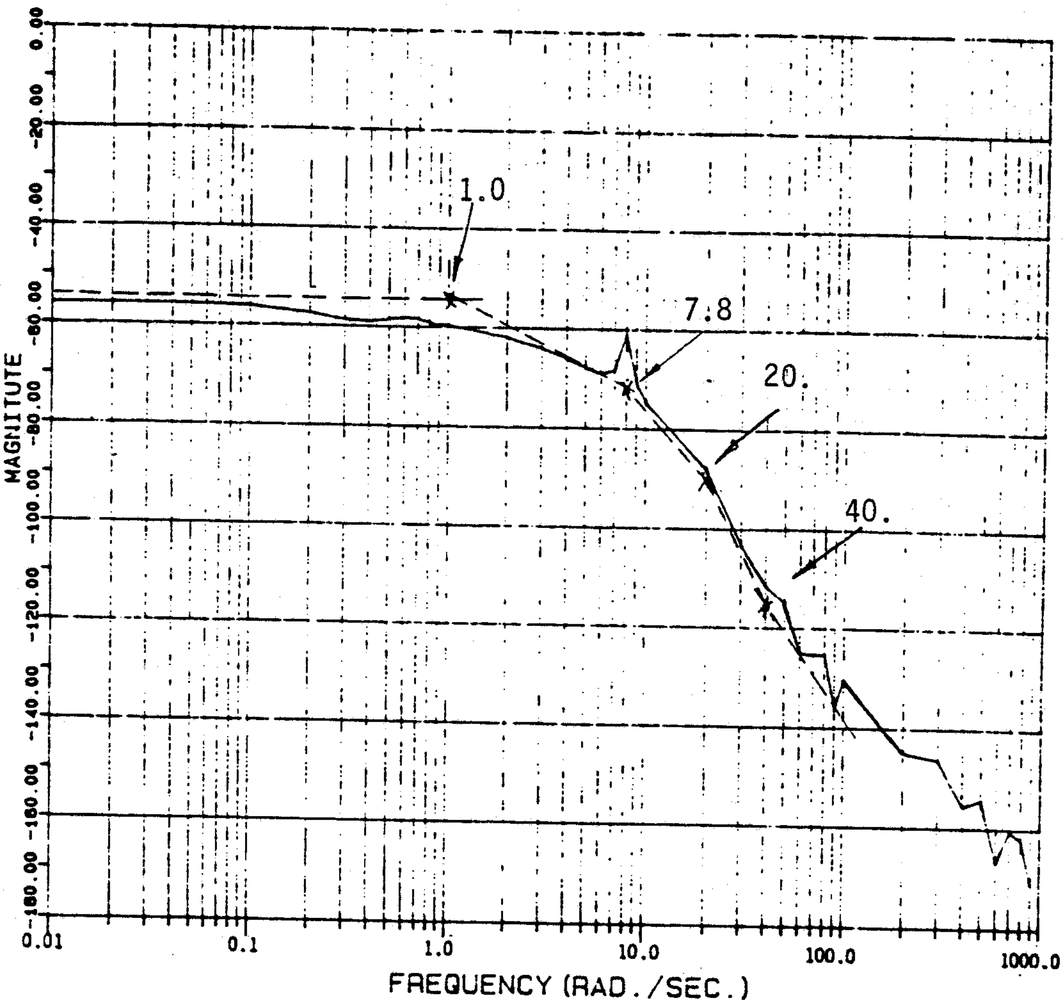


Figure 3.8 Bode diagram of the system for input of U(t)=0.1

Table 3.2

System frequency response data calculated from the time response data shown graphically in Figure 3.7

FREQ.(RAD)	REAL PART	IMAG. PART	MAGNITUTE(dB)	PHESE (DEG.)
0.0100	-0.0016	0.0000	-55.9117	178.7406
0.0200	-0.0016	0.0001	-55.9260	177.4852
0.0300	-0.0016	0.0001	-55.9499	176.2379
0.0400	-0.0016	0.0001	-55.9831	175.0027
0.0500	-0.0016	0.0002	-56.0258	173.7837
0.0600	-0.0016	0.0002	-56.0776	172.5851
0.0700	-0.0015	0.0002	-56.1386	171.4110
0.0800	-0.0015	0.0003	-56.2084	170.2657
0.0900	-0.0015	0.0003	-56.2869	169.1534
0.1000	-0.0015	0.0003	-56.3737	168.0784
0.2000	-0.0012	0.0004	-57.6023	160.3364
0.3000	-0.0011	0.0004	-58.8619	160.0409
0.4000	-0.0011	0.0003	-59.0769	163.6266
0.5000	-0.0011	0.0004	-58.4965	162.6627
0.6000	-0.0011	0.0005	-58.1815	156.6195
0.7000	-0.0010	0.0006	-58.5192	149.8664
0.8000	-0.0009	0.0006	-59.2429	146.2045
0.9000	-0.0009	0.0006	-59.7149	146.0262
1.0000	-0.0009	0.0006	-59.6567	145.3880
2.0000	-0.0004	0.0007	-62.0323	122.6588
3.0000	-0.0002	0.0006	-64.0893	106.4662
4.0000	0.0000	0.0005	-66.0324	93.8123
5.0000	0.0000	0.0004	-67.8968	85.8256
6.0000	0.0000	0.0003	-69.1303	84.8983
7.0000	0.0000	0.0004	-68.0951	89.0833
8.0000	0.0003	0.0008	-60.9154	68.2994
9.0000	0.0003	0.0000	-70.7925	-8.8501
10.0000	0.0002	0.0001	-74.8540	23.0921
20.0000	0.0000	0.0000	-88.1162	-114.4752
30.0000	0.0000	0.0000	-103.1574	-85.2167
40.0000	0.0000	0.0000	-111.5279	-85.8467
50.0000	0.0000	0.0000	-114.8956	-92.2803
60.0000	0.0000	0.0000	-125.0179	-135.3057
70.0000	0.0000	0.0000	-125.4282	-50.2103
80.0000	0.0000	0.0000	-125.1782	-124.6291
90.0000	0.0000	0.0000	-136.2529	85.3428
100.0000	0.0000	0.0000	-130.2089	-72.3304
200.0000	0.0000	0.0000	-145.0528	59.8891
300.0000	0.0000	0.0000	-146.3687	-119.2006
400.0000	0.0000	0.0000	-155.8237	-168.5028
500.0000	0.0000	0.0000	-154.0981	-110.4562
600.0000	0.0000	0.0000	-166.9139	98.3255
700.0000	0.0000	0.0000	-160.2943	97.9679
800.0000	0.0000	0.0000	-162.3147	-71.0801
899.9999	0.0000	0.0000	-171.1640	13.7601

3.3.3 Determining the Laplace function of system output from Bode plot

The purpose of this step was to use the straight line approximation approach on the Bode diagram to find each ot the factors of the system output function(see the description in 3.2.3). The straight lines slops 0, -20, -40, etc. db/decade are these approximations.

The first approximation to the output function(in Laplace form) for the output of the system has been found to be:

$$C'(S)=\frac{0.049(S+40)}{(S+1)(S^2+2.5S+61.15)(S+20)} \qquad (3.10)$$

The actual sign of equation 3.10 could not be determined from the frequency response tests. It was found subsequently in time response test (see Section 3.3.6) that the sign of the C'(S) function should be negative.

3.3.4 Checking the approximate results in the frequency-domain and determining the final system output function C(S)

The function in (3.10) above was checked in the frequency domain first and it was found that it did not match the original one(Figure 3.8) very well. Adjustments were made using the process described in Section 3.3.3 to determine an adjusted output function.

This adjusted output function of the system for the input U(t)=0.1 is then as given by (3.11):

$$C(S)=\frac{0.045(S+40)}{(S+1)(S^2+1.1S+61.15)(S+20)} \tag{3.11}$$

The output response Bode diagram calculated from (3.11) is shown in Figure 3.9 and its data is shown in Table 3.3.

Comparing these with Figure 3.8 and Table 3.2, it is seen that the results are well matched.

3.3.5 Obtaining the preliminary transfer function G'(S)

So far, only the system output function has been dealt with. To find the transfer function of the system, it is necessary to consider the input function as well.

Since in Laplace form the transfer function of the system G(S) can be obtained by the equation:

$$G(S)= C(S)/R(S)$$

where C(S) is output function of system in Laplace form

and R(S) is input function of system in Laplace form.

The R(S) for this problem is: $R(S)= \frac{0.1}{S}$

So, the G(S) is: $G(S)= 10SC(S)$

$$G'(S)=\frac{0.49S(S+40)}{(S+1)(S^2+2.5S+61.15)(S+20)} \tag{3.12}$$

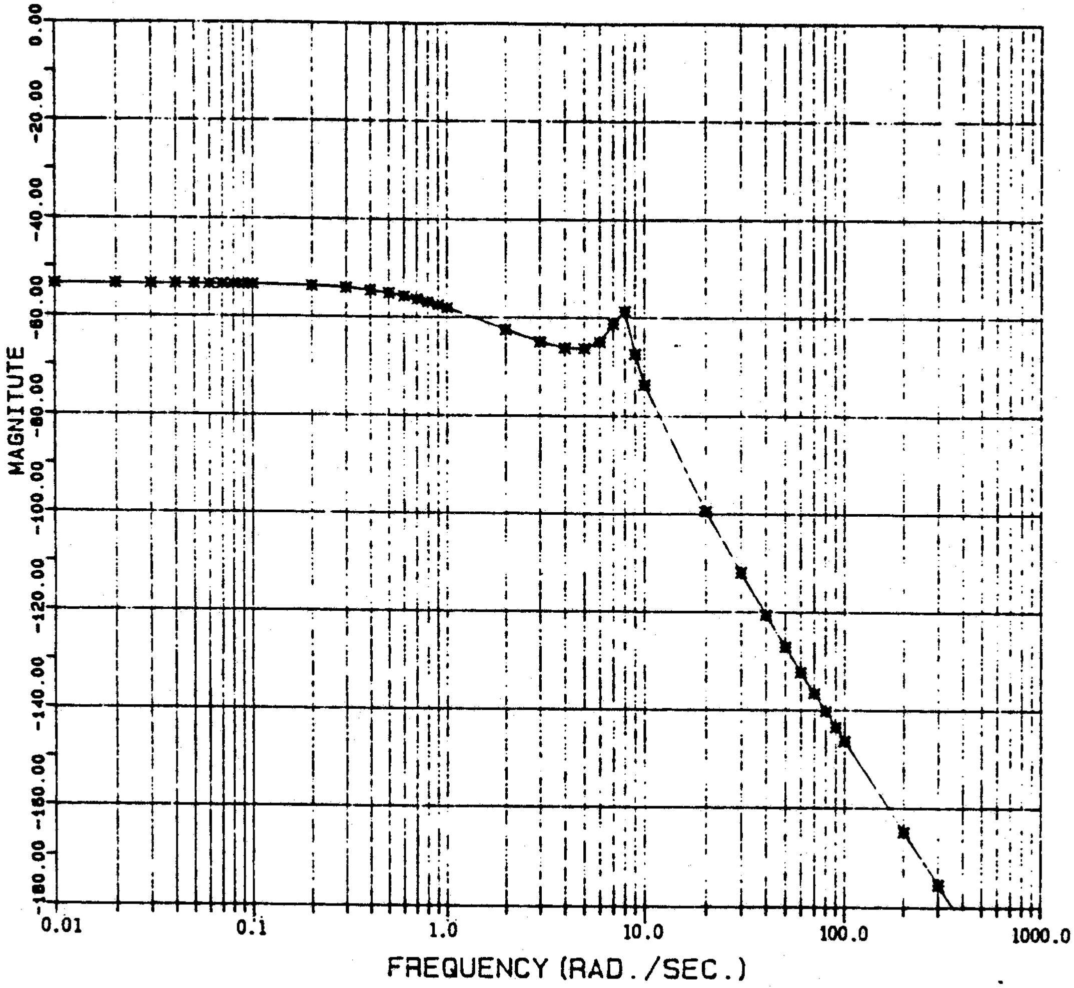


Figure 3.9 Bode diagram of the system output C(S)

Table 3.3

Frequency response data(plotted in Figure 3.9) of the system output C(S)

```
FREQUENCY RESPONSE
PROBLEM IDENTIFICATION -
*******************************************

GAIN =  4.500000E-02

NUMERATOR COEFFICIENTS - IN ASCENDING POWERS OF S

4.000000E+01 1.000000E+00

NUMERATOR ROOTS ARE
  REAL PART         IMAG. PART
-4.000000E+01 0.000000E+00
DENOMINATOR COEFFICIENTS - IN ASCENDING POWERS OF S

8.559951E+02 1.281050E+03 9.791251E+01 2.180000E+01 1.000000E+00

DENOMINATOR ROOTS ARE
  REAL PART         IMAG. PART
-7.000000E-01 0.000000E+00
-5.500000E-01 7.800000E+00
-5.500000E-01-7.800000E+00
-2.000000E+01 0.000000E+00

*******************************************
```

RADIAN FREQ.	REAL PART	IMAGINAL PART	MAGNITUDE	PHASE (DEG)
1.000000E-02	2.102377E-03	-3.093797E-05	-5.354485E+01	-8.430876E-01
2.000000E-02	2.101061E-03	-6.183837E-05	-5.354747E+01	-1.685842E+00
3.000000E-02	2.098872E-03	-9.266374E-05	-5.355183E+01	-2.527928E+00
4.000000E-02	2.095814E-03	-1.233770E-04	-5.355792E+01	-3.369017E+00
5.000000E-02	2.091896E-03	-1.539414E-04	-5.356575E+01	-4.208779E+00
6.000000E-02	2.087126E-03	-1.843210E-04	-5.357529E+01	-5.046888E+00
7.000000E-02	2.081516E-03	-2.144803E-04	-5.358654E+01	-5.883023E+00
8.000000E-02	2.075079E-03	-2.443850E-04	-5.359948E+01	-6.716866E+00
9.000000E-02	2.067832E-03	-2.740015E-04	-5.361411E+01	-7.548105E+00
1.000000E-01	2.059789E-03	-3.032976E-04	-5.363039E+01	-8.376437E+00
2.000000E-01	1.940448E-03	-5.725092E-04	-5.387947E+01	-1.643816E+01
3.000000E-01	1.768974E-03	-7.853031E-04	-5.426436E+01	-2.393795E+01
4.000000E-01	1.573215E-03	-9.352617E-04	-5.474992E+01	-3.073111E+01
5.000000E-01	1.375922E-03	-1.028240E-03	-5.530114E+01	-3.677113E+01
6.000000E-01	1.191496E-03	-1.075935E-03	-5.588835E+01	-4.208241E+01
7.000000E-01	1.026880E-03	-1.090816E-03	-5.648907E+01	-4.672932E+01
8.000000E-01	8.839612E-04	-1.083543E-03	-5.708753E+01	-5.079223E+01
9.000000E-01	7.618095E-04	-1.062232E-03	-5.767337E+01	-5.435276E+01
1.000000E+00	6.582192E-04	-1.032644E-03	-5.824023E+01	-5.748612E+01
2.000000E+00	1.819863E-04	-7.172526E-04	-6.261560E+01	-7.576299E+01
3.000000E+00	5.094499E-05	-5.521987E-04	-6.512128E+01	-8.472893E+01
4.000000E+00	-1.042150E-05	-4.814327E-04	-6.634726E+01	-9.124010E+01
5.000000E+00	-6.300280E-05	-4.725463E-04	-6.643459E+01	-9.759426E+01
6.000000E+00	-1.550865E-04	-5.330276E-04	-6.511209E+01	-1.062226E+02
7.000000E+00	-5.015408E-04	-6.894645E-04	-6.138523E+01	-1.260335E+02
8.000000E+00	-1.051954E-03	4.569711E-04	-5.880933E+01	1.565198E+02
9.000000E+00	-1.394967E-04	3.961515E-04	-6.753513E+01	1.093987E+02
1.000000E+01	-2.597768E-05	2.033105E-04	-7.376648E+01	9.728145E+01
2.000000E+01	2.304649E-06	1.021344E-05	-9.960088E+01	7.728427E+01
3.000000E+01	6.765746E-07	2.382935E-06	-1.121211E+02	7.414946E+01
4.000000E+01	2.515598E-07	8.893143E-07	-1.206846E+02	7.420544E+01
5.000000E+01	1.117822E-07	4.241450E-07	-1.271581E+02	7.523560E+01
6.000000E+01	5.647103E-08	2.348892E-07	-1.323387E+02	7.648177E+01
7.000000E+01	3.137418E-08	1.437156E-07	-1.366477E+02	7.768514E+01
8.000000E+01	1.874552E-08	9.439403E-08	-1.403331E+02	7.876791E+01
8.999999E+01	1.185899E-08	6.536941E-08	-1.435519E+02	7.971754E+01
1.000000E+02	7.855552E-09	4.716384E-08	-1.464090E+02	8.054372E+01
2.000000E+02	5.064987E-10	5.694062E-09	-1.648573E+02	8.491682E+01
3.000000E+02	1.006366E-10	1.675798E-09	-1.754999E+02	8.656338E+01
4.000000E+02	3.190757E-11	7.052949E-10	-1.830237E+02	8.740973E+01
5.000000E+02	1.308180E-11	3.607115E-10	-1.888511E+02	8.792301E+01
6.000000E+02	6.312005E-12	2.086194E-10	-1.936089E+02	8.826701E+01
7.000000E+02	3.408128E-12	1.313277E-10	-1.976299E+02	8.851347E+01
8.000000E+02	1.998188E-12	8.795852E-11	-2.011122E+02	8.869865E+01
8.999999E+02	1.247632E-12	6.176610E-11	-2.041832E+02	8.884286E+01

$G'(S)$ is the preliminary transfer function of the system. This result must be checked in the time-domain.

3.3.6 Checking the preliminary results in the time-domain and determining the final transfer function G(S)

Because the original test data was from the time domain, so the time domain check is necessary. Step 3 may be repeated if the results are not reasonably accurate. The time domain check result(time response of equation (3.12)) is shown in Figure 3.10 and Table 3.4. Compared with the original(Figure 3.7), the results are acceptable. The difference is mainly because the frequencys higher than 40rad/sec. were not considered in this study since they are not relevant to this power system situation. The judgement of the acceptability of the results is based on the knowledge that the use of them led ultimately to a satisfactory power system stabilizer design.

After these checks and final adjustments, the final transfer function of the system was determined to be:

$$G(S)=\frac{-0.45S(S+40)}{(S+1)(S^2+1.1S+61.15)(S+20)}$$

3.4 Programs for Determination of Transfer Function from Test Data

To carry out the analysis described in section 3.3, six computer programs were used. These are:

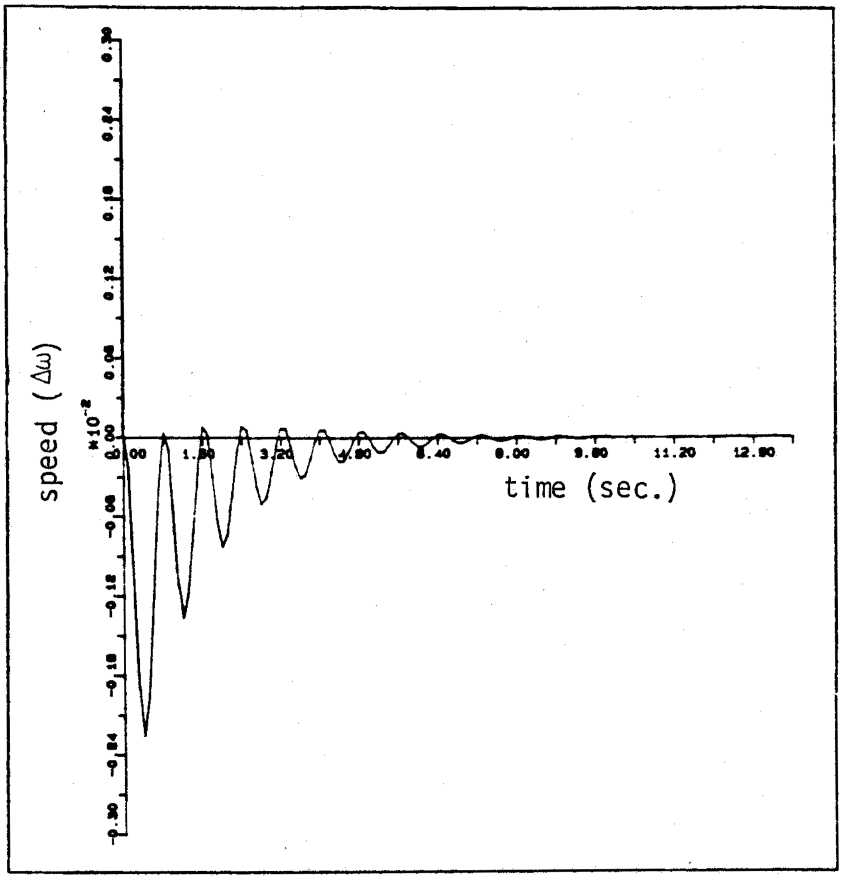


Figure 3.10 Time response from the system transfer function G(S)

Table 3.4

Time response data from the system transfer function G(S)

```
1SIMULATION #    1
 RUN         #    1
 LIST        #    1
```

	time	ω		time	ω
1	0.0000000E+00	0.0000000E+00	52	5.0999975E+00	-6.9524111E-05
2	1.0000000E-01	-2.6874899E-04	53	5.1999974E+00	-1.1250980E-04
3	2.0000000E-01	-1.0913330E-03	54	5.2999973E+00	-1.1081710E-04
4	3.0000001E-01	-1.8860280E-03	55	5.3999972E+00	-6.8557318E-05
5	4.0000001E-01	-2.2566181E-03	56	5.4999971E+00	-1.1806270E-05
6	5.0000000E-01	-1.9588780E-03	57	5.5999970E+00	2.8014170E-05
7	6.0000002E-01	-1.1948470E-03	58	5.6999969E+00	3.1965159E-05
8	7.0000005E-01	-3.9449451E-04	59	5.7999969E+00	2.7071560E-06
9	8.0000007E-01	3.5063200E-05	60	5.8999968E+00	-3.9201161E-05
10	9.0000010E-01	-6.9609603E-05	61	5.9999967E+00	-6.8455098E-05
11	1.0000001E+00	-5.6368433E-04	62	6.0999966E+00	-6.9398309E-05
12	1.1000001E+00	-1.1055410E-03	63	6.1999965E+00	-4.3619501E-05
13	1.2000002E+00	-1.3648040E-03	64	6.2999964E+00	-7.2832522E-06
14	1.3000002E+00	-1.2025890E-03	65	6.3999963E+00	1.9271140E-05
15	1.4000002E+00	-7.2780321E-04	66	6.4999962E+00	2.3144290E-05
16	1.5000002E+00	-2.1142750E-04	67	6.5999961E+00	5.1954021E-06
17	1.6000003E+00	7.9342557E-05	68	6.6999960E+00	-2.1856260E-05
18	1.7000003E+00	2.7641710E-05	69	6.7999959E+00	-4.1650608E-05
19	1.8000003E+00	-2.8437009E-04	70	6.8999958E+00	-4.3552671E-05
20	1.9000003E+00	-6.4124831E-04	71	6.9999957E+00	-2.7899579E-05
21	2.0000002E+00	-8.2642533E-04	72	7.0999956E+00	-4.6727878E-06
22	2.1000001E+00	-7.4125867E-04	73	7.1999955E+00	1.2991380E-05
23	2.2000000E+00	-4.4691449E-04	74	7.2999954E+00	1.6350359E-05
24	2.3000000E+00	-1.1408080E-04	75	7.3999953E+00	5.4050820E-06
25	2.3999999E+00	8.2273807E-05	76	7.4999952E+00	-1.2007250E-05
26	2.4999998E+00	5.9554419E-05	77	7.5999951E+00	-2.5332740E-05
27	2.5999997E+00	-1.3661530E-04	78	7.6999950E+00	-2.7381140E-05
28	2.6999996E+00	-3.7073731E-04	79	7.7999949E+00	-1.7926161E-05
29	2.7999995E+00	-5.0119072E-04	80	7.8999949E+00	-3.1049890E-06
30	2.8999994E+00	-4.5864971E-04	81	7.9999948E+00	8.6168111E-06
31	2.9999993E+00	-2.7662670E-04	82	8.0999947E+00	1.1340480E-05
32	3.0999992E+00	-6.2331652E-05	83	8.1999950E+00	4.7101562E-06
33	3.1999991E+00	6.9936483E-05	84	8.2999954E+00	-6.4666642E-06
34	3.2999990E+00	6.2371313E-05	85	8.3999958E+00	-1.5396619E-05
35	3.3999989E+00	-6.0413731F-05	86	8.4999962E+00	-1.7239019E-05
36	3.4999988E+00	-2.1344640E-04	87	8.5999966E+00	-1.1562310E-05
37	3.5999987E+00	-3.0433520E-04	88	8.6999969E+00	-2.1222550E-06
38	3.6999986E+00	-2.8478750E-04	89	8.7999973E+00	5.6377598E-06
39	3.7999985E+00	-1.7254170E-04	90	8.8999977E+00	7.7540653E-06
40	3.8999984E+00	-3.4736720E-05	91	8.9999981E+00	3.7676821E-06
41	3.9999983E+00	5.4137101E-05	92	9.0999985E+00	-3.3869680E-06
42	4.0999985E+00	5.3955540E-05	93	9.1999989E+00	-9.3467479E-06
43	4.1999984E+00	-2.2542939E-05	94	9.2999992E+00	-1.0865450E-05
44	4.2999983E+00	-1.2223370E-04	95	9.3999996E+00	-7.4810650E-06
45	4.3999982E+00	-1.8498060E-04	96	9.5000000E+00	-1.4800510E-06
46	4.4999981E+00	-1.7739720E-04	97	9.6000004E+00	3.6452479E-06
47	4.5999980E+00	-1.0840040E-04	98	9.7000008E+00	5.2413479E-06
48	4.6999979E+00	-1.9902091E-05	99	9.8000011E+00	2.8650429E-06
49	4.7999978E+00	3.9662678E-05	100	9.9000015E+00	-1.7024470E-06
50	4.8999977E+00	4.2641419E-05	101	1.0000002E+01	-5.6650392E-06
51	4.9999976E+00	-4.7894182E-06			

Loadflow	program (LFP)
Network reduction	program (NRP)
Dynamic simulation	program (PSDS)
Time to frequency translating	program (TFTR)
Frequency responses	program (FRESP)
The system simulation	program (DARE)

Their relationships to each other and data requirements are shown in Figure 3.11.

3.4.1 Loadflow program (LFP)

The loadflow program used in this particular project uses the Newton-Raphson method to calculate the system loadflows.

3.4.2 Network reduction program (NRP)

The NRP program is one of the two supporting programs for the PSDS program[18]. It is used to determine the matrix of driving point and transfer admittances of a given network as seen from the terminals of a selected group of generator busses. The system loads are converted to constant admittances using the bus voltages obtained from a previous loadflow.

3.4.3 Power system dynamic simulation program (PSDS)

The PSDS program is a special purpose program for

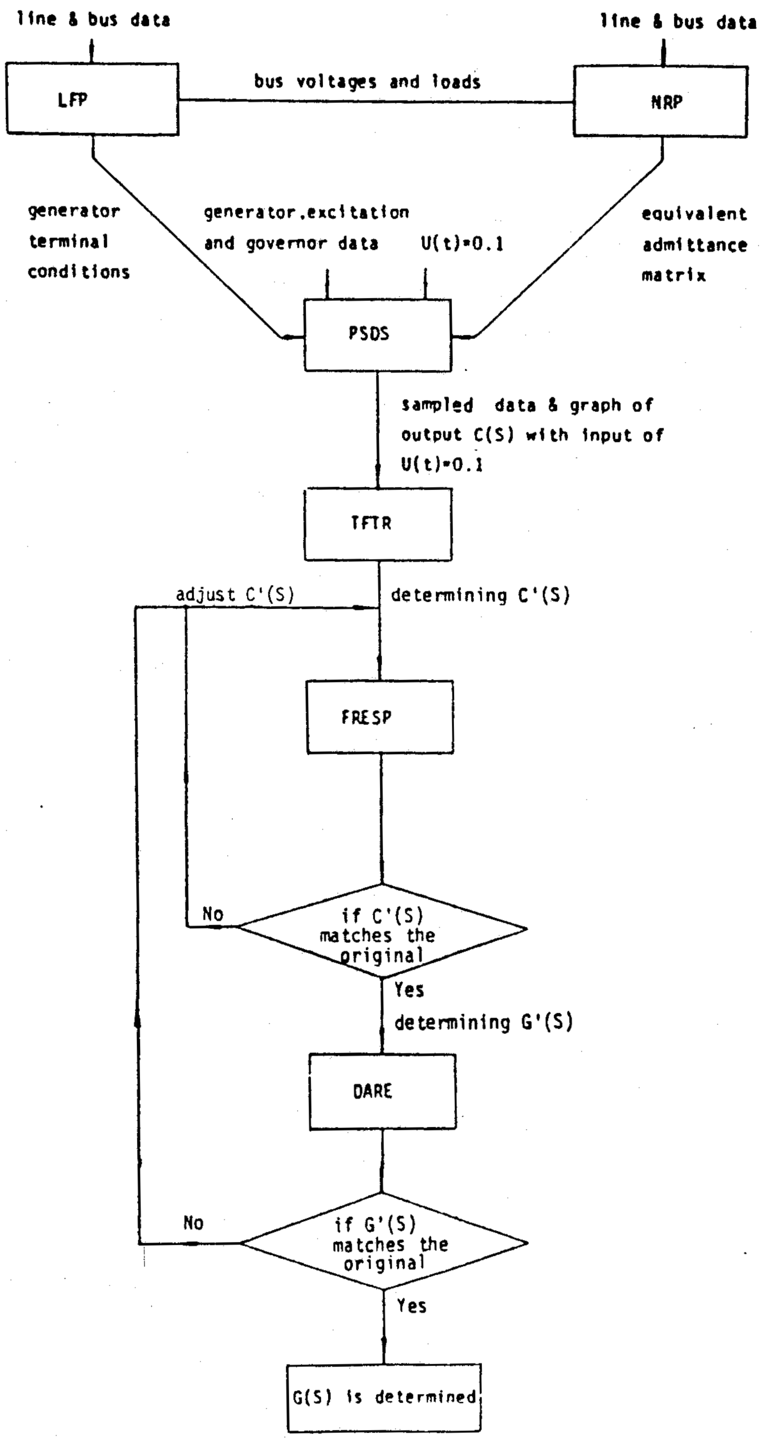


Figure 3.11 The relationship and data requirments of the programs

allowing detailed study of the effects of generators, excitation systems and turbine-governors on power system transient and dynamic stability. The details of description of the program are in the reference [18].

3.4.4 Time to frequency translating program (TFTR)

This program is made for translating time domain functions to frequency domain function. It is also used for drawing the Bode diagram to obtain the preliminary transfer function of the system. This program was written by this author.

The input of this program is 'ROT.DAT' which is generated by the PSDS program as shown in Figure 3.11.

3.4.5 Frequency responses program (FRESP)

FRESP program is used to obtain and plot the frequency response of a rational transfer function over a specified range of frequencies. The plot can be in the form of either Bode or Nyquist diagrams.

3.4.6 The system simulation program (DARE)

DARE[4,5] is a program for checking the transfer function G(S) back to the time domain. The input of DARE is a system state-space representation which is shown in Table 3.5.

Table 3.5 The DARE program input file

```
$dl
*       CHECK TIME-DOMAIN OUTPUT FROM TRANSFER FUNCTION.
*
        g(1)=y(2)
        g(2)=y(3)
        g(3)=y(4)
        g(4)=p(1)*y(1)+p(2)*y(2)+p(3)*y(3)+p(4)*y(4)+p(5)
*
        y(101)=p(6)*y(1)+p(7)*y(2)+p(8)*y(3)+p(9)*y(4)
end
system
4,1,9
dt
tmax
10.0
user
LI LI
ident
check transfer function
state
0.,0.,0.,0.
param
-855.9951,-1281.05,-97.9125,-21.8,-.045,0.0,40.,1.,0.0
npoint
101
width
101
end
list(time,0.0,0.0,0)y(101)
w
plotxt(time,0.0,0.0,0)y(101)
C(t)
end
```

3.5 The Accuracy of the Test Method

To discuss the accuracy of the method, it is necessary that the origin of the errors be identified. To check this, consider the processes separately. First of all, working with the simulated system, the accuracy of results is affected by the accuracy of the modeling of the system. In the diagram Figure 2.2, the Boundary Dam Power Plant is shown to be represented as six machines connected with a infinite bus(i.e. a external system). This involves many individual components, the accuracy of modeling each component has a direct bearing on the absolute accuracy of the results. The experience of the industry has indicated that the level of detail used in this case is appropriate for the particular problem under study.

Secondly, in the process of system simulation to obtain the time-domain test data errors may occur. These errors can be caused by poor modeling of the elements of the system, such as generators, turbines etc.

A process which causes error is the sampling process which converts a continuous function to a discrete function The error is controlled by choosing a proper number of samples per cycle as described in 3.3.2.

As stated in 3.3.2, the time-domain output function can be translated into the frequency-domain to obtain the Bode

Diagram of the system output function. To implement the translation, the Fourier transform equation for a triangular pulse was used in this project. It improves the accuracy, but it is still an approximate method to represent the real function. So, this is the fourth factor which affects the accuracy of the test method.

The fifth factor that affects the accuracy of the test method is from the straight line approximation which is described in 3.3.3. Straight line approximation is basicly a manual task. It is very difficult to identify the number and location of breakpoints when they are close together. Examining the phase plot will help to increase the accuracy because of the phase characteristics associated with break points. The accuracy can be improved by adjusting a number of break points and their locations after checking back to the original function curve. Reference [15] suggests several ways to improve the result, these methods were employed in this study.

Although there are still some factors which may cause error in the test method, it is still a very useful method of obtaining the transfer function of the system in practice. This is particularly true if the accuracy required is not too high. Although the methods suggested here were used on a simulation of a real system, these same methods can be applied to an actual system in the field.

3.6 Conclusion

In this chapter, the process for obtaining the transfer function of a system is described step by step. Since there is no direct method for time-domain test results, translations from time-domain to frequency-domain were used to obtain the transfer function from a Bode diagram. Some adjustments have to be used in the process of the time-domain check. Section 3.4 described the programs which were used for these steps. Section 3.5 discussed the factors which affect the accuracy of the process. A quantitative analysis of accuracy was not carried out; however, from the overall results of this study it was concluded that the accuracy was adequate for the purpose of illustrating the principle of the method. Several of the steps illustrated here used manual methods of calculation. Most of these could be automated using computer methods.

4. POWER SYSTEM STABILIZER DESIGN

A Power System Stabilizer(PSS) is used for the purpose of improving power system stability. A PSS is basically a lead/lag network. The power system stabilizer design procedure involves selecting its parameters to satisfy the stability and dynamic response requirements demanded by the industry.

In this chapter, two of the most practical PSS design methods are discussed in detail using the Boundary Dam Power Plant of the Saskatchewan Power Corporation as an illustrative example. A wide range of other design methods are discussed in References[3,12,17].

4.1 PSS Design Methods

There are several methods to determine the stabilizer parameters, in general these methods are all based upon feedback control theory. Different approaches are used for different purposes in various electrical power systems. Two of the most important methods, the Root Locus and the Phase Compensation Methods, are discussed in this section.

4.1.1 Root Locus Method (RLM)

The root locus method for designing a power system stabilizer[2] is a consistent approach for the particular application of the general problem of controller synthesis.

It is applied here specifically to the power stabilizer design problem, but it also has more general applications in the whole area of controller design and controller parameter determination for electric power generating plants.

The root locus method is a technique which tracks the changes in the roots of the characteristic equation of a system as its parameters are changed. It is a convenient, orderly method used to check the lightly damped modes of the system and to show the effect of adding more damping at a generating station. Damping moves the lightly damped characteristic roots of the system further to the left in the complex s-plane. By tracking these changes in values of the characteristic roots, the satisfactory parameters of the stabilizer can be determined.

In multimachine systems with multiple lightly damped roots and several poorly damped modes of oscillation, several stabilizers are normally needed and these are usually introduced in time sequence. In this case, the problem becomes relatively complicated because as a stabilizer acts to change particular eigenvalues from poorly damped undesired values to more desired values, it may also alter, somewhat, the eigenvalues defined by stabilizers previously specified in the design sequence. It is important that the final complete systems be checked to assure that no undesirable modes result.

It also should be pointed out that the parameters determined by the root locus method for a stabilizer are not unique. The choice of a particular group of parameter values will be affected to some extent by noise considerations and hardware limitations. Still, the root locus approach gives a quantitative basis for the tuning process.

The root locus method for selection of parameters of the stabilizers in a multimachine system is described in more detail in reference[11]. The specific calculations for the particular design case of the Boundary Dam Plant are illustrated in Section 4.2.3 of the thesis.

4.1.2 Phase Compensation Method (PCM)

The root locus method has to deal with the system transfer function which varies because of the variation of the system load and operating conditions. It may be difficult to determine the transfer function, even with low accuracy. Also, many calculations are required for selecting the parameters of a stabilizer; therefore another more practical method was needed. The Phase Compensation Method (PCM)[10] was introduced for this purpose.

The stabilizer is to vary the air gap flux of a machine so as to provide positive damping for particular oscillatory modes in the system. That means that a PSS must make the air gap flux($\Delta E_q'$) vary in phase with the rotor speed change($\Delta\omega$) at the specific oscillation frequency(see Figure 2.3), to produce positive damping torque in the system. Table 4.1 presents information regarding the damping and synchronizing effects of $\Delta E_q'$ for various phase shift angles associated with the frequency response transfer function $\frac{\Delta E_q'}{\Delta\omega}(j\omega_n)$ for oscillating frequencies ω_n.

Table 4.1 Synchronizing and damping effects of $\frac{\Delta E_q'}{\Delta\omega}(j\omega_n)$

Synchronizing and Damping Effects	
$\angle\frac{\Delta E_q'}{\Delta\omega}(j\omega_n)$	Effect
$+90^\circ$	negative synchronizing
0° to $+90^\circ$	positive damping and negative synchronizing
0°	positive damping
0° to -90°	positive damping and positive synchronizing
-90°	positive synchronizing torque
-90° to -180°	positive synchronizing and negative damping

Over the frequency range of concern (i.e. for the frequencies indicated by eigen-value analysis as the dominant system modes) it is desirable to design the PSS so that the phase difference of the transfer function $\frac{\Delta E_q'}{\Delta\omega}$ is in the range of -30° to $+30^\circ$. This will assure good damping with minimal effects on synchronizing torque.

In addition to the suitable angle range, sufficient gain is also needed to affect the damping of the system oscillation, but not so high as to cause the system to go unstable. The block diagram of the system, including stabilizer, is shown in Figure 4.1. The input to the stabilizer is and its output is fed into the exciter along with other exciter inputs R_{ref}. G(S) includes all of the features of the power system.

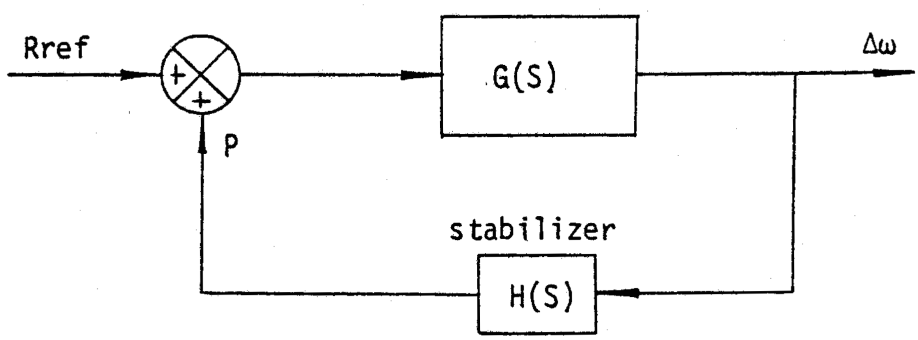


Figure 4.1 Block diagram of the system including stabilizer

When the system is operating, it satisfies the closed loop characteristic equation:

$$1-G(S)H(S)=0$$

Therefore $$|G(S)H(S)| = 1 \tag{4.1}$$

and the phase angle is 0

G(S) can be determined by testing the system. Hence the gain K_s for the PSS can be determined from equation (4.1).

There are three major advantages of the Phase Compensation Method(PCM) compared with the Root Locus Method(RLM).

First of all, the PCM is based on system tests, so it is a practical method. The method reflects system changes, so it has more accuracy than the RLM which uses a fixed linearized model of the system. It can be complemented by computer methods as well.

The second advantage is that it allows for a wide range of angle and gain to give the desired results. It is not unduly sensitive to precision of calculation during the design process.

The third advantage of PCM can be seen in the process of design. It entails much less work compared with the RLM. Hence, much less design time will be needed.

The illustration of the numerical calculation of a specific application of the PCM to the Boundary Dam Plant are given in Section 4.2.3.

4.2 Design Process

4.2.1 Determination of effective stabilizer locations

The oscillations in a multimachine system are normally made up of several inter-machine modes. Dynamic instabilities are generally associated with the lower frequency modes(normally 0.05 to 0.5 HZ or 1.0 to 10.0 radians/second). These oscillations can be well damped by a properly tuned stabilizer at every machine. In practical terms, this course is often difficult and costly, since it involves retrofitting stabilizers to old machines, many of which do not have electronic exciters. Stabilizers are ineffective if applied at nodes of the lightly damped modes. On the other hand, stabilizers are most needed on the machines which have the greatest effect on dynamic instabilities of the multimachine system. Therefore, how to determine the effective stabilizer locations is the first step of stabilizer design. A method for doing this is described in detail in references [8] and [6]. Essentially this method consists of determining the eigen values and corresponding eigen vectors of the system and selecting the PSS locations based on eigen-vector component values. For the problem which was of concern in this project, this method was used to advantage.

Table 4.2 shows the results of eigen-value and eigen-vector calculations for the Boundary Dam Plant with no PSS units. Figure 4.2 shows graphically the eigen-values and eigen vectors normalized on the largest eigen vector value component for each unit. The eigen values(resonant frequencies) range from a low of 0.0270 radians/second to a high of 18.3471 radians/second. The bar graphs indicate normalized values of the eigen vectors corresponding to these frequencies. According to Figure 4.2, it can be seen that all machines in the Boundary Dam Plant would oscillate in synchronism with the external system(infinite bus) at a

Table 4.2

The results of eigen-values and eigen-vectors

of the Boundary Dam Power Plant

No power system stabilizer

The eigen-values of the system

Real part	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
imaginary part	18.3471	15.2116	7.2899	11.3895	11.2471	0.0270	17.4976
	-18.3471	-15.2116	-7.2899	-11.3895	-11.2471	-0.0270	-17.4976

The eigen-vectors of the system

Unit								
	1	0.0009	0.0000	0.0685	-0.0849	-0.0207	-2.2892	0.0000
		0.0000	0.0076	0.0000	0.0000	0.0000	-0.0002	0.0000
	2	0.0008	0.0000	0.0701	0.0043	0.0865	-2.2845	0.0000
		0.0000	0.0071	0.0000	0.0000	0.0000	-0.0002	0.0000
	3	0.0189	0.0000	0.0468	0.0117	-0.0103	-2.2946	-0.0311
		0.0000	-0.0354	0.0000	0.0000	0.0000	-0.0002	0.0285
	4	0.0189	0.0000	0.0468	0.0117	-0.0103	-2.2946	0.0311
		0.0000	-0.0354	0.0000	0.0000	0.0000	-0.0002	-0.0285
	5	-0.0474	0.0000	0.0454	0.0107	-0.0094	-2.2946	0.0000
		0.0000	-0.0254	0.0000	0.0000	0.0000	-0.0002	0.0000
	6	0.0019	0.0000	0.0570	0.0280	-0.0232	-2.2960	0.0000
		0.0000	0.0253	0.0000	0.0000	0.0000	-0.0002	0.0000
	7	0.0000	0.0000	-0.0015	-0.0001	0.0001	-2.2965	0.0000
		0.0000	0.0001	0.0000	0.0000	0.0000	-0.0002	0.0000

The normalized eigen-vectors

Unit								
	1	-0.0180	-0.2150	0.9778	1.0000	-0.2393	0.9968	0.0000
		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	2	-0.0174	-0.2004	1.0000	-0.0502	1.0000	0.9948	0.0000
		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	3	-0.3993	1.0000	0.6683	-0.1376	-0.1191	0.9992	-1.0000
		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	4	-0.3993	1.0000	0.6683	-0.1376	-0.1191	0.9992	1.0000
		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	5	1.0000	0.7180	0.6483	-0.1259	-0.1090	0.9992	0.0000
		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	6	-0.0406	-0.7136	0.8132	-0.3304	-0.2685	0.9998	0.0000
		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	7	-0.0003	-0.0022	-0.0216	0.0009	0.0009	1.0000	0.0000
		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

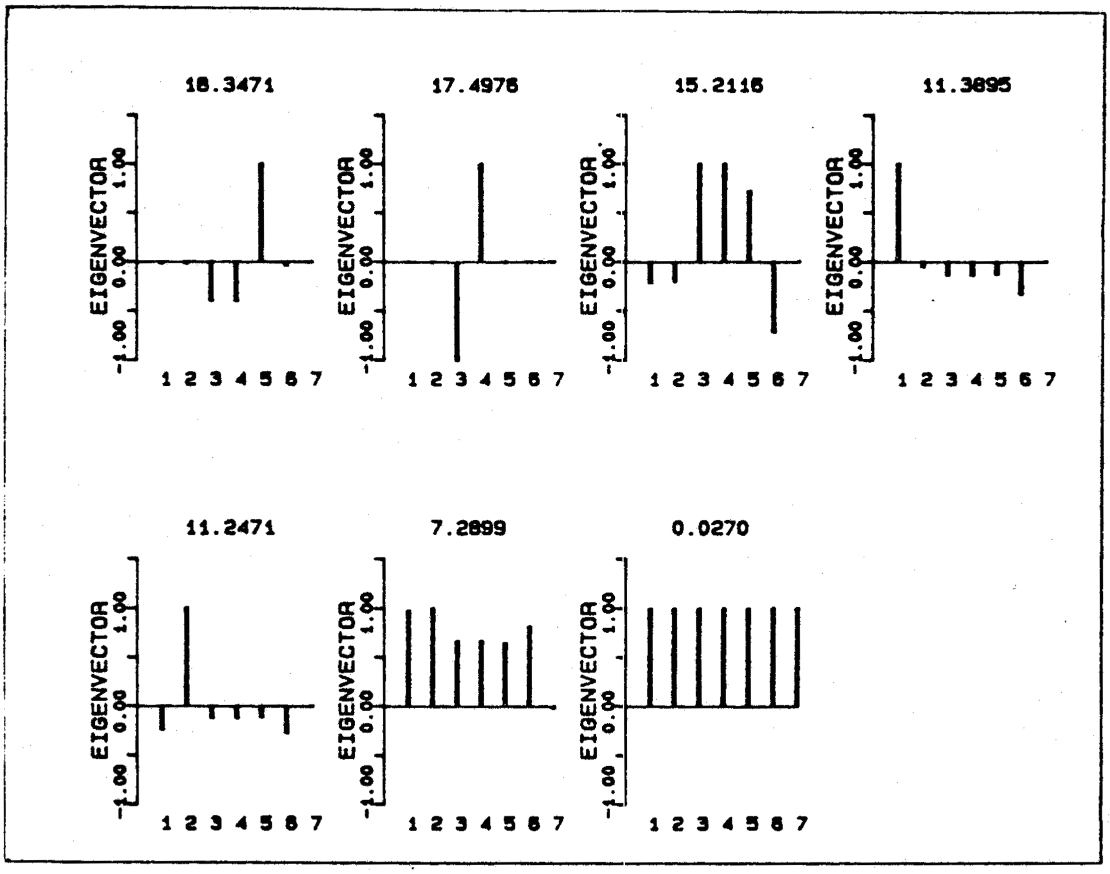


Figure 4.2 Normalized principle eigen-values & eigen-vectors of Boundary Dam Power Plant

frequency of 0.0270 radians/second. At a frequency of 7.2899 r/s, all the machines in the Boundary Dam Plant would oscillate with respect to the external system. Machine #2 would oscillate with respect to the rest of the machines in the plant at a frequency of 11.2471 r/s; similarly, machine #1 versuses the rest of the machines at a frequency of 11.3895 r/s. At a frequency of 15.2116 r/s, machine #1, #2 and #6 would oscillate versus machine #3, #4 and #5. At a frequency of 17.4976 r/s, machine #3 would oscillate with respect to machine #4. Machine #5 would tend to oscillate with respect to the rest of machines in the plant at the frequency of 18.3471 r/s. To determine the best location of effective stabilizers in the plant, Table 4.3 can be used.

Table 4.3

Modes of oscillation in the Boundary Dam Plant

Unit	Poorly Damped Frequency Involved (rad./sec.)					
	18.3471	17.4976	15.2116	11.3895	11.2471	7.2899
1				*		*
2					*	*
3		*	*			*
4		*	*			*
5	*		*			*
6						*

For example, it appears that a stabilizer on Unit #6 would tend to be effective for damping only the 7.2899 r/s oscillation. The 18.3471 r/s oscillation would require a stabilizer on Unit #5 since that is the only unit which participates in that mode.

To simplify the design of the stabilizer in preliminary investigations, it was decided to choose the machine which had the smallest number of frequency modes involved. At the frequency of 7.2899 r/s, all the machines in the plant would oscillate against the external system. The first step in stabilizing the plant is to deal with this mode. According to Table 4.3, machine #6 is the unit with the smallest number of frequency modes involved. A stabilizer for damping of the oscillation at about 7.3 r/s was needed for machine #6. Also, machine #6 is equipped with a modern static excitation system which would make the incremental cost of applying an effective stabilizer low[8] and this would be significant it it were decided to proceed with the actual application in the plant.

4.2.2 Determination of the type of stabilizer

As mentioned in Chapter 1, there are various alternative stabilizers from which to choose. In the Boundary Dam problem, it was determined to use a speed input conventional stabilizer because it is a strong system with all machines in the plant tightly coupled electrically.

4.2.3 Application of the design method

The choice of a technique for designing of the stabilizers is the next step after determining the best locations for them.

There are different methods of design, as mentioned in 4.1, for different problems; so the choice of a specific design method must be suited to the system being dealt with. The problem in this project deals with a strong multimachine system which is suitable for a speed-input stabilizer[14]. From a practical point of view, a conventional stabilizer is required. Therefore, the root locus method and the phase compensation method were used for selecting the parameters of the stabilizer on machine #6.

The Root Locus Method

The RLM was used for the Boundary Dam problem by following the process described below:

(1) Determine the transfer function of the system

The preliminary step for designing of the stabilizer for the Boundary Dam Plant is to find the transfer function G(S) of the system upon which the PSS will act. The method which was used in this project is described in Chapter 3.

The transfer function determined in section 3.3 is:

$$G(S)=\frac{-0.45S(S+40)}{(S+1)(S^2+1.1S+61.15)(S+20)}$$

(2) Selecting the parameters of the stabilizer

The damping ratio of the second order pole pair in this transfer function(4.1) described by Equation is low (ζ=0.07). The eigenvalues of this system were found to be: -1, $-0.55 \pm j7.8$ and -20; therefore, a supplementary stabilizer is needed to increase the damping of the complex roots.

Assume the transfer function of stabilizer to be[11] as given by Equation 4.2. This is a general form of transfer function which corresponds to that of most PSS devices now available from commercial vendors:

$$H(S)=\frac{K_s(aS^2+bS+1)}{(T_2S+1)(T_4S+1)}x\frac{T_3S}{(T_3S+1)} \qquad (4.2)$$

In Equation 4.2 T_2, T_4, T_3 are assumed to be 0.05 seconds[11], in line with current practice. The block diagram of the controlled system including a stabilizer on the machine is shown in Figure 4.3:

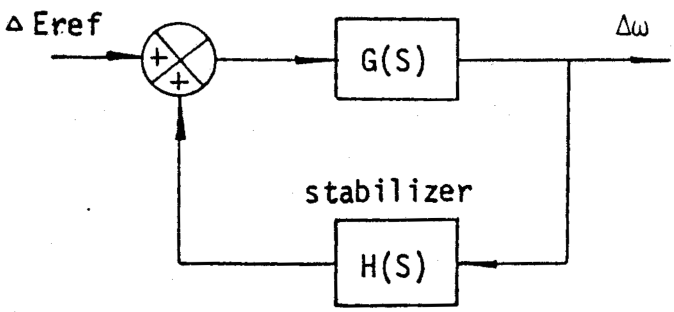


Figure 4.3 The block diagram a system with a stabilizer on the machine

The characteristic equation of the system is:

$$1-G(S)H(S)=0.0 \qquad (4.3)$$

Where G(S) is the transfer function of the entire system as seen from generator #6.

Substituting G(S) and H(S) gives:

$$(S+1)(S^2+1.1S+61.15)(S+20)^4+180K_S S^2(S+40)(aS^2+bS+1)=0 \qquad (4.4)$$

Changing the damping ratio of the complex roots from 0.07 to 0.5 while keeping the natural frequency unchanged, requires moving the roots $-0.55 \pm j7.8$ to $-3.9 \pm j7.8$.

The substitution of $s=-3.9+j7.8$ in Equation 4.4 gives:

$$(-32{,}732{,}326+j31{,}702{,}620)+K_s[a(10{,}701{,}978+j14{,}269{,}304)$$
$$+a(-31{,}055{,}632+j23{,}291{,}724)+b(914{,}699-j1{,}829{,}398)$$
$$+b(3{,}981{,}491+j1{,}990{,}75.6)-234{,}538-j510{,}477.6]=0 \qquad (4.5)$$

Setting the real and imaginary parts of equation(4.4) equal to zero gives respectively:

$$20{,}353{,}654aK_s-4{,}896{,}190bK_s+(234{,}538K_s+32{,}723{,}326)=0 \qquad (4.6)$$

and

$$37{,}561{,}028aK_s+161{,}348bK_s-(510{,}448K_s-31{,}702{,}620)=0 \qquad (4.7)$$

Now, there are two equations(4.6 and 4.7) and three unknowns(a,b and K_s). The additional degree of freedom can be used to control the eigenvalues of the equation(4.5).

Choosing: $K_s = 200$

gives: $a = 0.009$

and $b = 0.118$

Putting these parameters into the PSS transfer function gives:

$$H(S)=\frac{1.8(S^2+13.3S+111)}{(0.05S+1)^2}x\frac{0.05S}{(0.05S+1)} \tag{4.8}$$

This was tested by simulation and the gain K_s was found to be too high, which made the system go unstable. It was adjusted to give the response shown in Figure 4.4. With the adjusted value of K_s, the modified value of H(S) was:

$$H(S)=\frac{0.5(S^2+13.3S+111)}{(0.05S+1)^2}x\frac{0.05S}{(0.05S+1)} \tag{4.9}$$

The open loop transfer function of the modified system is:

$$G(S)H(S)=\frac{-90S^2(S+40)(S^2+13.3S+111)}{(S+1)(S^2+1.1S+61.15)(S+20)^4} \tag{4.10}$$

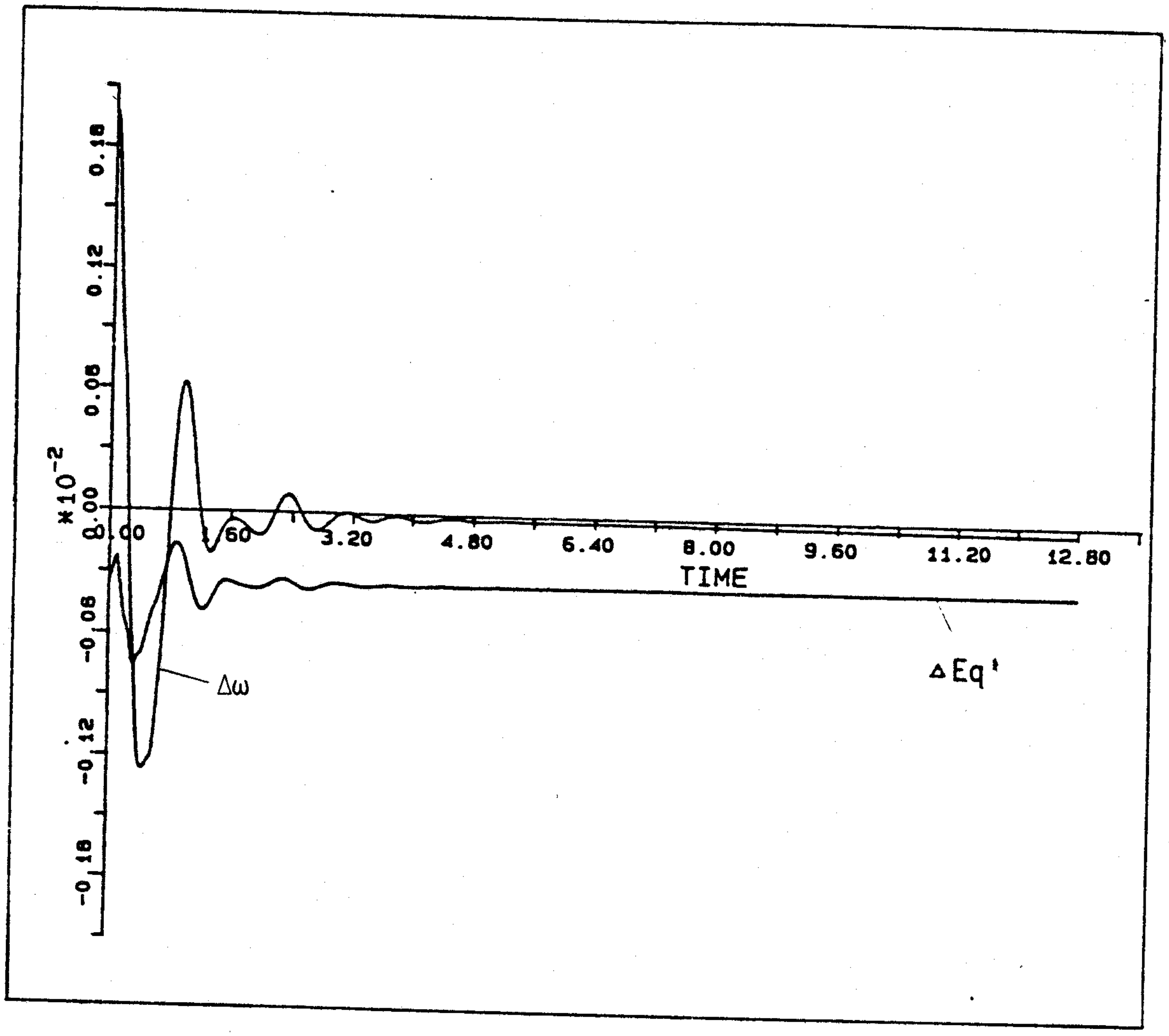


Figure 4.4 System response for bus #9 fault. The PSS, which is designed by using the RLM, is on machine #6.

Now, checking the system root values in Table 4.4, the pair of complex eigenvalues of the system with the stabilizer on machine #6 have been moved from $-0.55 \pm j7.8$ to about $-1.543 \pm j7.754$ (i.e. ζ from 0.07 to 0.2). The time response as shown in Figure 4.4 indicates satisfactory performance in terms of the type of response expected by operating engineers in the field.

The Phase Compensation Method

As an alternative to the root locus relocation approach illustrated in the foregoing paragraphs, the Phase Compensation Method was also used. Again, for the Boundary Dam Plant project, a PSS was to be installed on machine #6 to damp the dominant oscillation of the system at about 7.3 r/s.

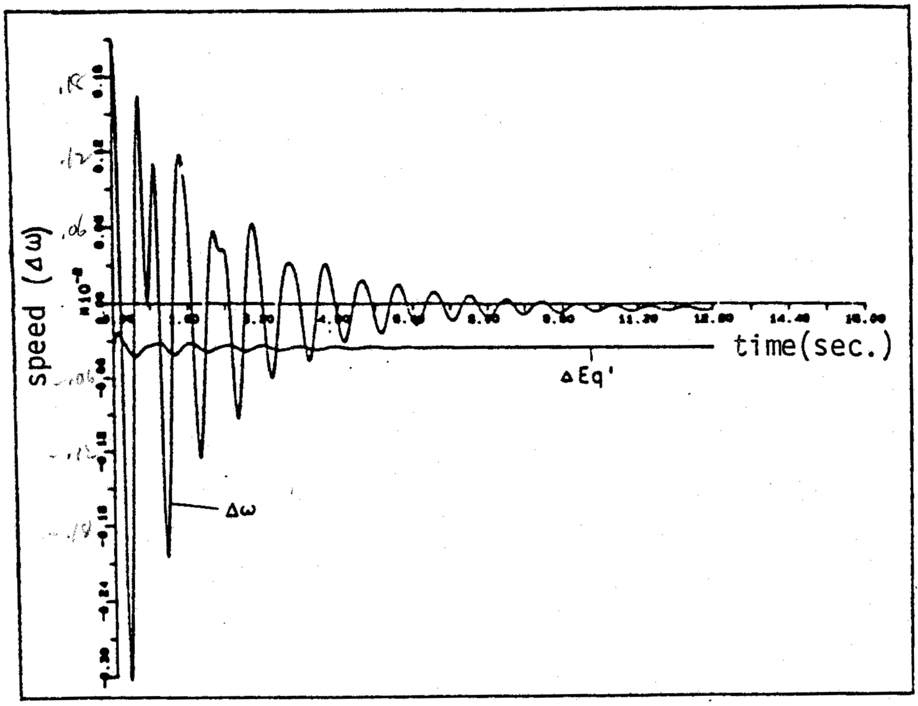
To find out the phase compensation which would be required from the PSS, in the PSDS simulation of the system H(S) was set equal to 1 and a fault was applied to bus #9 giving the time responses of machine #6 as shown in Figure 4.5. A phase difference between $\Delta E_q'$ and ω of about 126° was found at the system oscillation frequency of about 8 r/s.

Table 4.4

Root locus values for the system with PSS on machine #6

```
ROOT LOCUS PROGRAM
PROBLEM IDENTIFICAT  ON -
*********************************************
NUMERATOR COEFFICIENTS IN ASCENDING POWERS OF S

0.000E+00  0.000E+00  4.439E+03  6.430E+02  5.330E+01 1.000E+00

OPEN-LOOP ZEROES
  REAL PART  IMAG. PART
  0.000E+00  0.000E+00
  0.000E+00  0.000E+00
 -6.650E+00  8.170E+00
 -6.650E+00 -8.170E+00
 -4.000E+01  0.000E+00

DENOMINATOR COEFFICIENTS IN ASCENDING POWERS OF S

9.783E+06  1.192E+07  2.475E+06  3.815E+05  4.208E+04  2.630E+03

8.210E+01     1.000E+00

OPEN-LOOP POLES
  REAL PART  IMAG. PART
 -1.000E+00  0.000E+00
 -5.500E-01  7.800E+00
 -5.500E-01 -7.800E+00
 -2.000E+01  0.000E+00
 -2.000E+01  0.000E+00
 -2.000E+01  0.000E+00
 -2.000E+01  0.000E+00

MIN. GAIN =   8.00E+01            MAX. GAIN =   3.50E+02
*********************************************
   1      GAIN =  8.000E+01

        ROOTS ARE
  REAL PART  IMAG. PART

 -1.415E+00 -7.763E+00
 -1.415E+00  7.763E+00
 -1.897E+01 -1.297E+01
 -1.897E+01  1.297E+01
 -3.112E+01  0.000E+00
 -9.175E+00  0.000E+00
 -1.042E+00  0.000E+00

   2      GAIN =  9.206E+01

        ROOTS ARE
  REAL PART  IMAG. PART

 -1.886E+01 -1.356E+01
 -1.886E+01  1.356E+01
 -3.145E+01  0.000E+00
 -1.543E+00 -7.754E+00
 -1.543E+00  7.754E+00
 -8.790E+00  0.000E+00
 -1.049E+00  0.000E+00

   3      GAIN =  1.059E+02

        ROOTS ARE
  REAL PART  IMAG. PART

 -1.875E+01 -1.418E+01
 -1.875E+01  1.418E+01
 -3.178E+01  0.000E+00
 -1.689E+00 -7.743E+00
 -1.689E+00  7.743E+00
 -8.386E+00  0.000E+00
 -1.057E+00  0.000E+00
```

9



Fiqure 4.5 Response of machine #6 for bus #9 fault
when H(S)=1

The PSS transfer function given by equation(4.2) in another form is:

$$H(S)=\frac{K_s(S^2+2\zeta\omega_n S+\omega_n^2)}{(T_1S+1)(T_2S+1)}\times\frac{T_3S}{(T_3S+1)}$$

Setting: $T_1= T_2= T_3= 0.05$ second as before,

and the damping ratio: $\zeta= 0.5$

Then the stabilizer for machine #6 is:

$$H_6(S)=\frac{0.05K_sS(S^2+\omega_n S+\omega_n^2)}{(0.05S+1)^3}$$

The corresponding frequency response function is:

$$H_6(j\omega)=\frac{0.05\ K_s(-\omega_n\ +j(\omega_n^2-\omega^2))}{(1+j0.05\omega)^3}$$

To have $\Delta E_q'$ in phase with $\Delta\omega$ at 8 r/s requires that the phase angle of the PSS be:

$$\phi_6=\tan^{-1}(\frac{\omega_n^2-\omega^2}{-\omega_n\omega})-3\tan^{-1}(0.05\omega)=-126^{\circ}$$

At the system oscillation frequency of 8 r/s,

$$\tan^{-1}(\frac{\omega_n^2-64}{-8\omega_n})=-126^{\circ}+65.4^{\circ}=-60.6^{\circ}$$

$$\omega_n^2-14.2\omega_n-64=0$$

$$\omega_n = 17.8$$

$$\omega_n^2 = 316.84$$

Therefore, the required transfer function for $H_6(S)$ is:

$$H_6(S)=\frac{0.4\ K_s(S^2+17.8S+316.84)}{(0.05S+1)^3}$$

For the purpose of finding the gain K_s, input a sinusoidal signal at frequency 8 r/s to the point P in the simulation(Figure 4.1). The output time response is shown in Figure 4.6 The magnitude of the system transfer function can be found from the magnitude ratio $\Delta\omega/\Delta E_q'$ in figure 4.6; i.e.

$$G_6(S) = \frac{7}{50} = 0.14$$

$$\text{Now} H_6(S) = \frac{0.4K_s((316.84-64)+j(17.8x8))}{(1+j0.4)^3}$$

Using equation (4.1):

$$0.14x35.94K_s = 1$$

$$K_s = 0.2$$

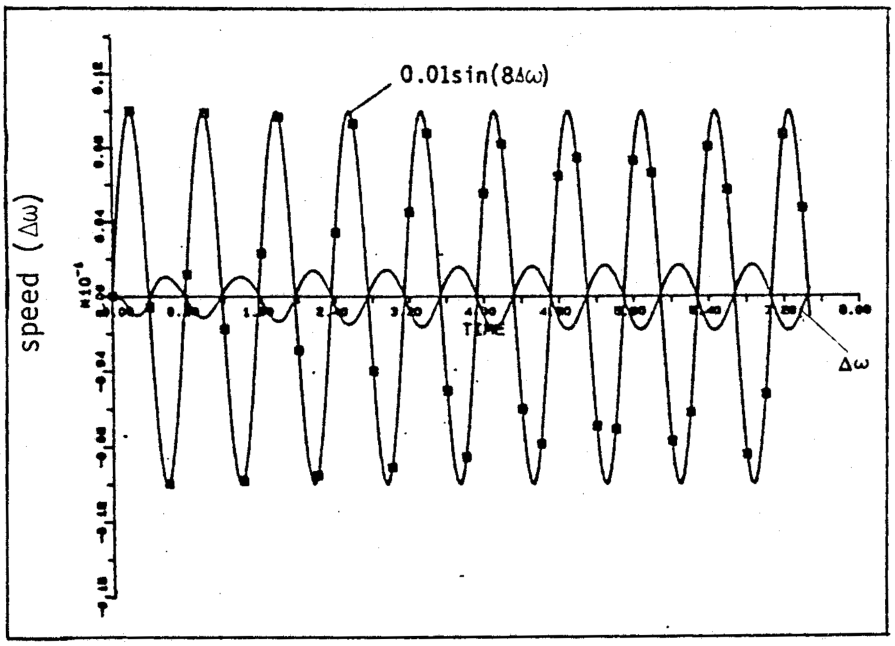


Figure 4.6 Machine #6 open-loop time response

Thus the complete stabilizer transfer function for machine #6 to damp the system oscillation at the 8 r/s frequency mode has been found to be:

$$H_6(S)=\frac{0.2(S^2+17.8S+316.84)}{(0.05S+1)^2}\times\frac{0.05S}{(0.05S+1)} \tag{4.11}$$

Machine #5 was chosen as the location to put on a PSS for damping the oscillation at the 18 r/s frequency mode. The stabilizer found by following the same PCM process as for machine #6 was.

$$H_5(S)=\frac{0.01(S^2+12.6S+160)}{(0.05S+1)^2}\times\frac{0.05S}{(0.05S+1)}$$

Checking the results

The last step in designing the Power System Stabilizer is to do a simulation of the system to check the result. The process and block diagram of this are shown in Chapter 3. The programs are shown in Appendices.

The results

Figures 4.7 and 4.8 present time response determined on the simulation. They show the rotor speed($\Delta\omega$) changes before and after putting a PSS on machine #6 respectively. These time responses were created by a simulated fault on bus #9 for 0.02 seconds. The phase difference between $\Delta E_q'$

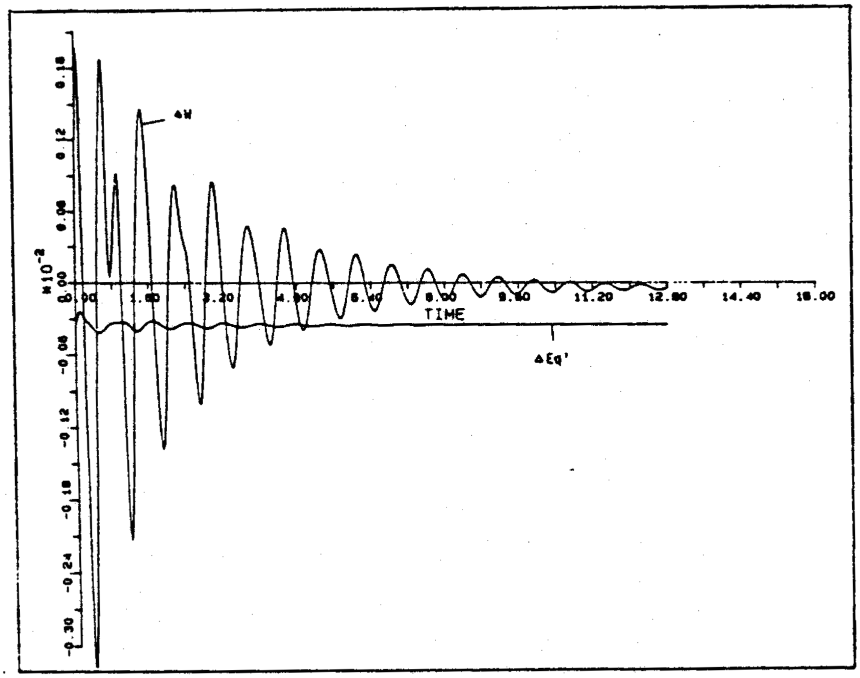


Figure 4.7 Response of machine #6 without PSS on when a bus #9 fault occurs

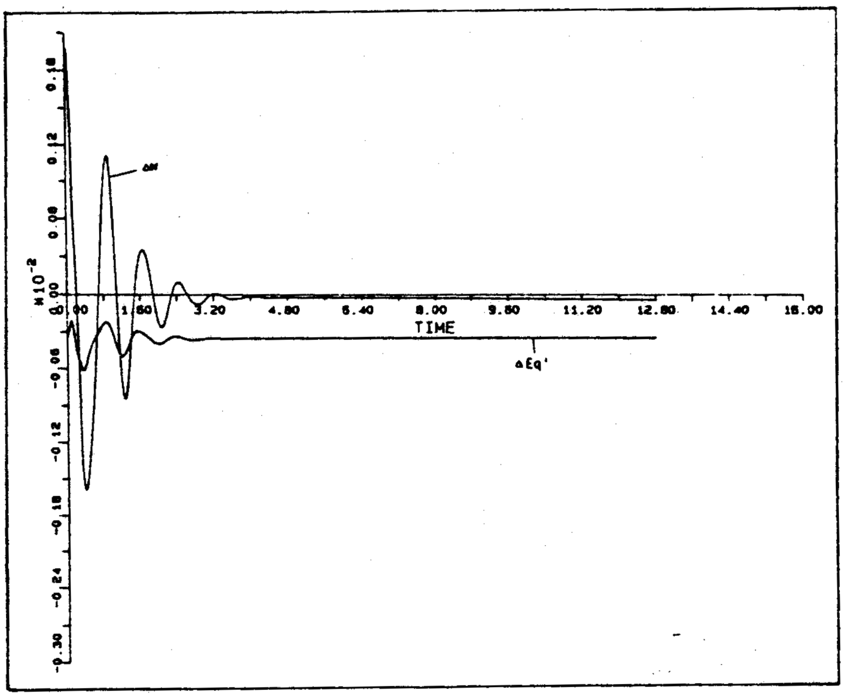


Figure 4.8 Response of machine #6 with PSS on when bus #9 fault occurs

10

and $\Delta\omega$ about -126° can be seen in Figure 4.7. Some higher frequency effects are shown in the second and fourth period of the oscillation. These oscillations are still not well damped up to 12.8 seconds. After installing a PSS on machine #6 under the same disturbance(Figure 4.8), the phase difference between $\Delta E'_q$ and $\Delta\omega$ is forced to be near zero. There is a marked decrease on the magnitude of the oscillation. The PSS decreased the system stabilization time from over 12.8 seconds to about 4 seconds. The improvement of the stability by supplying the stabilizer is obvious.

Comparing equation (4.9) and (4.11), it can be seen that they are two different stabilizers. Comparing Figure 4.4 and 4.8, it can be found that they both give a satisfactory result for the same problem or system. This means that the choice of stabilizer parameters is not unique.

Figure 4.9 shows the time responses of the rotor speed deviations($\Delta\omega$) of all the machines in the Boundary Dam Plant with no PSS applied when a bus #9 fault occurred. In agreement with the eigen-value analysis results, there are several oscillation frequency modes in the plant and approximately 8 r/s is the dominant frequency mode. Since machines #1 and #2 have the same capacity which is smaller than the others, they are more sensitive to the system disturbance and have the same time responses with greater

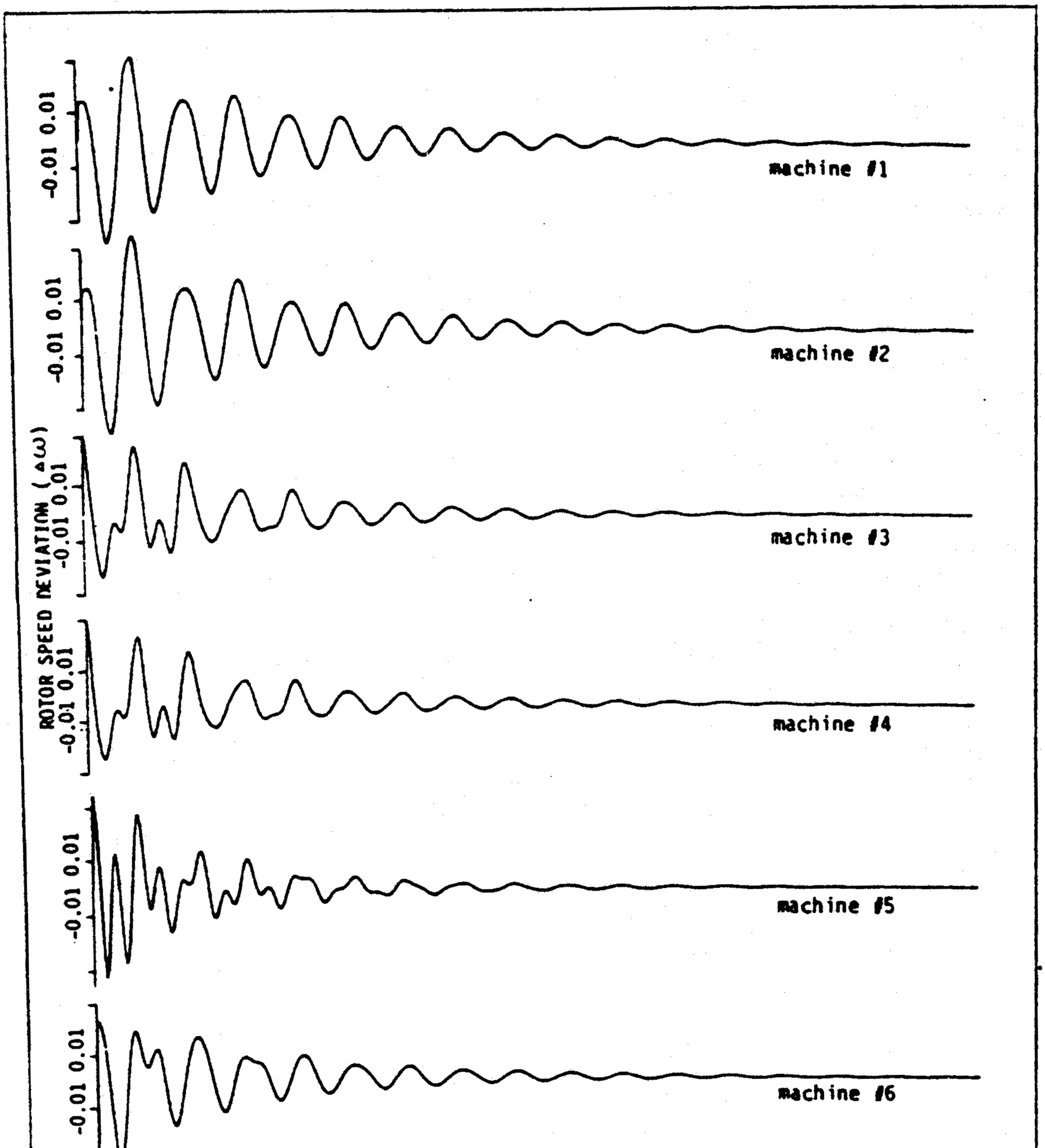


Figure 4.9 Response of machines without PSS when bus #9 fault occurred

oscillation magnitudes. Machines #3 and #4 also have the same time responses because they have the same capacity. They have more oscillation frequencies involved as shown in eigen-value and eigen-vector analysis. Their oscillation magnitudes are smaller because they have larger generating capacities compared the machines #1 and #2. It can be seen that the highest frequency(about 18 r/s) was involved in the time response of machine #5 only. As can be seen in Figure 4.9 also, machine #6 has the smallest number of frequency modes involved when it was oscillating compared with machine #3, #4 and #5 which have larger generating capacities. Figure 4.10 shows the results after providing a stabilizer on machine #6. The system is well damped at its dominant frequency mode of 7.2899 r/s, but there are still some higher frequency modes which are most obvious in the time response of machine #5. To damp out this higher frequency, a PSS for machine #5 was provided. The results of this are shown in Figure 4.11. Compared with Figure 4.10, it can be seen that the high frequency component(about 18 r/s) in machine #3, #4 and #5 was well damped and the stabilization time for the system was much shortened from over 12.8 seconds to about 3.20 seconds by supplying two stabilizers on machines #5 and #6 respectively.

4.3 Conclusion

Two methods of designing a Power System Stabilizer are

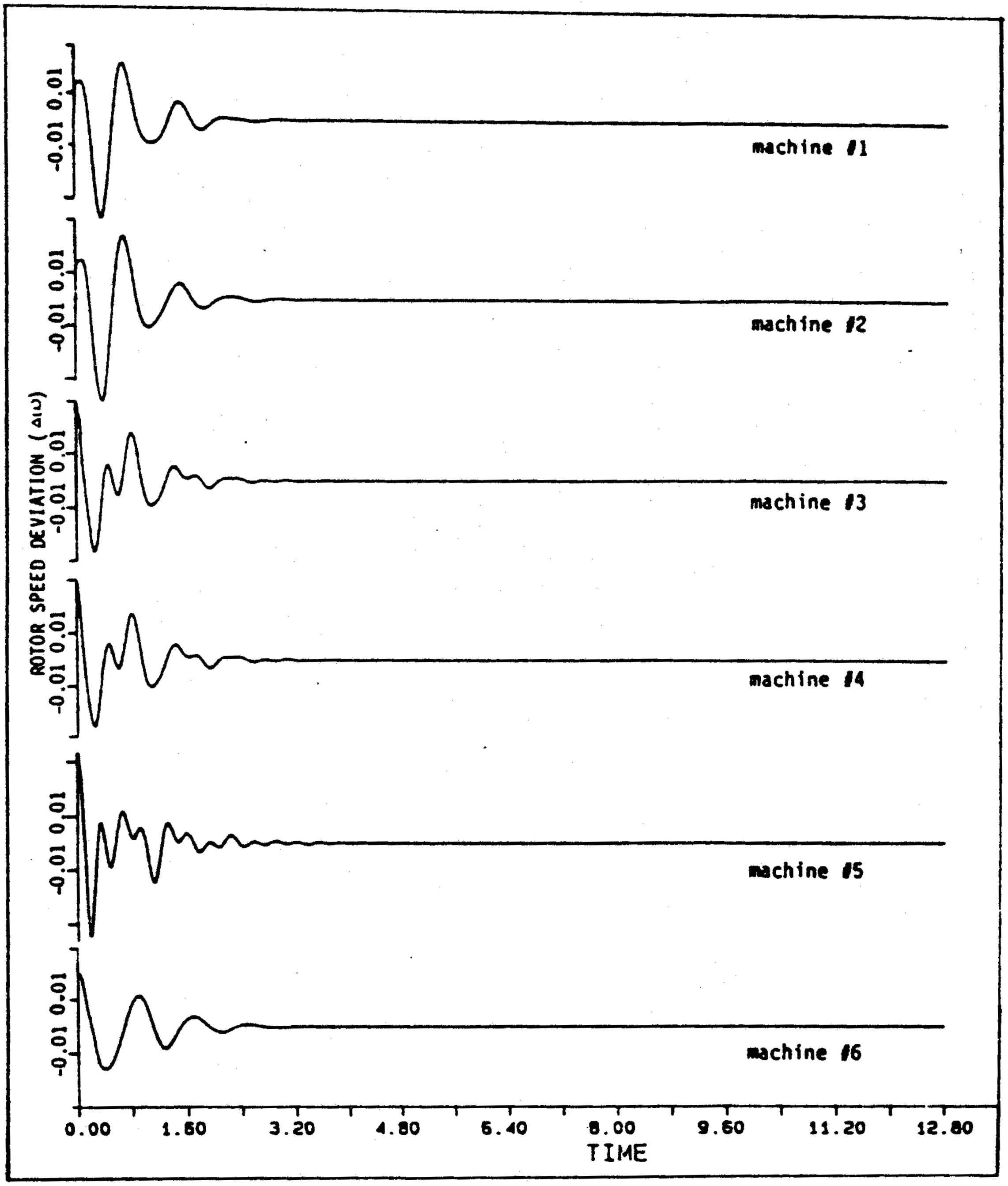


Figure 4.10 Response of machines with PSS on machine #6 when bus #9 fault occurred

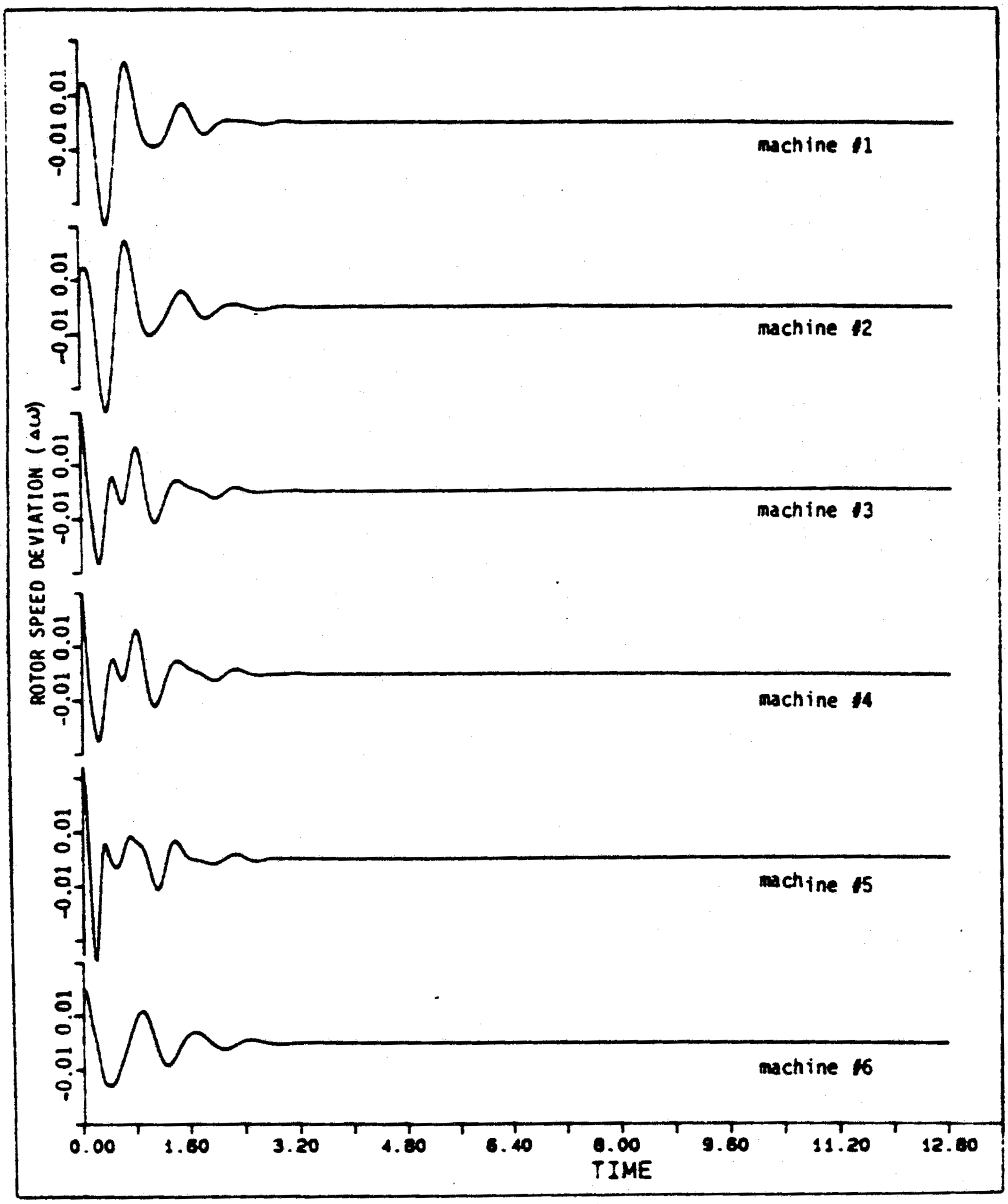


Figure 4.11 Response of machines with PSS on machines #6 and #5 when bus #9 fault occurred

discussed in this chapter. The first is the Root Locus Method(RLM) which is commonly used. The RLM poses some difficulties in finding the system transfer function and the calculations for selecting parameters of the stabilizer.

The second method is based on the phase compensation principle. It has some advantages compared with the Root Locus Method. It is faster, more accurate and more flexible.

The principle eigen-values and eigen-vectors were used in this project to find the best location of the system stabilizer. The usefullness of this approach is well proved by the system response simulation results which are shown in Figures 4.9, 4.10 and 4.11.

5. CONCLUSIONS AND RECOMMENDATION FOR FURTHER RESEARCH

5.1 Conclusions

The purpose of the studies reported in this thesis was to show how a multimachine electrical power plant would oscillate with different oscillation frequency modes and how the power system stabilizer(s) would affect these oscillation mode(s). The Boundary Dam Power Plant of the Saskatchewan Power Corporation system was used as an illustrative example. In general, it was found that the eigen-value and eigen-vector method of analysis and the root locus and phase compensation methods of designing stabilizers could be applied successfully to the problem studied.

In Chapter 1, the basic concepts of steady-state stability of electrical power systems are briefly reviewed. The principle and variety of stabilizers are described. Speed-input stabilizers were used for the studies in this project.

In Chapter 2, it is shown how the Boundary Dam Plant was represented in the PSDS computer simulation program[18]. This approach was found to be appropriate for these studies. Block diagrams and analog-computer type diagrams of the machines and their controllers with their parameters are shown in this chapter. Additional models were required to represent the static exciter with transient gain reduction and the static exciter with an auxiliary stabilizer. These are described also in this chapter.

Chapter 3 shows the step-by-step process for obtaining the transfer function of a system using the test method. This is needed in order to design the stabilizer(s) using the Root Locus Method. Since there is no direct method to identify a system using time-domain test results, translations from time-domain to frequency-domain are needed and these are described in this chapter to obtain the Bode diagram. The system transfer function can be determined from the Bode diagram directly. It was found that the final result had to be checked back against the original time-domain results in order to obtain satisfactory accuracy. Some adjustments had to be made during the process. The accuracy of the method is discussed in Section 3.5. In general it was found that the accuracy of this method is adequate for the stabilizer design.

In Chapter 4, the eigen-value and eigen-vector method was used to determine the unit(s) on which the installation of PSS would be most effective for damping the oscillations in the multimachine Boundary Dam Plant. The system time response results which are shown in Figures 4.9, 4.10 and 4.11 demonstrate proof of the method. Also, two methods of designing stabilizers are discussed and illustrated in this chapter. One is the Root Locus Method(RLM) which is commonly used. The RLM requires specific numerical values for the system transfer function. Because of this, the RLM involves excessive work for the selection of actual parameters in the stabilizer design. An alternate method for designing the stabilizer(s) which does not require the identification of the system transfer function is the Phase Compensation Method(PCM). This method is based on the principle of designing a stabilizer to compensate the phase shift between the air gap flux deviation ($\Delta E_q'$) and the rotor speed deviation($\Delta\omega$). If the phase compensation is correct this results in a positive damping torque to damp the system oscillation. The PCM was found to have several specific advantages compared with the RLM. These advantages include less computational work, lower sensitivity to the precision of the models or the calculations and greater accuracy due to its dependence on system test data. This method is applicable to an actual field situation and is quite simple to implement.

The most significant contributions of the work reported in this thesis are the use of the eigen-value and eigen-vector method to a multimachine power plant to choose optimum stabilizer locations; and the use of the Phase Compensation Method to design the stabilizers required. The eigen-value and eigen-vector method which was used is described in Reference [6]. The time responses of the

Boundary Dam Plant following a fault are shown in Figure 4.9. This shows the oscillation of the system at several frequency modes which are in agreement with the eigen-value and eigen-vector analysis results. Using this method, the machine(s) which are the most effective to which the stabilizer(s) should be applied can be determined. The Phase Compensation Method was used to design the stabilizers which were chosen by the eigen-value and eigen-vector analysis. The PCM was found to have some advantages, as noted above, compared with the Root Locus Method which is used more commonly. Because the gain requirement for different oscillation frequency modes can not be satisfied using the PCM, more than one stabilizer is needed for damping these frequency modes.

5.2 Recommendation for Further Research

As mentioned above, with the PCM stabilizer design method, only one specific poorly damped oscillation frequency can be considered at a time. Therefore in this case two stabilizers were needed to gain the desired results. There will be fewer stabilizers required if the stabilizer can be designed in such way that it can satisfy more than one poorly damped oscillation frequency mode. It is suggested that further research be undertaken to study the extension of the PCM to cover a broader frequency range of modes.

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7. APPENDICES

Table 7.1

The system time response data(speed in p.u.) for the input disturbance of 0.1 p.u. step in air gap flux of unit #6

TIME(sec.)	UNIT 1(p.u.)	UNIT 2(p.u.)	UNIT 3(p.u.)	UNIT 4(p.u.)	UNIT 5(p.u.)	UNIT 6(p.u.)
0.0000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
0.0250	-0.0000081	-0.0000083	0.0000090	0.0000048	0.0000019	-0.0000473
0.0500	-0.0000321	-0.0000329	0.0000385	0.0000259	0.0000026	-0.0001981
0.0750	-0.0000708	-0.0000725	0.0000803	0.0000642	-0.0000003	-0.0004343
0.1000	-0.0001240	-0.0001267	0.0001206	0.0001134	-0.0000002	-0.0007309
0.1250	-0.0001911	-0.0001948	0.0001436	0.0001614	0.0000101	-0.0010584
0.1500	-0.0002716	-0.0002762	0.0001360	0.0001935	0.0000342	-0.0013858
0.1750	-0.0003640	-0.0003693	0.0000902	0.0001975	0.0000691	-0.0016831
0.2000	-0.0004665	-0.0004721	0.0000061	0.0001663	0.0001067	-0.0019253
0.2250	-0.0005761	-0.0005819	-0.0001087	0.0001004	0.0001365	-0.0020944
0.2500	-0.0006893	-0.0006950	-0.0002402	0.0000080	0.0001495	-0.0021809
0.2750	-0.0008013	-0.0008069	-0.0003706	-0.0000964	0.0001415	-0.0021849
0.3000	-0.0009069	-0.0009122	-0.0004808	-0.0001946	0.0001149	-0.0021147
0.3250	-0.0009998	-0.0010050	-0.0005539	-0.0002678	0.0000792	-0.0019854
0.3500	-0.0010735	-0.0010788	-0.0005774	-0.0002999	0.0000486	-0.0018164
0.3750	-0.0011213	-0.0011267	-0.0005450	-0.0002800	0.0000395	-0.0016280
0.4000	-0.0011366	-0.0011424	-0.0004572	-0.0002040	0.0000661	-0.0014391
0.4250	-0.0011142	-0.0011204	-0.0003207	-0.0000755	0.0001374	-0.0012646
0.4500	-0.0010501	-0.0010568	-0.0001476	0.0000951	0.0002545	-0.0011142
0.4750	-0.0009429	-0.0009496	0.0000469	0.0002924	0.0004099	-0.0009918
0.5000	-0.0007936	-0.0007999	0.0002459	0.0004980	0.0005885	-0.0008961
0.5250	-0.0006064	-0.0006114	0.0004337	0.0006933	0.0007702	-0.0008220
0.5500	-0.0003887	-0.0003914	0.0005968	0.0008618	0.0009335	-0.0007624
0.5750	-0.0001506	-0.0001497	0.0007252	0.0009914	0.0010591	-0.0007098
0.6000	0.0000955	0.0001014	0.0008135	0.0010750	0.0011339	-0.0006584
0.6250	0.0003359	0.0003480	0.0008607	0.0011114	0.0011526	-0.0006052
0.6500	0.0005563	0.0005756	0.0008696	0.0011048	0.0011188	-0.0005502
0.6750	0.0007435	0.0007705	0.0008463	0.0010634	0.0010442	-0.0004969
0.7000	0.0008857	0.0009205	0.0007990	0.0009984	0.0009458	-0.0004508
0.7250	0.0009742	0.0010162	0.0007369	0.0009216	0.0008431	-0.0004187
0.7500	0.0010039	0.0010516	0.0006686	0.0008445	0.0007544	-0.0004070
0.7750	0.0009733	0.0010247	0.0006019	0.0007758	0.0006936	-0.0004201
0.8000	0.0008853	0.0009378	0.0005421	0.0007215	0.0006677	-0.0004597
0.8250	0.0007463	0.0007969	0.0004923	0.0006835	0.0006760	-0.0005244
0.8500	0.0005661	0.0006114	0.0004527	0.0006604	0.0007106	-0.0006084
0.8750	0.0003558	0.0003927	0.0004190	0.0006451	0.0007556	-0.0006941
0.9000	0.0001283	0.0001539	0.0003849	0.0006278	0.0007914	-0.0007611
0.9250	-0.0001022	-0.0000902	0.0003458	0.0005995	0.0007995	-0.0007960
0.9500	-0.0003212	-0.0003244	0.0002996	0.0005540	0.0007661	-0.0007931
0.9750	-0.0005157	-0.0005344	0.0002465	0.0004898	0.0006855	-0.0007543
1.0000	-0.0006744	-0.0007083	0.0001890	0.0004099	0.0005620	-0.0006875
1.0250	-0.0007894	-0.0008369	0.0001308	0.0003212	0.0004094	-0.0006049
1.0500	-0.0008562	-0.0009146	0.0000762	0.0002330	0.0002490	-0.0005210
1.0750	-0.0008736	-0.0009393	0.0000295	0.0001553	0.0001053	-0.0004493
1.1000	-0.0008440	-0.0009126	-0.0000053	0.0000969	0.0000013	-0.0004007
1.1250	-0.0007724	-0.0008391	-0.0000253	0.0000643	-0.0000463	-0.0003811
1.1500	-0.0006658	-0.0007259	-0.0000287	0.0000604	-0.0000300	-0.0003906
1.1750	-0.0005329	-0.0005821	-0.0000148	0.0000845	0.0000465	-0.0004234
1.2000	-0.0003830	-0.0004175	0.0000156	0.0001327	0.0001695	-0.0004688
1.2250	-0.0002253	-0.0002426	0.0000607	0.0001983	0.0003178	-0.0005133
1.2500	-0.0000687	-0.0000674	0.0001174	0.0002731	0.0004668	-0.0005426
1.2750	0.0000792	0.0000990	0.0001818	0.0003487	0.0005932	-0.0005441
1.3000	0.0002120	0.0002487	0.0002494	0.0004173	0.0006789	-0.0005096
1.3250	0.0003247	0.0003757	0.0003157	0.0004733	0.0007144	-0.0004363
1.3500	0.0004141	0.0004757	0.0003764	0.0005129	0.0006994	-0.0003276
1.3750	0.0004787	0.0005462	0.0004279	0.0005350	0.0006426	-0.0001926
1.4000	0.0005182	0.0005868	0.0004674	0.0005409	0.0005593	-0.0000452
1.4250	0.0005338	0.0005984	0.0004936	0.0005334	0.0004681	0.0000986
1.4500	0.0005276	0.0005838	0.0005061	0.0005162	0.0003870	0.0002224
1.4750	0.0005026	0.0005464	0.0005054	0.0004933	0.0003302	0.0003122
1.5000	0.0004621	0.0004906	0.0004927	0.0004676	0.0003049	0.0003583
1.5250	0.0004098	0.0004213	0.0004696	0.0004411	0.0003106	0.0003562
1.5500	0.0003492	0.0003431	0.0004376	0.0004139	0.0003392	0.0003074
1.5750	0.0002832	0.0002606	0.0003977	0.0003848	0.0003772	0.0002188
1.6000	0.0002147	0.0001773	0.0003507	0.0003512	0.0004082	0.0001015
1.6250	0.0001454	0.0000964	0.0002968	0.0003104	0.0004170	-0.0000308
1.6500	0.0000767	0.0000198	0.0002359	0.0002599	0.0003928	-0.0001641
1.6750	0.0000094	-0.0000514	0.0001682	0.0001981	0.0003311	-0.0002857

1.7000	-0.0000565	-0.0001169	0.0000945	0.0001255	0.0002356	-0.0003857
1.7250	-0.0001208	-0.0001767	0.0000167	0.0000448	0.0001170	-0.0004582
1.7500	-0.0001833	-0.0002315	-0.0000623	-0.0000395	-0.0000083	-0.0005016
1.7750	-0.0002436	-0.0002814	-0.0001379	-0.0001207	-0.0001216	-0.0005177
1.8000	-0.0003007	-0.0003265	-0.0002048	-0.0001913	-0.0002051	-0.0005113
1.8250	-0.0003528	-0.0003662	-0.0002570	-0.0002438	-0.0002452	-0.0004885
1.8500	-0.0003975	-0.0003992	-0.0002888	-0.0002716	-0.0002349	-0.0004556
1.8750	-0.0004320	-0.0004235	-0.0002959	-0.0002707	-0.0001752	-0.0004178
1.9000	-0.0004529	-0.0004367	-0.0002757	-0.0002396	-0.0000746	-0.0003785
1.9250	-0.0004570	-0.0004362	-0.0002286	-0.0001805	0.0000519	-0.0003389
1.9500	-0.0004415	-0.0004193	-0.0001574	-0.0000986	0.0001861	-0.0002985
1.9750	-0.0004047	-0.0003843	-0.0000681	-0.0000020	0.0003093	-0.0002552
2.0000	-0.0003459	-0.0003301	0.0000316	0.0000995	0.0004056	-0.0002071
2.0250	-0.0002662	-0.0002571	0.0001325	0.0001960	0.0004640	-0.0001522
2.0500	-0.0001682	-0.0001671	0.0002253	0.0002780	0.0004806	-0.0000903
2.0750	-0.0000562	-0.0000636	0.0003020	0.0003384	0.0004580	-0.0000229
2.1000	0.0000640	0.0000487	0.0003565	0.0003730	0.0004047	0.0000467
2.1250	0.0001857	0.0001640	0.0003857	0.0003809	0.0003332	0.0001134
2.1500	0.0003017	0.0002756	0.0003894	0.0003644	0.0002578	0.0001713
2.1750	0.0004047	0.0003768	0.0003706	0.0003288	0.0001911	0.0002148
2.2000	0.0004882	0.0004612	0.0003343	0.0002807	0.0001431	0.0002390
2.2250	0.0005468	0.0005232	0.0002872	0.0002278	0.0001184	0.0002411
2.2500	0.0005768	0.0005586	0.0002360	0.0001769	0.0001167	0.0002206
2.2750	0.0005762	0.0005649	0.0001870	0.0001335	0.0001327	0.0001796
2.3000	0.0005451	0.0005414	0.0001448	0.0001005	0.0001576	0.0001227
2.3250	0.0004858	0.0004895	0.0001116	0.0000785	0.0001809	0.0000562
2.3500	0.0004021	0.0004120	0.0000875	0.0000654	0.0001932	-0.0000130
2.3750	0.0002991	0.0003136	0.0000706	0.0000577	0.0001872	-0.0000779
2.4000	0.0001832	0.0001998	0.0000573	0.0000505	0.0001600	-0.0001330
2.4250	0.0000611	0.0000771	0.0000438	0.0000395	0.0001128	-0.0001744
2.4500	-0.0000603	-0.0000477	0.0000263	0.0000212	0.0000511	-0.0002007
2.4750	-0.0001748	-0.0001681	0.0000024	-0.0000060	-0.0000166	-0.0002131
2.5000	-0.0002764	-0.0002779	-0.0000286	-0.0000415	-0.0000803	-0.0002144
2.5250	-0.0003608	-0.0003717	-0.0000656	-0.0000825	-0.0001307	-0.0002088
2.5500	-0.0004243	-0.0004455	-0.0001055	-0.0001248	-0.0001604	-0.0002009
2.5750	-0.0004649	-0.0004960	-0.0001439	-0.0001629	-0.0001655	-0.0001948
2.6000	-0.0004817	-0.0005217	-0.0001760	-0.0001915	-0.0001461	-0.0001933
2.6250	-0.0004753	-0.0005222	-0.0001971	-0.0002061	-0.0001060	-0.0001974
2.6500	-0.0004471	-0.0004984	-0.0002038	-0.0002040	-0.0000521	-0.0002060
2.6750	-0.0003998	-0.0004525	-0.0001942	-0.0001846	0.0000074	-0.0002165
2.7000	-0.0003364	-0.0003875	-0.0001685	-0.0001497	0.0000639	-0.0002251
2.7250	-0.0002610	-0.0003074	-0.0001288	-0.0001026	0.0001105	-0.0002272
2.7500	-0.0001776	-0.0002166	-0.0000790	-0.0000486	0.0001427	-0.0002190
2.7750	-0.0000905	-0.0001199	-0.0000239	0.0000069	0.0001592	-0.0001976
2.8000	-0.0000038	-0.0000223	0.0000314	0.0000585	0.0001616	-0.0001619
2.8250	0.0000787	0.0000717	0.0000824	0.0001021	0.0001538	-0.0001128
2.8500	0.0001537	0.0001578	0.0001255	0.0001350	0.0001413	-0.0000531
2.8750	0.0002184	0.0002325	0.0001586	0.0001563	0.0001296	0.0000124
2.9000	0.0002709	0.0002929	0.0001812	0.0001669	0.0001230	0.0000782
2.9250	0.0003098	0.0003373	0.0001941	0.0001689	0.0001242	0.0001385
2.9500	0.0003346	0.0003648	0.0001991	0.0001651	0.0001332	0.0001876
2.9750	0.0003453	0.0003751	0.0001984	0.0001583	0.0001477	0.0002214
3.0000	0.0003427	0.0003693	0.0001939	0.0001507	0.0001636	0.0002371
3.0250	0.0003280	0.0003486	0.0001869	0.0001434	0.0001757	0.0002340
3.0500	0.0003025	0.0003151	0.0001780	0.0001362	0.0001789	0.0002133
3.0750	0.0002678	0.0002710	0.0001666	0.0001278	0.0001690	0.0001775
3.1000	0.0002258	0.0002188	0.0001514	0.0001163	0.0001441	0.0001306
3.1250	0.0001780	0.0001609	0.0001307	0.0000991	0.0001045	0.0000768
3.1500	0.0001260	0.0000995	0.0001031	0.0000743	0.0000530	0.0000205
3.1750	0.0000711	0.0000368	0.0000677	0.0000410	-0.0000055	-0.0000344
3.2000	0.0000148	-0.0000255	0.0000246	-0.0000007	-0.0000647	-0.0000850
3.2250	-0.0000417	-0.0000856	-0.0000245	-0.0000487	-0.0001181	-0.0001294
3.2500	-0.0000971	-0.0001422	-0.0000769	-0.0000997	-0.0001599	-0.0001665
3.2750	-0.0001499	-0.0001938	-0.0001287	-0.0001493	-0.0001857	-0.0001959
3.3000	-0.0001987	-0.0002393	-0.0001754	-0.0001925	-0.0001934	-0.0002181
3.3250	-0.0002417	-0.0002773	-0.0002127	-0.0002246	-0.0001831	-0.0002333
3.3500	-0.0002774	-0.0003066	-0.0002368	-0.0002421	-0.0001574	-0.0002420
3.3750	-0.0003039	-0.0003262	-0.0002451	-0.0002427	-0.0001203	-0.0002441
3.4000	-0.0003195	-0.0003348	-0.0002365	-0.0002263	-0.0000770	-0.0002395
3.4250	-0.0003229	-0.0003317	-0.0002118	-0.0001944	-0.0000325	-0.0002279
3.4500	-0.0003131	-0.0003164	-0.0001736	-0.0001504	0.0000086	-0.0002087
3.4750	-0.0002898	-0.0002888	-0.0001254	-0.0000989	0.0000430	-0.0001819
3.5000	-0.0002531	-0.0002495	-0.0000720	-0.0000450	0.0000691	-0.0001477
3.5250	-0.0002042	-0.0001994	-0.0000179	0.0000065	0.0000865	-0.0001071
3.5500	-0.0001448	-0.0001403	0.0000323	0.0000513	0.0000965	-0.0000618
3.5750	-0.0000775	-0.0000745	0.0000752	0.0000866	0.0001011	-0.0000140
3.6000	-0.0000054	-0.0000047	0.0001087	0.0001110	0.0001025	0.0000333
3.6250	0.0000680	0.0000657	0.0001318	0.0001247	0.0001028	0.0000772
3.6500	0.0001389	0.0001336	0.0001450	0.0001291	0.0001034	0.0001147
3.6750	0.0002037	0.0001955	0.0001497	0.0001263	0.0001047	0.0001433
3.7000	0.0002589	0.0002484	0.0001477	0.0001190	0.0001064	0.0001612
3.7250	0.0003017	0.0002895	0.0001411	0.0001094	0.0001071	0.0001677
3.7500	0.0003297	0.0003166	0.0001319	0.0000993	0.0001053	0.0001629
3.7750	0.0003416	0.0003285	0.0001212	0.0000897	0.0000993	0.0001481
3.8000	0.0003369	0.0003245	0.0001096	0.0000805	0.0000878	0.0001250

3.8250	0.0003160	0.0003047	0.0000970	0.0000710	0.0000703	0.0000962
3.8500	0.0002800	0.0002702	0.0000827	0.0000599	0.0000471	0.0000641
3.8750	0.0002310	0.0002228	0.0000659	0.0000457	0.0000195	0.0000313
3.9000	0.0001717	0.0001648	0.0000458	0.0000275	-0.0000106	-0.0000002
3.9250	0.0001051	0.0000990	0.0000220	0.0000048	-0.0000408	-0.0000291
3.9500	0.0000345	0.0000288	-0.0000053	-0.0000220	-0.0000686	-0.0000545
3.9750	-0.0000364	-0.0000426	-0.0000353	-0.0000517	-0.0000917	-0.0000765
4.0000	-0.0001043	-0.0001117	-0.0000664	-0.0000822	-0.0001085	-0.0000952
4.0250	-0.0001662	-0.0001754	-0.0000967	-0.0001111	-0.0001179	-0.0001112
4.0500	-0.0002191	-0.0002308	-0.0001238	-0.0001359	-0.0001199	-0.0001251
4.0750	-0.0002610	-0.0002754	-0.0001457	-0.0001543	-0.0001152	-0.0001373
4.1000	-0.0002902	-0.0003074	-0.0001605	-0.0001646	-0.0001051	-0.0001479
4.1250	-0.0003058	-0.0003256	-0.0001672	-0.0001660	-0.0000911	-0.0001565
4.1500	-0.0003074	-0.0003294	-0.0001652	-0.0001585	-0.0000748	-0.0001624
4.1750	-0.0002956	-0.0003190	-0.0001551	-0.0001431	-0.0000578	-0.0001645
4.2000	-0.0002713	-0.0002953	-0.0001378	-0.0001216	-0.0000410	-0.0001619
4.2250	-0.0002361	-0.0002597	-0.0001151	-0.0000960	-0.0000250	-0.0001536
4.2500	-0.0001921	-0.0002142	-0.0000887	-0.0000686	-0.0000100	-0.0001390
4.2750	-0.0001415	-0.0001612	-0.0000606	-0.0000414	0.0000042	-0.0001180
4.3000	-0.0000869	-0.0001034	-0.0000326	-0.0000159	0.0000178	-0.0000912
4.3250	-0.0000310	-0.0000435	-0.0000058	0.0000068	0.0000314	-0.0000596
4.3500	0.0000239	0.0000157	0.0000187	0.0000263	0.0000448	-0.0000250
4.3750	0.0000755	0.0000716	0.0000406	0.0000427	0.0000581	0.0000106
4.4000	0.0001216	0.0001219	0.0000596	0.0000564	0.0000706	0.0000449
4.4250	0.0001607	0.0001646	0.0000759	0.0000678	0.0000815	0.0000759
4.4500	0.0001916	0.0001982	0.0000894	0.0000773	0.0000898	0.0001015
4.4750	0.0002135	0.0002219	0.0001001	0.0000850	0.0000945	0.0001202
4.5000	0.0002258	0.0002349	0.0001077	0.0000907	0.0000946	0.0001311
4.5250	0.0002287	0.0002374	0.0001117	0.0000937	0.0000894	0.0001339
4.5500	0.0002225	0.0002296	0.0001117	0.0000932	0.0000786	0.0001286
4.5750	0.0002078	0.0002123	0.0001068	0.0000882	0.0000626	0.0001161
4.6000	0.0001853	0.0001865	0.0000965	0.0000781	0.0000420	0.0000975
4.6250	0.0001563	0.0001536	0.0000806	0.0000623	0.0000181	0.0000739
4.6500	0.0001218	0.0001150	0.0000591	0.0000410	-0.0000076	0.0000468
4.6750	0.0000831	0.0000723	0.0000328	0.0000149	-0.0000334	0.0000176
4.7000	0.0000415	0.0000271	0.0000028	-0.0000145	-0.0000577	-0.0000123
4.7250	-0.0000015	-0.0000190	-0.0000294	-0.0000456	-0.0000789	-0.0000419
4.7500	-0.0000444	-0.0000644	-0.0000618	-0.0000761	-0.0000960	-0.0000701
4.7750	-0.0000859	-0.0001074	-0.0000923	-0.0001038	-0.0001079	-0.0000959
4.8000	-0.0001244	-0.0001466	-0.0001189	-0.0001267	-0.0001144	-0.0001186
4.8250	-0.0001587	-0.0001806	-0.0001398	-0.0001432	-0.0001154	-0.0001375
4.8500	-0.0001874	-0.0002082	-0.0001537	-0.0001523	-0.0001112	-0.0001518
4.8750	-0.0002093	-0.0002282	-0.0001600	-0.0001535	-0.0001026	-0.0001610
4.9000	-0.0002234	-0.0002400	-0.0001584	-0.0001472	-0.0000903	-0.0001645
4.9250	-0.0002291	-0.0002429	-0.0001496	-0.0001344	-0.0000752	-0.0001621
4.9500	-0.0002259	-0.0002369	-0.0001345	-0.0001164	-0.0000582	-0.0001537
4.9750	-0.0002137	-0.0002219	-0.0001144	-0.0000948	-0.0000402	-0.0001394
5.0000	-0.0001930	-0.0001986	-0.0000910	-0.0000713	-0.0000219	-0.0001198
5.0250	-0.0001644	-0.0001677	-0.0000657	-0.0000474	-0.0000041	-0.0000957
5.0500	-0.0001290	-0.0001305	-0.0000401	-0.0000243	0.0000127	-0.0000684
5.0750	-0.0000884	-0.0000885	-0.0000154	-0.0000030	0.0000279	-0.0000393
5.1000	-0.0000442	-0.0000435	0.0000074	0.0000158	0.0000411	-0.0000099
5.1250	0.0000015	0.0000026	0.0000278	0.0000320	0.0000519	0.0000181
5.1500	0.0000467	0.0000477	0.0000453	0.0000453	0.0000600	0.0000434
5.1750	0.0000892	0.0000900	0.0000595	0.0000558	0.0000652	0.0000645
5.2000	0.0001272	0.0001274	0.0000704	0.0000637	0.0000673	0.0000806
5.2250	0.0001588	0.0001584	0.0000779	0.0000688	0.0000662	0.0000911
5.2500	0.0001826	0.0001815	0.0000819	0.0000712	0.0000620	0.0000956
5.2750	0.0001975	0.0001956	0.0000823	0.0000706	0.0000547	0.0000945
5.3000	0.0002028	0.0002003	0.0000791	0.0000669	0.0000447	0.0000882
5.3250	0.0001984	0.0001952	0.0000722	0.0000598	0.0000324	0.0000775
5.3500	0.0001845	0.0001808	0.0000618	0.0000494	0.0000182	0.0000632
5.3750	0.0001619	0.0001577	0.0000480	0.0000357	0.0000027	0.0000463
5.4000	0.0001317	0.0001270	0.0000312	0.0000191	-0.0000134	0.0000276
5.4250	0.0000954	0.0000902	0.0000121	0.0000003	-0.0000294	0.0000081
5.4500	0.0000548	0.0000490	-0.0000087	-0.0000199	-0.0000446	-0.0000117
5.4750	0.0000117	0.0000053	-0.0000301	-0.0000404	-0.0000584	-0.0000312
5.5000	-0.0000319	-0.0000389	-0.0000513	-0.0000601	-0.0000701	-0.0000498
5.5250	-0.0000739	-0.0000816	-0.0000711	-0.0000778	-0.0000793	-0.0000673
5.5500	-0.0001125	-0.0001209	-0.0000886	-0.0000926	-0.0000856	-0.0000832
5.5750	-0.0001460	-0.0001552	-0.0001028	-0.0001038	-0.0000888	-0.0000971
5.6000	-0.0001730	-0.0001829	-0.0001132	-0.0001108	-0.0000889	-0.0001087
5.6250	-0.0001925	-0.0002030	-0.0001194	-0.0001136	-0.0000859	-0.0001175
5.6500	-0.0002038	-0.0002147	-0.0001212	-0.0001122	-0.0000800	-0.0001231
5.6750	-0.0002066	-0.0002176	-0.0001187	-0.0001070	-0.0000716	-0.0001251
5.7000	-0.0002010	-0.0002119	-0.0001122	-0.0000985	-0.0000611	-0.0001232
5.7250	-0.0001875	-0.0001978	-0.0001023	-0.0000873	-0.0000492	-0.0001173
5.7500	-0.0001668	-0.0001764	-0.0000896	-0.0000741	-0.0000363	-0.0001073
5.7750	-0.0001401	-0.0001486	-0.0000747	-0.0000596	-0.0000230	-0.0000935
5.8000	-0.0001088	-0.0001158	-0.0000582	-0.0000443	-0.0000097	-0.0000765
5.8250	-0.0000743	-0.0000797	-0.0000408	-0.0000287	0.0000030	-0.0000570
5.8500	-0.0000382	-0.0000418	-0.0000232	-0.0000133	0.0000148	-0.0000358
5.8750	-0.0000021	-0.0000039	-0.0000059	0.0000016	0.0000252	-0.0000141

5.9000	0.0000324	0.0000325	0.0000106	0.0000155	0.0000340	0.0000071
5.9250	0.0000640	0.0000657	0.0000257	0.0000281	0.0000409	0.0000267
5.9500	0.0000915	0.0000946	0.0000388	0.0000389	0.0000457	0.0000438
5.9750	0.0001139	0.0001180	0.0000496	0.0000476	0.0000481	0.0000574
6.0000	0.0001304	0.0001351	0.0000576	0.0000537	0.0000480	0.0000671
6.0250	0.0001406	0.0001455	0.0000623	0.0000568	0.0000452	0.0000725
6.0500	0.0001442	0.0001488	0.0000636	0.0000567	0.0000397	0.0000733
6.0750	0.0001413	0.0001451	0.0000611	0.0000530	0.0000317	0.0000699
6.1000	0.0001321	0.0001349	0.0000549	0.0000458	0.0000213	0.0000623
6.1250	0.0001172	0.0001186	0.0000451	0.0000353	0.0000089	0.0000512
6.1500	0.0000973	0.0000970	0.0000320	0.0000218	-0.0000048	0.0000371
6.1750	0.0000732	0.0000711	0.0000162	0.0000060	-0.0000194	0.0000206
6.2000	0.0000459	0.0000419	-0.0000016	-0.0000113	-0.0000340	0.0000025
6.2250	0.0000164	0.0000108	-0.0000206	-0.0000294	-0.0000479	-0.0000165
6.2500	-0.0000140	-0.0000211	-0.0000398	-0.0000471	-0.0000603	-0.0000356
6.2750	-0.0000442	-0.0000526	-0.0000584	-0.0000635	-0.0000707	-0.0000541
6.3000	-0.0000731	-0.0000824	-0.0000752	-0.0000779	-0.0000783	-0.0000713
6.3250	-0.0000995	-0.0001094	-0.0000894	-0.0000893	-0.0000830	-0.0000865
6.3500	-0.0001225	-0.0001325	-0.0001005	-0.0000974	-0.0000845	-0.0000991
6.3750	-0.0001411	-0.0001509	-0.0001078	-0.0001019	-0.0000828	-0.0001085
6.4000	-0.0001546	-0.0001638	-0.0001112	-0.0001026	-0.0000781	-0.0001143
6.4250	-0.0001624	-0.0001709	-0.0001107	-0.0000998	-0.0000708	-0.0001163
6.4500	-0.0001644	-0.0001717	-0.0001063	-0.0000937	-0.0000614	-0.0001143
6.4750	-0.0001602	-0.0001663	-0.0000985	-0.0000848	-0.0000506	-0.0001083
6.5000	-0.0001502	-0.0001549	-0.0000878	-0.0000737	-0.0000389	-0.0000987
6.5250	-0.0001346	-0.0001381	-0.0000748	-0.0000609	-0.0000269	-0.0000859
6.5500	-0.0001143	-0.0001164	-0.0000602	-0.0000472	-0.0000151	-0.0000706
6.5750	-0.0000900	-0.0000909	-0.0000447	-0.0000330	-0.0000040	-0.0000534
6.6000	-0.0000628	-0.0000625	-0.0000289	-0.0000189	0.0000060	-0.0000353
6.6250	-0.0000339	-0.0000327	-0.0000136	-0.0000055	0.0000147	-0.0000172
6.6500	-0.0000045	-0.0000025	0.0000007	0.0000068	0.0000219	0.0000000
6.6750	0.0000241	0.0000266	0.0000136	0.0000176	0.0000274	0.0000156
6.7000	0.0000506	0.0000534	0.0000245	0.0000265	0.0000311	0.0000289
6.7250	0.0000738	0.0000768	0.0000331	0.0000332	0.0000329	0.0000392
6.7500	0.0000928	0.0000958	0.0000392	0.0000377	0.0000326	0.0000463
6.7750	0.0001067	0.0001096	0.0000425	0.0000396	0.0000303	0.0000501
6.8000	0.0001150	0.0001176	0.0000431	0.0000388	0.0000259	0.0000505
6.8250	0.0001174	0.0001196	0.0000408	0.0000355	0.0000196	0.0000476
6.8500	0.0001138	0.0001154	0.0000357	0.0000296	0.0000116	0.0000419
6.8750	0.0001044	0.0001054	0.0000281	0.0000214	0.0000022	0.0000337
6.9000	0.0000897	0.0000899	0.0000182	0.0000113	-0.0000082	0.0000233
6.9250	0.0000703	0.0000699	0.0000065	-0.0000004	-0.0000191	0.0000114
6.9500	0.0000473	0.0000461	-0.0000065	-0.0000130	-0.0000301	-0.0000018
6.9750	0.0000217	0.0000196	-0.0000204	-0.0000261	-0.0000405	-0.0000155
7.0000	-0.0000054	-0.0000083	-0.0000345	-0.0000391	-0.0000500	-0.0000295
7.0250	-0.0000328	-0.0000364	-0.0000482	-0.0000512	-0.0000579	-0.0000431
7.0500	-0.0000592	-0.0000635	-0.0000608	-0.0000621	-0.0000641	-0.0000560
7.0750	-0.0000836	-0.0000884	-0.0000719	-0.0000712	-0.0000682	-0.0000677
7.1000	-0.0001048	-0.0001101	-0.0000809	-0.0000781	-0.0000702	-0.0000779
7.1250	-0.0001221	-0.0001277	-0.0000875	-0.0000827	-0.0000699	-0.0000860
7.1500	-0.0001348	-0.0001405	-0.0000915	-0.0000848	-0.0000676	-0.0000918
7.1750	-0.0001423	-0.0001480	-0.0000928	-0.0000844	-0.0000634	-0.0000950
7.2000	-0.0001445	-0.0001500	-0.0000914	-0.0000816	-0.0000576	-0.0000955
7.2250	-0.0001414	-0.0001465	-0.0000874	-0.0000766	-0.0000505	-0.0000931
7.2500	-0.0001332	-0.0001377	-0.0000811	-0.0000697	-0.0000426	-0.0000880
7.2750	-0.0001204	-0.0001242	-0.0000728	-0.0000612	-0.0000342	-0.0000802
7.3000	-0.0001037	-0.0001065	-0.0000628	-0.0000516	-0.0000255	-0.0000702
7.3250	-0.0000838	-0.0000857	-0.0000518	-0.0000411	-0.0000168	-0.0000584
7.3500	-0.0000618	-0.0000625	-0.0000400	-0.0000303	-0.0000086	-0.0000453
7.3750	-0.0000384	-0.0000381	-0.0000279	-0.0000195	-0.0000008	-0.0000315
7.4000	-0.0000149	-0.0000136	-0.0000161	-0.0000091	0.0000061	-0.0000177
7.4250	0.0000079	0.0000101	-0.0000049	0.0000006	0.0000120	-0.0000045
7.4500	0.0000289	0.0000319	0.0000052	0.0000091	0.0000167	0.0000075
7.4750	0.0000474	0.0000509	0.0000138	0.0000162	0.0000198	0.0000178
7.5000	0.0000626	0.0000665	0.0000206	0.0000215	0.0000213	0.0000259
7.5250	0.0000739	0.0000781	0.0000254	0.0000249	0.0000209	0.0000315
7.5500	0.0000811	0.0000852	0.0000279	0.0000261	0.0000186	0.0000345
7.5750	0.0000838	0.0000876	0.0000281	0.0000251	0.0000145	0.0000348
7.6000	0.0000821	0.0000855	0.0000257	0.0000218	0.0000086	0.0000324
7.6250	0.0000761	0.0000789	0.0000210	0.0000163	0.0000013	0.0000275
7.6500	0.0000662	0.0000682	0.0000141	0.0000089	-0.0000072	0.0000204
7.6750	0.0000528	0.0000538	0.0000052	-0.0000002	-0.0000163	0.0000114
7.7000	0.0000365	0.0000366	-0.0000053	-0.0000104	-0.0000257	0.0000008
7.7250	0.0000179	0.0000171	-0.0000167	-0.0000214	-0.0000350	-0.0000109
7.7500	-0.0000020	-0.0000038	-0.0000288	-0.0000325	-0.0000435	-0.0000232
7.7750	-0.0000226	-0.0000252	-0.0000408	-0.0000433	-0.0000509	-0.0000357
7.8000	-0.0000430	-0.0000463	-0.0000521	-0.0000532	-0.0000570	-0.0000477
7.8250	-0.0000623	-0.0000663	-0.0000624	-0.0000619	-0.0000614	-0.0000588
7.8500	-0.0000799	-0.0000842	-0.0000711	-0.0000688	-0.0000640	-0.0000686
7.8750	-0.0000949	-0.0000994	-0.0000778	-0.0000738	-0.0000647	-0.0000767
7.9000	-0.0001069	-0.0001114	-0.0000823	-0.0000767	-0.0000636	-0.0000826
7.9250	-0.0001153	-0.0001196	-0.0000845	-0.0000775	-0.0000608	-0.0000862
7.9500	-0.0001198	-0.0001238	-0.0000843	-0.0000760	-0.0000565	-0.0000872

7.9750	-0.0001203	-0.0001238	-0.0000818	-0.0000726	-0.0000510	-0.0000857
8.0000	-0.0001169	-0.0001196	-0.0000771	-0.0000673	-0.0000446	-0.0000817
8.0250	-0.0001095	-0.0001116	-0.0000706	-0.0000605	-0.0000375	-0.0000755
8.0500	-0.0000987	-0.0001000	-0.0000625	-0.0000525	-0.0000301	-0.0000674
8.0750	-0.0000849	-0.0000853	-0.0000534	-0.0000438	-0.0000225	-0.0000576
8.1000	-0.0000686	-0.0000683	-0.0000436	-0.0000346	-0.0000152	-0.0000468
8.1250	-0.0000507	-0.0000496	-0.0000335	-0.0000254	-0.0000083	-0.0000354
8.1500	-0.0000319	-0.0000301	-0.0000235	-0.0000166	-0.0000022	-0.0000240
8.1750	-0.0000129	-0.0000105	-0.0000141	-0.0000084	0.0000029	-0.0000131
8.2000	0.0000054	0.0000082	-0.0000055	-0.0000011	0.0000069	-0.0000032
8.2250	0.0000221	0.0000253	0.0000018	0.0000049	0.0000095	0.0000053
8.2500	0.0000367	0.0000401	0.0000078	0.0000096	0.0000106	0.0000121
8.2750	0.0000484	0.0000519	0.0000121	0.0000126	0.0000103	0.0000170
8.3000	0.0000569	0.0000603	0.0000145	0.0000139	0.0000085	0.0000197
8.3250	0.0000617	0.0000649	0.0000150	0.0000133	0.0000053	0.0000203
8.3500	0.0000628	0.0000657	0.0000135	0.0000110	0.0000008	0.0000188
8.3750	0.0000600	0.0000626	0.0000100	0.0000069	-0.0000047	0.0000154
8.4000	0.0000537	0.0000557	0.0000048	0.0000013	-0.0000110	0.0000102
8.4250	0.0000440	0.0000455	-0.0000019	-0.0000056	-0.0000179	0.0000035
8.4500	0.0000314	0.0000323	-0.0000099	-0.0000134	-0.0000251	-0.0000044
8.4750	0.0000166	0.0000169	-0.0000187	-0.0000219	-0.0000322	-0.0000132
8.5000	0.0000001	-0.0000002	-0.0000279	-0.0000305	-0.0000390	-0.0000226
8.5250	-0.0000172	-0.0000182	-0.0000372	-0.0000388	-0.0000451	-0.0000322
8.5500	-0.0000347	-0.0000363	-0.0000460	-0.0000467	-0.0000502	-0.0000416
8.5750	-0.0000516	-0.0000537	-0.0000542	-0.0000537	-0.0000542	-0.0000505
8.6000	-0.0000672	-0.0000697	-0.0000613	-0.0000595	-0.0000567	-0.0000585
8.6250	-0.0000808	-0.0000836	-0.0000672	-0.0000641	-0.0000579	-0.0000653
8.6500	-0.0000919	-0.0000948	-0.0000715	-0.0000671	-0.0000577	-0.0000707
8.6750	-0.0001000	-0.0001030	-0.0000741	-0.0000685	-0.0000563	-0.0000743
8.7000	-0.0001049	-0.0001078	-0.0000749	-0.0000683	-0.0000536	-0.0000761
8.7250	-0.0001064	-0.0001090	-0.0000740	-0.0000665	-0.0000499	-0.0000760
8.7500	-0.0001045	-0.0001068	-0.0000714	-0.0000633	-0.0000454	-0.0000741
8.7750	-0.0000993	-0.0001011	-0.0000672	-0.0000588	-0.0000403	-0.0000703
8.8000	-0.0000911	-0.0000924	-0.0000617	-0.0000532	-0.0000347	-0.0000648
8.8250	-0.0000804	-0.0000811	-0.0000550	-0.0000467	-0.0000289	-0.0000580
8.8500	-0.0000676	-0.0000676	-0.0000476	-0.0000397	-0.0000231	-0.0000502
8.8750	-0.0000533	-0.0000527	-0.0000397	-0.0000324	-0.0000174	-0.0000416
8.9000	-0.0000382	-0.0000369	-0.0000317	-0.0000251	-0.0000121	-0.0000327
8.9250	-0.0000229	-0.0000210	-0.0000239	-0.0000181	-0.0000074	-0.0000239
8.9500	-0.0000081	-0.0000056	-0.0000166	-0.0000118	-0.0000035	-0.0000155
8.9750	0.0000057	0.0000086	-0.0000100	-0.0000062	-0.0000006	-0.0000079
9.0000	0.0000178	0.0000210	-0.0000044	-0.0000017	0.0000011	-0.0000015
9.0250	0.0000278	0.0000312	-0.0000001	0.0000015	0.0000017	0.0000035
9.0500	0.0000354	0.0000388	0.0000028	0.0000033	0.0000010	0.0000070
9.0750	0.0000401	0.0000434	0.0000041	0.0000037	-0.0000009	0.0000088
9.1000	0.0000420	0.0000451	0.0000038	0.0000025	-0.0000040	0.0000089
9.1250	0.0000408	0.0000436	0.0000019	-0.0000001	-0.0000082	0.0000072
9.1500	0.0000369	0.0000392	-0.0000015	-0.0000040	-0.0000131	0.0000039
9.1750	0.0000303	0.0000321	-0.0000063	-0.0000090	-0.0000187	-0.0000009
9.2000	0.0000213	0.0000225	-0.0000124	-0.0000150	-0.0000246	-0.0000069
9.2250	0.0000104	0.0000110	-0.0000193	-0.0000217	-0.0000306	-0.0000139
9.2500	-0.0000019	-0.0000019	-0.0000268	-0.0000287	-0.0000364	-0.0000216
9.2750	-0.0000152	-0.0000158	-0.0000345	-0.0000358	-0.0000417	-0.0000296
9.3000	-0.0000289	-0.0000300	-0.0000422	-0.0000426	-0.0000464	-0.0000378
9.3250	-0.0000424	-0.0000439	-0.0000494	-0.0000489	-0.0000501	-0.0000456
9.3500	-0.0000551	-0.0000571	-0.0000559	-0.0000543	-0.0000528	-0.0000528
9.3750	-0.0000667	-0.0000688	-0.0000613	-0.0000587	-0.0000544	-0.0000591
9.4000	-0.0000765	-0.0000788	-0.0000655	-0.0000618	-0.0000549	-0.0000642
9.4250	-0.0000842	-0.0000865	-0.0000682	-0.0000637	-0.0000542	-0.0000679
9.4500	-0.0000895	-0.0000917	-0.0000695	-0.0000641	-0.0000525	-0.0000701
9.4750	-0.0000923	-0.0000943	-0.0000693	-0.0000632	-0.0000499	-0.0000706
9.5000	-0.0000924	-0.0000940	-0.0000677	-0.0000610	-0.0000464	-0.0000695
9.5250	-0.0000898	-0.0000911	-0.0000647	-0.0000576	-0.0000423	-0.0000669
9.5500	-0.0000848	-0.0000856	-0.0000605	-0.0000533	-0.0000377	-0.0000628
9.5750	-0.0000774	-0.0000778	-0.0000554	-0.0000482	-0.0000328	-0.0000575
9.6000	-0.0000681	-0.0000680	-0.0000495	-0.0000425	-0.0000279	-0.0000512
9.6250	-0.0000574	-0.0000568	-0.0000431	-0.0000365	-0.0000231	-0.0000443
9.6500	-0.0000456	-0.0000445	-0.0000365	-0.0000305	-0.0000186	-0.0000371
9.6750	-0.0000332	-0.0000318	-0.0000300	-0.0000247	-0.0000146	-0.0000298
9.7000	-0.0000209	-0.0000191	-0.0000238	-0.0000193	-0.0000113	-0.0000229
9.7250	-0.0000092	-0.0000070	-0.0000182	-0.0000146	-0.0000087	-0.0000165
9.7500	0.0000016	0.0000040	-0.0000134	-0.0000107	-0.0000071	-0.0000111
9.7750	0.0000108	0.0000134	-0.0000096	-0.0000077	-0.0000064	-0.0000067
9.8000	0.0000182	0.0000208	-0.0000069	-0.0000059	-0.0000068	-0.0000035
9.8250	0.0000234	0.0000260	-0.0000055	-0.0000053	-0.0000081	-0.0000017
9.8500	0.0000263	0.0000288	-0.0000054	-0.0000059	-0.0000103	-0.0000012
9.8750	0.0000267	0.0000290	-0.0000066	-0.0000076	-0.0000134	-0.0000021
9.9000	0.0000247	0.0000267	-0.0000090	-0.0000104	-0.0000172	-0.0000044
9.9250	0.0000203	0.0000220	-0.0000126	-0.0000142	-0.0000214	-0.0000078
9.9500	0.0000138	0.0000151	-0.0000170	-0.0000187	-0.0000260	-0.0000122
9.9750	0.0000055	0.0000063	-0.0000223	-0.0000238	-0.0000307	-0.0000175
10.0000	-0.0000043	-0.0000039	-0.0000280	-0.0000293	-0.0000353	-0.0000234

10.0250	-0.0000150	-0.0000150	-0.0000341	-0.0000349	-0.0000396	-0.0000297
10.0500	-0.0000263	-0.0000267	-0.0000402	-0.0000404	-0.0000435	-0.0000361
10.0750	-0.0000376	-0.0000385	-0.0000460	-0.0000456	-0.0000468	-0.0000424
10.1000	-0.0000485	-0.0000497	-0.0000513	-0.0000501	-0.0000493	-0.0000483
10.1250	-0.0000586	-0.0000600	-0.0000560	-0.0000539	-0.0000510	-0.0000536
10.1500	-0.0000673	-0.0000689	-0.0000597	-0.0000569	-0.0000519	-0.0000580
10.1750	-0.0000743	-0.0000761	-0.0000625	-0.0000588	-0.0000518	-0.0000614
10.2000	-0.0000795	-0.0000813	-0.0000641	-0.0000597	-0.0000509	-0.0000637
10.2250	-0.0000826	-0.0000843	-0.0000645	-0.0000595	-0.0000493	-0.0000648
10.2500	-0.0000834	-0.0000850	-0.0000638	-0.0000583	-0.0000469	-0.0000646
10.2750	-0.0000821	-0.0000834	-0.0000620	-0.0000561	-0.0000439	-0.0000632
10.3000	-0.0000787	-0.0000797	-0.0000593	-0.0000532	-0.0000405	-0.0000606
10.3250	-0.0000734	-0.0000740	-0.0000556	-0.0000495	-0.0000367	-0.0000570
10.3500	-0.0000664	-0.0000666	-0.0000513	-0.0000453	-0.0000328	-0.0000525
10.3750	-0.0000580	-0.0000578	-0.0000464	-0.0000407	-0.0000289	-0.0000473
10.4000	-0.0000487	-0.0000481	-0.0000413	-0.0000359	-0.0000252	-0.0000417
10.4250	-0.0000389	-0.0000379	-0.0000360	-0.0000311	-0.0000217	-0.0000360
10.4500	-0.0000290	-0.0000275	-0.0000309	-0.0000266	-0.0000188	-0.0000303
10.4750	-0.0000194	-0.0000176	-0.0000261	-0.0000225	-0.0000164	-0.0000249
10.5000	-0.0000105	-0.0000084	-0.0000219	-0.0000190	-0.0000147	-0.0000201
10.5250	-0.0000027	-0.0000004	-0.0000183	-0.0000161	-0.0000137	-0.0000160
10.5500	0.0000038	0.0000062	-0.0000157	-0.0000142	-0.0000135	-0.0000129
10.5750	0.0000086	0.0000110	-0.0000140	-0.0000131	-0.0000142	-0.0000107
10.6000	0.0000116	0.0000139	-0.0000133	-0.0000131	-0.0000156	-0.0000097
10.6250	0.0000127	0.0000148	-0.0000137	-0.0000140	-0.0000178	-0.0000098
10.6500	0.0000118	0.0000137	-0.0000152	-0.0000158	-0.0000206	-0.0000110
10.6750	0.0000091	0.0000106	-0.0000176	-0.0000185	-0.0000239	-0.0000132
10.7000	0.0000046	0.0000058	-0.0000209	-0.0000219	-0.0000275	-0.0000165
10.7250	-0.0000014	-0.0000006	-0.0000248	-0.0000259	-0.0000313	-0.0000205
10.7500	-0.0000086	-0.0000083	-0.0000294	-0.0000302	-0.0000351	-0.0000251
10.7750	-0.0000168	-0.0000169	-0.0000342	-0.0000348	-0.0000388	-0.0000302
10.8000	-0.0000256	-0.0000261	-0.0000392	-0.0000394	-0.0000422	-0.0000355
10.8250	-0.0000347	-0.0000354	-0.0000441	-0.0000438	-0.0000451	-0.0000408
10.8500	-0.0000435	-0.0000446	-0.0000487	-0.0000478	-0.0000476	-0.0000459
10.8750	-0.0000518	-0.0000531	-0.0000528	-0.0000513	-0.0000493	-0.0000505
10.9000	-0.0000593	-0.0000608	-0.0000563	-0.0000541	-0.0000504	-0.0000545
10.9250	-0.0000656	-0.0000672	-0.0000590	-0.0000561	-0.0000508	-0.0000577
10.9500	-0.0000705	-0.0000721	-0.0000607	-0.0000572	-0.0000504	-0.0000601
10.9750	-0.0000739	-0.0000754	-0.0000616	-0.0000575	-0.0000493	-0.0000614
11.0000	-0.0000755	-0.0000768	-0.0000615	-0.0000569	-0.0000476	-0.0000617
11.0250	-0.0000754	-0.0000765	-0.0000604	-0.0000554	-0.0000454	-0.0000610
11.0500	-0.0000736	-0.0000744	-0.0000585	-0.0000533	-0.0000427	-0.0000592
11.0750	-0.0000702	-0.0000706	-0.0000558	-0.0000505	-0.0000397	-0.0000566
11.1000	-0.0000653	-0.0000654	-0.0000525	-0.0000472	-0.0000366	-0.0000532
11.1250	-0.0000591	-0.0000590	-0.0000487	-0.0000436	-0.0000334	-0.0000491
11.1500	-0.0000520	-0.0000516	-0.0000446	-0.0000398	-0.0000303	-0.0000447
11.1750	-0.0000443	-0.0000436	-0.0000403	-0.0000359	-0.0000274	-0.0000400
11.2000	-0.0000363	-0.0000353	-0.0000361	-0.0000321	-0.0000248	-0.0000354
11.2250	-0.0000283	-0.0000271	-0.0000321	-0.0000286	-0.0000227	-0.0000310
11.2500	-0.0000207	-0.0000194	-0.0000285	-0.0000256	-0.0000211	-0.0000269
11.2750	-0.0000139	-0.0000124	-0.0000254	-0.0000231	-0.0000202	-0.0000234
11.3000	-0.0000080	-0.0000065	-0.0000230	-0.0000213	-0.0000198	-0.0000206
11.3250	-0.0000033	-0.0000019	-0.0000213	-0.0000202	-0.0000202	-0.0000186
11.3500	-0.0000001	0.0000013	-0.0000205	-0.0000198	-0.0000211	-0.0000174
11.3750	0.0000015	0.0000028	-0.0000205	-0.0000203	-0.0000226	-0.0000172
11.4000	0.0000016	0.0000027	-0.0000214	-0.0000215	-0.0000247	-0.0000178
11.4250	0.0000000	0.0000010	-0.0000230	-0.0000234	-0.0000272	-0.0000193
11.4500	-0.0000030	-0.0000022	-0.0000254	-0.0000259	-0.0000299	-0.0000216
11.4750	-0.0000074	-0.0000068	-0.0000284	-0.0000289	-0.0000329	-0.0000246
11.5000	-0.0000130	-0.0000126	-0.0000318	-0.0000323	-0.0000359	-0.0000281
11.5250	-0.0000194	-0.0000192	-0.0000356	-0.0000359	-0.0000389	-0.0000321
11.5500	-0.0000265	-0.0000265	-0.0000396	-0.0000396	-0.0000418	-0.0000363
11.5750	-0.0000339	-0.0000341	-0.0000435	-0.0000432	-0.0000443	-0.0000405
11.6000	-0.0000414	-0.0000417	-0.0000473	-0.0000465	-0.0000465	-0.0000447
11.6250	-0.0000485	-0.0000489	-0.0000508	-0.0000495	-0.0000483	-0.0000485
11.6500	-0.0000549	-0.0000555	-0.0000538	-0.0000520	-0.0000495	-0.0000520
11.6750	-0.0000606	-0.0000613	-0.0000563	-0.0000540	-0.0000501	-0.0000548
11.7000	-0.0000651	-0.0000659	-0.0000581	-0.0000552	-0.0000501	-0.0000571
11.7250	-0.0000683	-0.0000692	-0.0000591	-0.0000558	-0.0000495	-0.0000585
11.7500	-0.0000702	-0.0000710	-0.0000595	-0.0000557	-0.0000484	-0.0000592
11.7750	-0.0000706	-0.0000715	-0.0000590	-0.0000549	-0.0000468	-0.0000590
11.8000	-0.0000696	-0.0000704	-0.0000579	-0.0000535	-0.0000448	-0.0000581
11.8250	-0.0000673	-0.0000680	-0.0000560	-0.0000515	-0.0000426	-0.0000563
11.8500	-0.0000637	-0.0000643	-0.0000537	-0.0000491	-0.0000401	-0.0000539
11.8750	-0.0000591	-0.0000595	-0.0000508	-0.0000463	-0.0000375	-0.0000510
11.9000	-0.0000536	-0.0000539	-0.0000476	-0.0000433	-0.0000350	-0.0000476
11.9250	-0.0000475	-0.0000476	-0.0000442	-0.0000402	-0.0000326	-0.0000439
11.9500	-0.0000411	-0.0000410	-0.0000408	-0.0000372	-0.0000304	-0.0000402
11.9750	-0.0000346	-0.0000344	-0.0000375	-0.0000342	-0.0000285	-0.0000365
12.0000	-0.0000284	-0.0000279	-0.0000344	-0.0000316	-0.0000271	-0.0000330

12.0250	-0.0000227	-0.0000220	-0.0000317	-0.0000294	-0.0000261	-0.0000299
12.0500	-0.0000177	-0.0000168	-0.0000294	-0.0000276	-0.0000255	-0.0000273
12.0750	-0.0000136	-0.0000126	-0.0000278	-0.0000264	-0.0000255	-0.0000253
12.1000	-0.0000106	-0.0000096	-0.0000267	-0.0000258	-0.0000260	-0.0000240
12.1250	-0.0000088	-0.0000077	-0.0000264	-0.0000259	-0.0000270	-0.0000235
12.1500	-0.0000083	-0.0000072	-0.0000268	-0.0000265	-0.0000285	-0.0000237
12.1750	-0.0000090	-0.0000079	-0.0000278	-0.0000278	-0.0000303	-0.0000246
12.2000	-0.0000110	-0.0000100	-0.0000294	-0.0000296	-0.0000325	-0.0000262
12.2250	-0.0000141	-0.0000132	-0.0000317	-0.0000319	-0.0000348	-0.0000284
12.2500	-0.0000181	-0.0000174	-0.0000343	-0.0000346	-0.0000374	-0.0000312
12.2750	-0.0000230	-0.0000225	-0.0000374	-0.0000375	-0.0000399	-0.0000343
12.3000	-0.0000284	-0.0000282	-0.0000406	-0.0000405	-0.0000424	-0.0000377
12.3250	-0.0000343	-0.0000343	-0.0000439	-0.0000435	-0.0000446	-0.0000412
12.3500	-0.0000402	-0.0000405	-0.0000471	-0.0000464	-0.0000466	-0.0000447
12.3750	-0.0000460	-0.0000465	-0.0000501	-0.0000490	-0.0000482	-0.0000480
12.4000	-0.0000515	-0.0000521	-0.0000528	-0.0000513	-0.0000494	-0.0000510
12.4250	-0.0000564	-0.0000572	-0.0000550	-0.0000531	-0.0000501	-0.0000536
12.4500	-0.0000605	-0.0000614	-0.0000568	-0.0000545	-0.0000504	-0.0000556
12.4750	-0.0000636	-0.0000646	-0.0000579	-0.0000552	-0.0000501	-0.0000571
12.5000	-0.0000657	-0.0000667	-0.0000585	-0.0000554	-0.0000494	-0.0000579
12.5250	-0.0000667	-0.0000677	-0.0000584	-0.0000550	-0.0000483	-0.0000581
12.5500	-0.0000665	-0.0000675	-0.0000577	-0.0000541	-0.0000468	-0.0000575
12.5750	-0.0000652	-0.0000661	-0.0000564	-0.0000527	-0.0000451	-0.0000564
12.6000	-0.0000629	-0.0000636	-0.0000547	-0.0000508	-0.0000431	-0.0000547
12.6250	-0.0000596	-0.0000601	-0.0000525	-0.0000487	-0.0000411	-0.0000524
12.6500	-0.0000555	-0.0000559	-0.0000500	-0.0000463	-0.0000390	-0.0000498
12.6750	-0.0000509	-0.0000510	-0.0000473	-0.0000437	-0.0000370	-0.0000470
12.7000	-0.0000458	-0.0000457	-0.0000446	-0.0000412	-0.0000351	-0.0000439
12.7250	-0.0000406	-0.0000403	-0.0000418	-0.0000388	-0.0000335	-0.0000409
12.7500	-0.0000354	-0.0000350	-0.0000392	-0.0000366	-0.0000322	-0.0000381
12.7750	-0.0000305	-0.0000299	-0.0000369	-0.0000347	-0.0000312	-0.0000354
12.8000	-0.0000261	-0.0000254	-0.0000350	-0.0000331	-0.0000307	-0.0000332

7.2 The Simulation Program of Static Exciter with Transient Gain Reduction

```
C  STATIC EXCITATION SYSTEM WITH TRANSISENT GAIN REDUCTION
      SUBROUTINE AVR4(I)
      COMMON/BLOCK1/ TIME,TSTEP
      COMMON/BLOCK3/ KA(10),KF(10),TA(10),TF(10),KP(10),
     1 TL1(10),TL2(10),DUM(10,9)
      COMMON/BLOCK5/ VT(10),CT(10),EF(10),PM(10)
      COMMON/BLOCK6/ PLUG(10,16),OUT(10,16),SAVE(10,16)
      COMMON/BLOCK9/ PRTVAR(10,20)
      COMPLEX VT,CT
      REAL KA,KF,KP,VREF(10)
C  ENTER HERE FOR EACH INTEGRATION STEP.
C  DEFINE INTEGRATOR OUTPUTS.
      X5=OUT(I,5)
      X6=OUT(I,6)
      X7=OUT(I,7)
C  CALCULATE INTERMEDIATE VARIABLES.
      EF(I)=X6
      VMAG=CABS(VT(I))
      IF(X6.GT.KP(I)*VMAG) EF(I)=KP(I)*VMAG
      IF(X6.LT.-KP(I)*VMAG) EF(I)=-KP(I)*VMAG
      X2=EF(I)*KF(I)/TF(I)-X7
      X1=VREF(I)-VMAG
      X4=X1-X2
```

```
      X3=X4*TL1(I)/TL2(I)+X5
C  CALCULATE INTEGRATOR INPUTS.
      PLUG(I,5)=X4/TL2(I)-X3/TL2(I)
      PLUG(I,6)=X3*KA(I)/TA(I)-X6/TA(I)
      PLUG(I,7)=X2/TF(I)
      RETURN
C  ENTER HERE TO CALCULATE INITIAL CONDITIONS.
      ENTRY AVR4IC(I)
      OUT(I,5)=EF(I)/KA(I)
      OUT(I,6)=EF(I)
      OUT(I,7)=EF(I)*KF(I)/TF(I)
      VREF(I)=CABS(VT(I))+EF(I)/KA(I)
C  CHECK IF INITIAL CONDITIONS ARE WITHIN LIMITS.
      VMAG=CABS(VT(I))
      IF(EF(I).GT.KP(I)*VMAG) WRITE(16,1020) I
      IF(EF(I).LT.-KP(I)*VMAG) WRITE(16,1020) I
1020  FORMAT('0**** AVR VOLTAGE LIMIT IS EXCEEDED BY
     1 INITIAL FIELD ON',' UNIT',I3/)
      RETURN
      END
```

7.3 The Simulation Program of Static Exciter with Auxiliary Stabilizer

```
C  MODEL OF STATIC EXCITATERS WITH AUXILIARY STABILIZER
         SUBROUTINE AVR5(I,w)
         COMMON/BLOCK1/ TIME,TSTEP
         COMMON/BLOCK2/ PBASE(10),H(10),R(10),XL(10),XD(10),
     1   XD1(10),XQ(10),XQ1(10),TD1(10),TQ1(10),DAMP(10),
     1   C1(10),C2(10)
         COMMON/BLOCK3/ KA(10),KF(10),TA(10),TF(10),KP(10),
     1   T1(10),KS(10),B(10),C(10),T2(10),KT(10),TFD(10),
     1   DUM(10,2)
         COMMON/BLOCK5/ VT(10),CT(10),EF(10),PM(10)
         COMMON/BLOCK6/ PLUG(10,16),OUT(10,16),SAVE(10,16)
         COMMON/BLOCK9/ PRTVAR(10,20)
         COMPLEX VT,CT
         REAL KA,KF,KP,KT,KS,C,B,VREF(10)
C  ENTER HERE FOR EACH INTEGRATION STEP.
C  DEFINE INTEGRATOR OUTPUTS.
         OME=OUT(I,1)
         X11=OME
         IF (W.EQ.0) GO TO 17
         X11=.01*SIN(w*time)
17       X12=OUT(I,12)
         X5=OUT(I,13)
         X14=OUT(I,14)
```

```
      X15=OUT(I,15)
      X17=OUT(I,16)
C  CALCULATE INTERMEDIATE VARIABLES.
      EF(I)=X15
      VMAG=CABS(VT(I))
      IF(X15.GT.KP(I)*VMAG) EF(I)=KP(I)*VMAG
      IF(X15.LT.-KP(I)*VMAG) EF(I)=-KP(I)*VMAG
      X2=X12+B(I)*KS(I)*X11/(T2(I)**2)
      X13=X5+X11*KS(I)/T2(I)**2
      X3=X13+X14
      X16=EF(I)*KF(I)/TF(I)-X17
      X4=X3+VREF(I)-X16-VMAG
      PRTVAR(6,13)=X3
C  CALCULATE INTEGRATOR INPUTS.
      PLUG(I,12)=X11*C(I)*KS(I)/(T2(I)**2)-X13/(T2(I)**2)
      PLUG(I,13)=X2-2*X13/T2(I)
      PLUG(I,14)=-X3/T1(I)
      PLUG(I,15)=X4*KA(I)/TA(I)-X15/TA(I)
      PLUG(I,16)=1/TF(I)*X16
      RETURN
C  ENTER HERE TO CALCULATE INITIAL CONDITIONS.
      ENTRY AVR5IC(I)
      OUT(I,12)=0.0
      OUT(I,13)=0.0
      OUT(I,14)=0.0
      OUT(I,15)=EF(I)
```

```
      OUT(I,16)=EF(I)*KF(I)/TF(I)
      VREF(I)=EF(I)/KA(I)+CABS(VT(I))
C  CHECK IF INITIAL CONDITIONS ARE WITHIN LIMITS.
      VMAG=CABS(VT(I))
      IF(EF(I).GT.KP(I)*VMAG) WRITE(16,1020) I
      IF(EF(I).LT.-KP(I)*VMAG) WRITE(16,1020) I
1020  FORMAT('0**** AVR VOLTAGE LIMIT IS EXCEEDED BY
     1 INITIAL FIELD ON',' UNIT',I3/)
      RETURN
      END
```