Sudan University of Science &Technology
College of Engineering
School of Electrical & NuclearEngineering

Assessment of PSS Performance for Damping Low Frequency Oscillations in power system

تقييم أداء متحكمة(PSS) لتخميد التذبذبات الصغيرة في منظومة القدرة الكهربائية

A Project Submitted In Partial Fulfillment for the Requirements of the Degree of B.Sc. (Honor) In Electrical Engineering

Prepared By:-

1- **Abubakr Mahjoub Mohammed Mustafa**
2- **Osman Hassan khader Osman**
3- **Azzam Emad Aldeen Abdlmoneam**
4- **Mohammed Amin khidir Mohammed**

Supervised By:

Dr. Mohammed Osman Hassan

October 2017

الآية

قال تعالى :

" اللَّهُ لَا إِلَهَ إِلَّا هُوَ الْحَيُّ الْقَيُّومُ لَا تَأْخُذُهُ سِنَةٌ وَلَا نَوْمٌ لَهُ مَا فِي السَّمَاوَاتِ وَمَا فِي الْأَرْضِ مَنْ ذَا الَّذِي يَشْفَعُ عِنْدَهُ إِلَّا بِإِذْنِهِ يَعْلَمُ مَا بَيْنَ أَيْدِيهِمْ وَمَا خَلْفَهُمْ وَلَا يُحِيطُونَ بِشَيْءٍ مِنْ عِلْمِهِ إِلَّا بِمَا شَاءَ وَسِعَ كُرْسِيُّهُ السَّمَاوَاتِ وَالْأَرْضَ وَلَا يَئُودُهُ حِفْظُهُمَا وَهُوَ الْعَلِيُّ الْعَظِيمُ "

صدق الله العظيم

البقرة (255)

DEDICATION

Every challenging work needs self-efforts as well as guidance of elders especially those who were very close to our hearts. Our humble effort is dedicated to our sweet and loving parents, our brothers, our sisters and our friends whose affection and encouragement make us able to get such success and honor. This project would have never been possible without their support and love.

ACKNOWLEDGEMENT

First and foremost we thank fully our god (Allah) who bestowed his blessings upon us. We would like to express our sincere gratitude to our advisor **Dr. Mohammed Osman Hassan** for his directions, excellent guidance and support to complete the work in his fair way.

Also we express our deep gratitude to **Ust. Ahmed Khalid Al-haj** for his insightful comments and suggestions which continually helped us to improve our understanding.

Lastly we need to thank our teachers in electrical and nuclear engineering school for their support.

Abstract

The power system consists of a number of synchronous generators in different power stations that rotate at synchronous speeds to feed the required loads in case of the stability. However, when these loads change or fault occurs that cause the swing of these machines due to inequality of input and output capacity of generators, the effect of this oscillation may transfer from one machine to another through the network of the system, which leads to increase the oscillation of some machines and system blackout or damping this swing and return to stability by using one of the damping controller.

In this research, the performance and efficiency of Power System Stabilizer (PSS) was studied by applying it to (3-machine 9-bus) by finding the eigenvalues and time domain simulation under different operating conditions represent the system's response to low oscillations which came from low change in mechanical input capacity, The results of eigenvalue analysis and time domain proved efficient and effective of PSS in enhancing stability and increasing the percentage of damping ratio.

المستخلص

تتكون منظومة القدرة الكهربائية من عدد من المولدات التزامنية في محطات القدرة المختلفة التي تدور بسرعات تزامنية لتغذية الأحمال المطلوبة منها في حالة الأستقرار, اما عند حدوث تغير في هذه الأحمال او حدوث عطل ما فان ذلك يتسبب في تأرجح هذه الماكينات بسبب عدم تساوي قدرتا الدخل والخرج للمولدات التزامنية , وينتقل تأثير هذا التأرجح من الة الى اخرى عبر شبكة المنظومة مما يؤدي الى زيادة تأرجح بعض الالات وخروجها من الخدمة او يتم اخماد هذا التأرجح والعودة الى الاستقرار باستخدام احد متحكمات التخميد.

في هذا البحث تم دراسة اداء وكفاءة متحكم(مثبت نظام القدرة) وذلك بتطبيقه على شبكة تضم ثلاث ماكينات وتسع قضبان وذلك بايجاد القيم المميزة والمحاكاة في حيز الزمن تحت ظروف تشغيلية مختلفة تمثل استجابة النظام للاهتزازات الخفيفة التي نشأت لتغير طفيف في قدرة الدخل الميكانيكية , نتائج تحليل القيم المميزة والمحاكاة في حيز الزمن للمنظومة أثبتت كفاءة وفعالية (مثبت نظام القدرة) في تعزيز الاستقرارية و زيادة نسبة التخميد.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

PSS	Power System Stabilizer
AVR	Automatic Voltage Regulator
HVDC	High Voltage Direct Current
LFO	Low Frequency Oscillation
DAE	Differential Equation
PF	Participation Factor
HPF	High-Pass Filter
LHP	Left Half Plane
DC	Direct Current
AC	Alternating Current
LPF	Low-Pass Filter
SPE	Sensitivity of PSS Effect
OPLI	Optimum PSS Location Index
GA	Genetic Algorithm
FACTS	Flexible AC Transmission System

LIST OF SYMBOLS

J	Total moment of inertia of the rotating masses, $Kg.m^2$
T_m	Mechanical torque supplied by the prime mover, $N.m$
T_e	Electrical torque developed in, $N.m$
T_a	Net accelerating torque, $N.m$
θ_m	Angular displacement of the rotor in rad, mech
T_s	Synchronizing torque coefficient
T_D	Damping torque coefficient
x	State vector
u	Input vector
λ	Eigenvalue
σ	Damping constant
ω	Angle speed
f	Frequency
ζ	Damping ratio
ϕ_i	Right eigenvector
ψ_i	Left eigenvector
P_i	Participation factor
V_s	Output signal
K_s	PSS gain
T_W	Washout filter time constant
$G_C(s)$	Compensation gain
T_1, T_2, T_3, T_4	Phase compensation time constants
$FILT(S)$	Transfer function of the filter
ω_n	Natural frequency
A	State matrix
VR_i	Limit constraints on AVR output
T_F	Damping torque
D	Damping constant, pu
ω_i	Rotor speed, rad/sec
ω_s	Synchronous speed, rad/sec
M_i	Mutual inductance, H
I_{qi}	Steady-state current along the q-axis
I_{di}	Steady-state current along the d-axis

$X_d^{'}$	Direct axis transient reactance(pu)
$X_q^{'}$	Quadrature axis transient reactance(pu)
$T_{do}^{'}$	Time constant for the field windings
$E_q^{'}$	q-axis component of voltage behind transient reactance (pu)
X_d	Synchronous reactance along the direct axis (d-axis),pu
E_{fd}	Steady-state-induced emf or open-circuit voltage, volt
$T_{do}^{'}$	d-axis open circuit time constant (s)
$E_{di}^{'}$	d-axis component of voltage behind transient reactance (pu)
X_{qi}	Synchronous reactance along the quadrature axis (q-axis),pu
T_A	Time constant of exciter system
K_A	AVR gain
V_{ref}	Reference excitation voltage, pu
V	Machine terminal voltage, pu
R_{s_i}	Armature resistance(pu)
θ	Bus voltage angle, Degree
P_{L_i}	Real power load, Watt
Y_{ik}	Transmission line admittance between node i and k, pu
α_{ik}	Transmission line admittance angle between node i and k, Degree
Q_{L_i}	Reactive power load, VAR
Δ	Deviation operator
$E_q^{'}$	q-axis component of voltage behind transient reactance, pu
$E_d^{'}$	d-axis component of voltage behind transient reactance, pu
$T_{qo}^{'}$	q-axis open circuit time constant (s)
I_d	d-axis component of current (pu)
$\lambda^{'}$	Critical swing modes after adding PSS
λ^{o}	Critical swing modes before adding PSS
I_q	q-axis component of current (pu)

CHAPTER ONE

INTRODUCTION

1.1 Background

Power system stability is a complex subject that has challenged power system engineers for many years. The historical review of this subject is useful for a better understanding of present-day stability problems. Environmental constraints restrict expansion of transmission network and the need for long distance power transfers has increased. As a result, stability has become a major concern in power systems. Accidents of power system blackouts caused by rotor angle instability, voltage instability or frequency instability.

Power system stability may be broadly defined as the property of a power system that enables it to remain in state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [1].

The power system stability can be classified into different types: angular stability, voltage stability and frequency stability. The angular stability can be categorized into small signal stability and transient stability. Small-signal stability is the ability of the system to return to its normal operating state following a small disturbance. Investigation of this kind of stability usually involves the analysis of the linearized state space equations that define the power system dynamics. On the other hand, , transient stability is the ability of the system to return to a normal operating state following a severe disturbance, such as a single-phase or multi-phase short-circuit or a generator lost. Under these conditions, the linearized power system model is not sufficient and the nonlinear equations must be used for the analysis [2].

1.2 Problem Statement

The power system stability problem is concerned with the behavior of the synchronous machines after they have been perturbed. If the perturbation does not involve any net change in power, the machines should return to their original state. If an unbalance between the supply and demand is created by a change in load, generation, or in network conditions, a new operating state is necessary. In any case all interconnected synchronous machines should remain in synchronism if the system is stable; i.e., they should all remain operating in parallel and at the same speed. The low frequency oscillations can be initiated by small disturbance. The range of it from 0.1 -2 Hz. Small disturbance can be occur due to incremental changes in system load.

1.3 Objectives

- Study and analysis the behavior of multi-machine power system without controllers after served to different faults and operating conditions.
- Design of power system stabilizer (PSS) controller for damping low frequency oscillations.
- Study the effect of PSS on damping low frequency oscillations in power system.

1.4 Methodology

First, differential Equations describing the power system, state space model were derived devolved and linearized. Eigenvalues has been computed from state matrix (A).The frequency modes have been determined from this eigenvalues then the PSS has been added in optimal location to increase the damping ratio which return the system in stability condition. And compared between the damping ratios before adding the PSS and after adding.

Finally software (Matlab/Simulink) was used to investigate the response of the system.

1.5 Thesis lay-out

Chapter One: This chapter represented a Background to power system stability, problem statement, project objectives and methodology of project.

Chapter Two: Includes the definition, classification of stability and modeling of power system.

Chapter Three: Linearization of multi-machines system and power system stabilizer (PSS) design.

Chapter Four: Represent the results of the eigenvalue analysis and time domain simulation of small signal stability. The case study (3-machines, 9-busbars).

Chapter Five: involve the project conclusion and recommendations.

CHAPTER TWO

POWER SYSTEM MODELING AND DEFINITION OF STABILITY

2.1 Main Components of Power Systems

An electric power system is a network of electrical components used to supply, transfer and use electric power. This power system is known as the grid and can be broadly divided into the generators that supply the power, the transmission system that carries the power from the generating centers to the load centers and the distribution system that feeds the power to nearby homes and industries.

One of the main difficulties in power systems is that the amount of active power consumed plus losses should always equal the active power produced.

The motion of the synchronous generator's rotor is determined by Newton's second law:

$$J\frac{d^2\theta_m}{dt^2} = T_a = T_m - T_e \tag{2.1}$$

Where: $J \equiv$ the total moment of inertia of the rotating mass ($Kg.m^2$).

$T_m \equiv$The mechanical torque supplied by the prime mover ($N.m$).

$T_e \equiv$The electrical torque developed in ($N.m$).

$T_a \equiv$The net accelerating torque ($N.m$).

$\theta_m \equiv$ The angular displacement of the rotor in rad (mech).

2.1.1 Generations

All power systems have one or more sources of power. Alternating current power is typically supplied by a rotor that spins in a magnetic field in a device known as a turbo generator. There have been a wide range of techniques used to spin a turbine's rotor, from steam heated using fossil fuel (including coal, gas and oil) or nuclear energy, falling water (hydroelectric power) and wind (wind power). The speed at which the rotor spins in combination with the number of generator poles determines the frequency of the alternating current produced by the generator.

All generators on a single synchronous system, for example the national grid, rotate at sub-multiples of the same speed and so generate electric current at the same frequency.

2.1.2 Loads

The loads that generation units supply range from household appliances to industrial machinery. Most loads expect a certain voltage and, for alternating current devices, a certain frequency and number of phases. Making sure that the voltage, frequency and amount of power supplied to the loads are in line with expectation is a highly important operation of requirement. In addition to the power used by a load to do useful work (termed real power) many alternating current devices also use an additional amount of power because they cause the alternating voltage and alternating current to become slightly out-of-sync (termed reactive power).

The reactive power like the real power must balance. So ideal power system must supply power, practically everywhere the customer demands, at all time, with good quality, economical, and rigorous safe requirements [3].

2.1.3 Transmission line modeling

Transmission Lines are modeled as a nominal π circuit as shown in Figure (2.1).

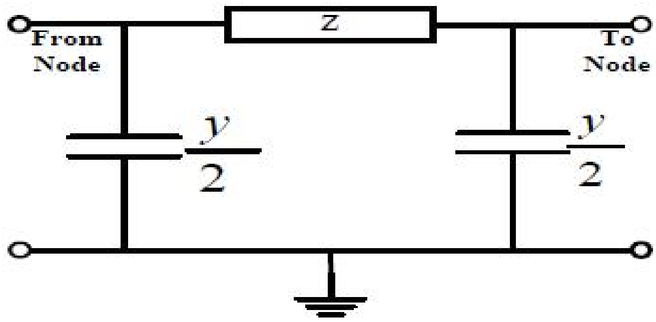

Figure 2.1: Transmission Lines as a nominal π circuit.

Z ≡ Represents the series impedance of the line.

$\frac{Y}{2}$ ≡ Represents half of the total line charging y, at each node.

2.1.4 Excitation system modeling

The main objective of the excitation system is to control the field current of the synchronous machine. The field current is controlled so as to regulate the terminal voltage of the machine.

There are three distinct types of excitation systems based on the power source for exciter:

- DC excitation systems: which utilize a DC generator with commutator.
- AC excitation systems: which use alternators and either stationary or rotating rectifiers to produce the direct current needed.
- Static excitation systems: in which the power is supplied through transformers and rectifiers. The first two types of exciters are also called rotating exciters which are mounted on the same shaft as the generator and driven by the prime mover [4].The exciters data that used are shown in Appendix (A.3).

2.2 Power System Stability Concepts and Classifications

Power system stability may be broadly defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state equilibrium after being subjected to a disturbance

Instability in a power may be manifested in many different ways depending on the system configuration and operating mode. Traditionally, the stability problem has been one of maintaining synchronous operation [1].

Classification is essential for meaningful practical analysis and resolution of power system stability problems, and Figure below show overall picture of this classification, which is:

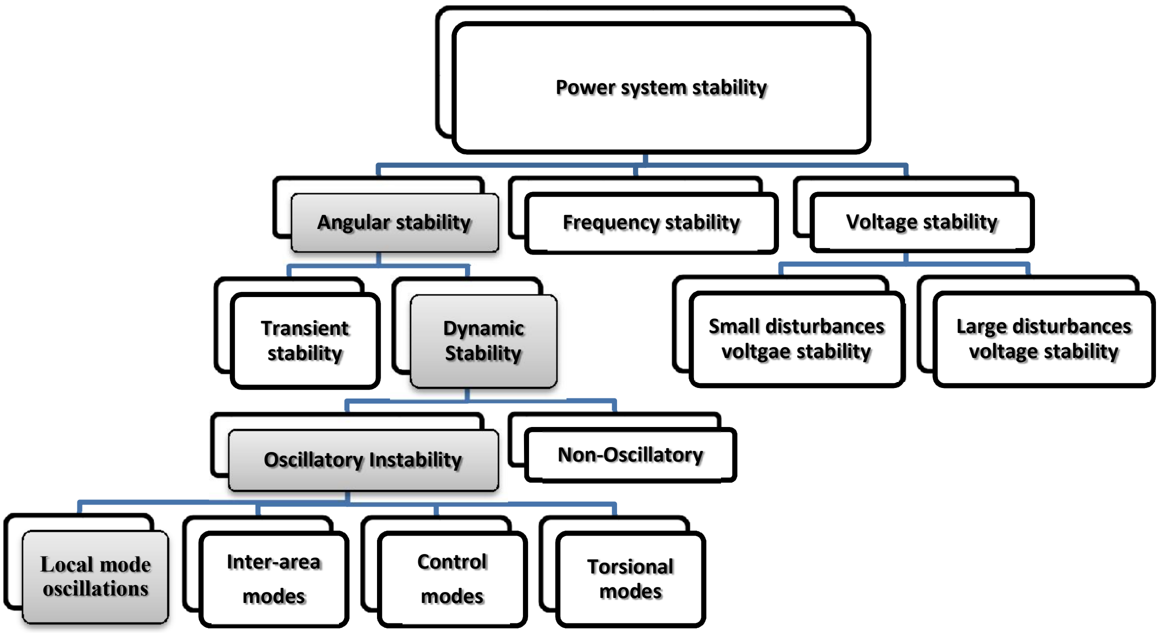

Figure 2.2: Classification of power system stability types.

- Rotor Angle Stability: refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance.
- Frequency Stability: refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load.
- Voltage stability: refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition.A system enters into a state of voltage instability when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable drop in voltage [1].

  Bbroadly classified into two main categories: Angle stability or rotor angle stability and voltage stability.

2.3 Rotor Angle Stability

Angle stability or rotor angle stability can be defined as previously as the ability of interconnected synchronous machines of a power system to remain in synchronism.

This stability problem involves the study of electromechanical oscillations inherent in power systems.

The rotor angle stability phenomena in terms of the following two types:

2.3.1 Small signal (small-disturbance)

Small signal (or small-disturbance) stability is the ability of the power system to maintain synchronism under small disturbances; it is causes by small variations in loads and generation.

2.3.2 Transient stability

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. Disturbance of widely varying degrees of severity and probability of occurrence can occur on the system. The system is, however designed and operated so as to be stable for a selected set of contingencies.

2.4 Modes of Oscillations

- Local mode oscillations, which are associated with the swing of units at generating station with respect to the rest of the power systems. Typical range of frequency of oscillations is 1-3 Hz. The term local is used because the oscillations are localized at one station or a small part of the power system.
- Inter-area mode oscillations, which are associated with the swing of many machines in one part of the system against the machines in other parts or areas. Typical range of frequency of these types of oscillations is less than 1 Hz. They are caused by two or more groups of closely coupled machines being interconnected by weak ties [4].
- Control modes are associated with generating units and other controls. Poorly tuned exciter, speed governors, HVDC converters and static VAR-compensator are the usual cause of instability of these modes.
- Torsional modes are associated with the turbine-generator shaft system rotational components. Instability of torsional modes may be caused by interaction with excitation controls, speed governors, HVDC controls, and series-capacitor-compensated lines, with frequencies ranging from 4 Hz [1].

There are two methods of analysis that are available to study the aforementioned electromechanical oscillations:

- A linearized single-machine infinite-bus system case that investigates only local oscillations.
- A multi-machine linearized analysis that computes the eigenvalues and also finds those machines that contribute to a particular eigenvalue for both local and inter-area modes.

2.5 Small Signal Stability Analysis Procedures

The small signal stability or LFO study of the system can be determined by system eigenvalues at an operating point. The relative participation of state variables and their contribution in certain oscillation mode are given by the corresponding elements in the right and left eigenvectors.

Hence, combination of left and right eigenvectors yield participation factor matrix. The participation factor matrix can be used to identify the dominant state variable in a particular mode.

The following steps are followed in studying LFO of power systems:

- Finding equilibrium or operating point.
- Linearization DAE model around the equilibrium point.
- Forming the reduced system state matrix.
- Finding eigenvalues, eigenvectors and Participation matrix.

In order for the system to be stable or oscillation free, all the eigenvalues should be located in the open left half plane. This means that real part of the eigenvalues should be negative and damping ratio should be positive with more than a pre specified value according to utilized practice (typically damping ratio should be higher than 0.05). If at least one of the eigenvalues has positive real part the system is said to be unstable .More specifically, in oscillatory unstable case.The drawback of eigenvalue analysis is that the higher order terms neglected from the linearized set of equation.

A disturbance is considered to be small if the equations that represent the dynamic performance of the system can be linearized for the purpose of analysis function of both the operating conditions and the disturbance. When linearizing a power system and plotting the eigenvalues in the complex plane, a compact description of the power system's dynamic behaviour is obtained.

2.5.1 The eigenvalue and modal analysis module

Eigenvalue analysis investigates the dynamic behaviour of a power system under different characteristic frequencies (modes).

Specifically it provides:

- Methods to investigate long-term stability.
- Allows a deeper view into eigenvectors.
- Determines the best damping locations.
- Allows an evaluation of damping strategies.

The results of an eigenvalue analysis are given as frequency and relative damping for each oscillatory mode, and the response of the system is caused by the location of the eigenvalues. The number of eigenvalues in a power system increases with the size of it.

2.5.2 State-space representation and linearization

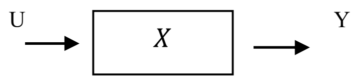

Figure 2.3 Dynamic system

Every dynamic system can be described with a state vector x, an input vector u, and an output vector **y**, as in figure (2.3). The state vector x contains the n state variables of the dynamic system. A state variable is a variable in the system that has to be time-derived through a time simulation. System in figure (2.3) can be described with the two functions f and g:

$$\dot{X} = f(X, U) \qquad (2.3)$$

$$Y = g(X, U) \qquad (2.4)$$

By disturbing the system in Figure (2.3) with small deviations in state vector X and the input vector **u**, the linearized form of the dynamic system can be written as:

$$\Delta\dot{X} = A\Delta X + B\Delta U \quad (2.5)$$

$$\Delta Y = C\Delta X + D\Delta U \quad (2.6)$$

The matrix Ain above equation is the state matrix of size $[n \times n]$ and the poles of the dynamic system are the roots of the equation.

$$\det(SI - A) = 0 \quad (2.7)$$

The values of s which satisfy the above are known as eigenvalues of matrix$A$, and above equation is referred to as the characteristic equation of matrix$A$, and the number of eigenvalues are always the same as the dimension of matrix$A$. Some of them can be multiple.

2.5.3 Eigenvalues in complex plane

The eigenvalues can be complex in the form of $\lambda = \sigma + j\omega$, where ω is given in Hz (not in radians/second). σ ≡ The damping constant and ω is the angle speed, and therefore it is useful to depict them in the complex plane. It is common to place eigenvalues in the complex plane. If an eigenvalue is damped, σ< 0, then it is located in the left-half plane, LHP. The left-half plane is the open left half of the complex plane, excluding the imaginary axis ($j\omega$-axis). Eigenvalues in the left-half plane are called stable eigenvalues.

The real component of an eigenvalue gives the damping, and the imaginary part gives the frequency of oscillation in Hz by:

$$f = \frac{\omega}{2\pi} \quad (2.8)$$

And the damping ratio:

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2+\omega^2}} \quad (2.9)$$

2.5.4 Eigenvectors

For every eigenvalue there exist two eigenvectors, right and left eigenvector. The right eigenvector gives information about the observability of oscillations. The left eigenvector gives information about the controllability. The combination of the right and left eigenvectors (residues) indicates the location of the damping controllers. For any eigenvalue λ_i, the column vector of dimension n, ϕ_i which satisfies in equation below is called the right eigenvector of A, which is:

$$A\phi_i = \lambda_i\phi_i \tag{2.10}$$

$$\phi_i = \begin{bmatrix} \phi_{1i} \\ \phi_{2i} \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \phi_{ni} \end{bmatrix} \tag{2.11}$$

The right eigenvector measures the activity of the state variables of mode. For any eigenvalue λ_i, the column vector of dimension n ,ψ_i which satisfies equation below is called the left eigenvector of A, which is:

$$\psi_i^T A = \lambda_i\psi_i^T \tag{2.12}$$

$$\psi_I = \begin{bmatrix} \psi_{i1} \\ \psi_{i2} \\ \vdots \\ \vdots \\ \vdots \\ \psi_{in} \end{bmatrix} \tag{2.13}$$

The left eigenvector weighs the contribution of the activity of the state variables to mode i.

2.5.5 Participation factors

The participation factor P is useful in identifying those states which have the most influence on any mode. The participation factor is non-dimensional.

$$P_i = \begin{bmatrix} P_{1i} \\ P_{2i} \\ \vdots \\ \vdots \\ \vdots \\ P_{ni} \end{bmatrix} \begin{bmatrix} \phi_{1i}\psi_{i1} \\ \phi_{2i}\psi_{i2} \\ \vdots \\ \vdots \\ \vdots \\ \phi_{ni}\psi_{in} \end{bmatrix} \qquad (2.14)$$

The element $P_{ki} = \phi_{ki}\psi_{ik}$ is called a participation factor. It is a measure of the relative participation of the kth state variable in the ith mode, and vice versa. In effect participation factors are useful in identifying those state variables which have the most influence on any mode.

The higher the value of participation factor of a state for a corresponding mode, the more active that state is in that mode when compared with the other states. Thus the values of participation factors can reveal which generators are involved in a particular mode. It reveal which machine or machines could go out of step for any known mode or modes that might cause problem in the power system in the advent of load variation.

The participation factors are used to identify the areas in the power system where any mode or (oscillation) has most of its effect [5].

2.6 Power System Stabilizer

PSS can help to damp generator rotor oscillations by providing an additional input signal that produces a torque component that is in phase with the rotor speed deviation [4].It consists of a washout circuit, dynamic compensator, torsional filter and limiter as shown in figure (2.4).The data of PSS are used shown in appendix(A.4).

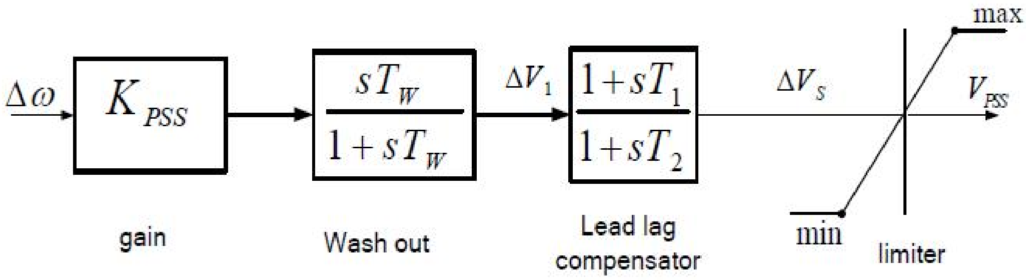

Figure 2.4: General representation of Power system stabilizer

2.6.1 Washout circuit

The washout circuit is provided to eliminate steady-state bias in the output of PSS which will modify the generator terminal voltage. The PSS is expected to respond only to transient variations in the input signal (say rotor speed). This is achieved by subtracting from it the low frequency components of the signal obtained by passing the signal through a low pass filter. The washout circuit acts essentially as a high pass filter and it must pass all frequencies that are of interest.

2.6.2 Phase compensator

The compensator is made up to single lead-lag stage where *Ks* is the gain of PSS and the time constants, T_1 was chosen to provide a phase lead for the input signal in the range of frequencies that are of interest (0.1 to 3.0 Hz). With static exciters, only one lead-lag stage may be adequate.

2.6.3 Gain

The gain of PSS is to be chosen to provide adequate damping of all critical mode under various operating conditions. Although PSS may be tuned to give optimum damping under such condition, the performance will not be optimal under other conditions. The critical modes include not only local and inter area modes, but other modes.

2.6.4 PSS output limits

The output of the PSS must be limited to prevent the up normal change in terminal voltage of PSS. The positive limit of PSS output is of importance during the change of load for higher value of the terminal voltage (due to the increase in speed or frequency).The negative limit of PSS output is of importance during the back swing of the rotor (after initial acceleration is over).

2.6.5 Input signal

The common signal which used as input to the PSS are: rotor speed deviation($\Delta\omega$), bus frequency (Δf), electrical power (ΔP_e). The signal must be obtained from local measurements. Since the basic function of power system stabilizer (PSS) is to add damping to the rotor oscillations [1]. In this work a speed signal is used as input signal. The overall transfer function of the PSS is:

$$T(S) = \frac{K_{PSS}(1+sT_1)(sT_W)}{(1+sT_2)(1+sT_W)} \quad (2.15)$$

CHAPTER THREE

MODELING, LINEARIZATION OF MULTI MACHINE POWER SYSTEM AND PSS DESIGN

3.1 Overview

When the system is subjected to a small changing, it tends to acquire a new operating state. During the transition between the initial state and the new state the system behavior is oscillatory. If the two states are such that all the state variables change only slightly (i.e., the variable X_i changes from $X_{i0}$to X_{i0}+ΔX_i where $\Delta X_i$is a small change inX_i), the system is operating near the initial state. The initial state may be considered as a quiescent operating condition for the system. To examine the behavior of the system when it is perturbed such that the new and old equilibrium states are nearly equal, the system equations are linearized about the quiescent operating condition. By this we mean that first-order approximations are made for the system Equations. The new linear Equations thus derived are assumed to be valid in a region near the quiescent condition.

The dynamic response of a linear system is determined by its characteristic equation (or equivalent information). Both the forced response and the free response are decided by the roots of this equation. From a point of view of stability the free response gives the needed information. If it is stable, any bounded input will give a bounded and therefore a stable output [5].

3.2 Multi-machine Model

To formulate a multi-machine small-signal model, the following assumptions are made without loss of generality:

- The stator and the network transient are neglected.
- The turbine governor dynamics are neglected resulting in constant mechanical torque T_{Mi} (i= no. of machines).
- The limit constraints on AVR output (VR_i) are deleted as the focus of interest is on modeling and simulation.
- The damping torque $T_{F_i} = D_i(\omega_i - \omega_s)$is assumed linear.

❖ Two-axis Model of Multi-machine System

➢ fourth order model differential equations

$$\dot{\delta}_i = \omega_i - \omega_s \tag{3.1}$$

$$\dot{\omega}_i = \frac{1}{M_i}\left[T_{Mi} - \dot{E}'_{qi}I_{qi} - \dot{E}'_{di}I_{di} - \left(X'_{di} - X'_{qi}\right)I_{di}I_{qi} - D_i(\omega_i - \omega_s)\right] \tag{3.2}$$

$$\dot{E}'_{qi} = \frac{1}{T'_{doi}}\left[-E'_{qi} + (X_{di} - X'_{di})I_{di} + E_{fdi}\right] \tag{3.3}$$

$$\dot{E}'_{di} = \frac{1}{T'_{qoi}}\left[-E'_{di} + \left(X_{qi} - X'_{qi}\right)I_{qi}\right] \tag{3.4}$$

A fast exciter has been added; whose state space Equation is

$$\dot{E}_{fdi} = -\frac{1}{T_{Ai}}E_{fdi} + \frac{K_{Ai}}{T_{Ai}}(V_{ref} - V_i) \tag{3.5}$$

For i=1, 2…m, where m= the number of machines.

➢ algebraic equations

✓ stator algebraic equations

$$0 = V_i e^{j\theta_i} + \left(R_{s_i} + jX'_{d_i}\right)\left(I_{d_i} + jI_{q_i}\right)e^{j(\delta_i - \pi/2)} - [E'_{d_i} + \left(X'_{q_i} - X'_{d_i}\right)I_{q_i} + jE'_{q_i}]e^{j(\delta_i - \pi/2)} \tag{3.6}$$

In polar form

$$E'_{d_i} - V_i \sin(\delta_i - \theta_i) - R_{s_i}I_{q_i} + X'_{q_i}I_{q_i} = 0 \tag{3.7}$$

$$E'_{q_i} - V_i \sin(\delta_i - \theta_i) - R_{s_i}I_{d_i} + X'_{d_i}I_{d_i} = 0 \tag{3.8}$$

For i =1, 2, 3. . . , m where m= the number of machines.

- ✓ **network equations**

  The network equation separate into generator buses equations and load buses equations.

- **Generator Buses**

$$I_{d_i}V_i \sin(\delta_i - \theta_i) + I_{q_i}V_i \cos(\delta_i - \theta_i)$$

$$+P_{L_i}(V_i) - \sum_{k=1}^{n} V_i\, V_k Y_{ik} \cos(\theta_i - \theta_k - \alpha_{ik}) = 0 \quad (3.9)$$

$$I_{d_i}V_i \cos(\delta_i - \theta_i) + I_{q_i}V_i \sin(\delta_i - \theta_i)$$

$$+Q_{L_i}(V_i) - \sum_{k=1}^{n} V_i\, V_k Y_{ik} \sin(\theta_i - \theta_k - \alpha_{ik}) = 0 \quad (3.10)$$

For i=1, 2, 3. . . , m where m= the number of machines.

- **Load Buses**

$$P_{L_i}(V_i) - \sum_{k=1}^{n} V_i\, V_k Y_{ik} \cos(\theta_i - \theta_k - \alpha_{ik}) = 0 \quad (3.11)$$

$$Q_{L_i}(V_i) - \sum_{k=1}^{n} V_i\, V_k Y_{ik} \sin(\theta_i - \theta_k - \alpha_{ik}) = 0 \quad (3.12)$$

3.3 Linearization

Let the state-space vector $x$have an initial state $x_0$at time= t_0, at the occurrence of a small disturbance, i.e., after$t = t_0^+$, the states will change slightly from their previous positions or values. Thus:

$$x = x + \Delta x \quad (3.13)$$

Note that x_0 need not be constant, but we do require that it be known.

The state-space model is in the form

$$\dot{x} = f(x, t) \quad (3.14)$$

Which

$$\dot{x}_0 + \Delta\dot{x} = f(x_0 + \Delta x, t) \quad (3.15)$$

From which we obtain the linearized state-space Equation

$$\Delta\dot{x} = A(x_0)\Delta x + B(x_0)u \tag{3.16}$$

Where A and B are state matrixes. Therefore the system variable be

$$\delta_i = \delta_{i0} + \Delta\delta_i \tag{3.17}$$

$$\omega_i = \omega_{i0} + \Delta\omega_i \tag{3.18}$$

$$\theta_i = \theta_{i0} + \Delta\theta_i \tag{3.19}$$

$$E'_{qi} = E'_{q_{i0}} + \Delta E'_{q_i} \tag{3.20}$$

$$E'_{di} = E'_{d_{i0}} + \Delta E'_{d_i} \tag{3.21}$$

$$V_i = V_i + \Delta V_i \tag{3.22}$$

$$E_{fdi} = E_{fdi} + \Delta E_{fdi} \tag{3.23}$$

3.3.1 Linearization of differential equations

The linearization of the DAEs (3.1) to (3.5) about any operating point yields

$$\Delta\dot{\delta}_i = \Delta\omega_i \tag{3.24}$$

$$\Delta\dot{\omega}_i = \frac{1}{M_i}\left[\Delta T_{Mi} - E'_{qi}\Delta I_{qi} - E'_{di}\Delta I_{di} - \Delta E'_{qi} I_{qi} - I_{di}\Delta E'_{di} - \left(X'_{qi} - X'_{di}\right) I_{di}\Delta I_{qi} - \left(X'_{q_i} - X'_{d_i}\right) I_{q_i}\Delta I_{di} - D_i\Delta\omega_i\right] \tag{3.25}$$

$$\Delta\dot{E}_{qi} = \frac{1}{T'_{di}}\left[-\Delta E'_{qi} + \left(X_{di} - X'_{d_i}\right)\Delta I_{di} + \Delta E_{fdi}\right] \tag{3.26}$$

$$\Delta\dot{E}_{di} = \frac{1}{T'_{qi}}\left[-\Delta E'_{di} - \left(X_{qi} - X'_{q_i}\right)\Delta I_{qi}\right] \tag{3.27}$$

$$\Delta\dot{E}_{fdi} = -\frac{1}{T_{A_i}}\Delta E_{fdi} + \frac{K_{A_i}}{T_{A_i}}\left(\Delta V_{ref} - \Delta V_i\right) \tag{3.28}$$

Writing (3.37) through (3.32) in matrix notation, we obtain

$$\begin{bmatrix} \Delta\dot{\delta}_i \\ \Delta\dot{\omega}_i \\ \Delta\dot{E}_{qi} \\ \Delta\dot{E}_{di} \\ \Delta\dot{E}_{fdi} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & -\frac{D_i}{M_i} & -\frac{I_{qi}}{M_i} & -\frac{I_{di}}{M_i} & 0 \\ 0 & 0 & -\frac{1}{T'_{di}} & 0 & \frac{1}{T_{di}} \\ 0 & 0 & 0 & -\frac{1}{T'_{qi}} & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{Ai}} \end{bmatrix} \begin{bmatrix} \Delta\delta_i \\ \Delta\omega_i \\ \Delta E'_{q_i} \\ \Delta E'_{d_i} \\ \Delta E_{fdi} \end{bmatrix} +$$

$$\begin{bmatrix} -\frac{\left(X'_{qi} - X'_{di}\right) I_{qi}}{M_i} & -\frac{\left(X'_{qi} - X'_{di}\right)}{M_i} \\ \frac{\left(X_{di} - X'_{di}\right)}{T'_{di}} & 0 \\ 0 & \frac{\left(X_{qi} - X'_{qi}\right)}{T'_{qi}} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta I_{di} \\ \Delta I_{qi} \end{bmatrix} +$$

$$\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -\frac{K_{Ai}}{T_{Ai}} \end{bmatrix} \begin{bmatrix} \Delta\theta_i \\ \Delta V_i \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{1}{M_i} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{K_{Ai}}{T_{Ai}} \end{bmatrix} \begin{bmatrix} \Delta T_{Mi} \\ \Delta V_{ref} \end{bmatrix} \tag{3.29}$$

Put

$$\Delta I_{gi} = \begin{pmatrix} \Delta I_{di} \\ \Delta I_{qi} \end{pmatrix}, \qquad \Delta V_{gi} = \begin{pmatrix} \Delta\theta_i \\ \Delta V_i \end{pmatrix}, \qquad \Delta V_i = \begin{pmatrix} \Delta T_{Mi} \\ \Delta V_{ref} \end{pmatrix}$$

Then

$$\Delta\dot{X}_i = A_{1i}\Delta X_i + B_{1i}\Delta I_{gi} + B_{2i}\Delta V_{gi} + E_i\Delta V_i \tag{3.30}$$

i=1… n

3.3.2 Linearization of algebraic equations

Linearization of the stator algebraic equations (3.7) and (3.8) gives

$$\Delta E'_{di} - \sin(\delta_i - \theta_i)\,\Delta V_i - V_i\cos(\delta_i - \theta_i)\,\Delta\delta_i + V_i\cos(\delta_i - \theta_i)\,\Delta\theta_i - R_{si}\Delta I_{di} + X'_{qi}\Delta I_{qi} = 0 \quad (3.31)$$

$$\Delta E'_{qi} - \cos(\delta_i - \theta_i)\,\Delta V_i + V_i\sin(\delta_i - \theta_i)\,\Delta\delta_i + V_i\sin(\delta_i - \theta_i)\,\Delta\theta_i - R_{si}\Delta I_{qi} + X'_{di}\Delta I_{di} = 0 \quad (3.32)$$

In matrix form:

$$\begin{bmatrix} -V_i\cos(\delta_i - \theta_i) & 0 & 0 & 1 & 0 \\ V_i\sin(\delta_i - \theta_i) & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta_i \\ \Delta\omega_i \\ \Delta E'_{q_i} \\ \Delta E'_{d_i} \\ \Delta E_{fdi} \end{bmatrix} + \begin{bmatrix} -R_{si} & -X'_{qi} \\ -X'_{di} & -R_{si} \end{bmatrix} \begin{bmatrix} \Delta I_{di} \\ \Delta I_{qi} \end{bmatrix}$$

$$+\begin{bmatrix} V_i\cos(\delta_i - \theta_i) & -\sin(\delta_i - \theta_i) \\ -V_i\sin(\delta_i - \theta_i) & -\cos(\delta_i - \theta_i) \end{bmatrix} \begin{bmatrix} \Delta\theta_i \\ \Delta V_i \end{bmatrix} = 0 \quad (3.33)$$

$$0 = C_{1i}\Delta X_i + D_{1i}\Delta I_{gi} + D_{2i}\Delta V_{gi} \quad (3.34)$$

In matrix notation, (3.33) can be written as:

$$0 = C_1\Delta X + D_1\Delta I_g + D_2\Delta V_g \quad (3.35)$$

WhereC_1,D_1, andD_2 are block diagonal.

3.3.3 Linearization of the network equations

For generator buses (3.9) and (3.10) in matrix form:

$$\begin{bmatrix} \left(I_{d_i}V_i\cos(\delta_i - \theta_i) - I_{q_i}V_i\sin(\delta_i - \theta_i)\right) & 0 & 0 & 0 & 0 \\ \left(-I_{d_i}V_i\,sin(\delta_i - \theta_i) - I_{q_i}V_i\,cos(\delta_i - \theta_i)\right) & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta_i \\ \Delta\omega_i \\ \Delta E'_{q_i} \\ \Delta E'_{d_i} \\ \Delta E_{fdi} \end{bmatrix}$$

$$+\begin{bmatrix} V_i\,sin(\delta_i-\theta_i) & -V_i\cos(\delta_i-\theta_i) \\ V_i\cos(\delta_i-\theta_i) & -V_i\,sin(\delta_i-\theta_i) \end{bmatrix}\begin{bmatrix}\Delta I_{di}\\ \Delta I_{qi}\end{bmatrix}+$$

$$\begin{bmatrix} -I_{d_i}V_i\cos(\delta_i-\theta_i)+I_{q_i}V_i\sin(\delta_i-\theta_i) & I_{d_i}V_i\,sin(\delta_i-\theta_i)+I_{q_i}V_i\,cos(\delta_i-\theta_i) \\ V_i\sum_{\substack{k=1\\k\neq i}}^{n}V_kY_{ik}\sin(\theta_i-\theta_k-\alpha_{ik}) & V_i\sum_{k=1}^{n}V_kY_{ik}\cos(\theta_i-\theta_k-\alpha_{ik})+\frac{\partial P_{Li}(V_i)}{\partial V_i} \\ I_{d_i}V_i\,sin(\delta_i-\theta_i)+I_{q_i}V_i\,cos(\delta_i-\theta_i) & I_{d_i}V_i\cos(\delta_i-\theta_i)-I_{q_i}V_i\sin(\delta_i-\theta_i) \\ -V_i\sum_{\substack{k=1\\k\neq i}}^{n}V_kY_{ik}\sin(\theta_i-\theta_k-\alpha_{ik}) & -V_i\sum_{k=1}^{n}V_kY_{ik}\cos(\theta_i-\theta_k-\alpha_{ik})+\frac{\partial Q_{Li}(V_i)}{\partial V_i} \\ 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix}\Delta\theta_i\\ \Delta V_i\end{bmatrix}+$$

$$\begin{bmatrix} -V_i\sum_{\substack{k=1\\k\neq i}}^{n}V_kY_{ik}\sin(\theta_i-\theta_k-\alpha_{ik}) & -V_i\sum_{k=1}^{n}V_kY_{ik}\cos(\theta_i-\theta_k-\alpha_{ik}) \\ -V_i\sum_{\substack{k=1\\k\neq i}}^{n}V_kY_{ik}\sin(\theta_i-\theta_k-\alpha_{ik}) & -V_i\sum_{\substack{k=1\\k\neq i}}^{n}V_kY_{ik}\sin(\theta_i-\theta_k-\alpha_{ik}) \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix}\Delta\theta_k\\ \Delta V_k\end{bmatrix}$$

i=1... n (3.36)

Rewriting (3.36) we obtain

$$0=\begin{bmatrix} C_{21} & \cdots & 0 \\ 0 & \ddots & 0 \\ 0 & \cdots & C_{2n}\end{bmatrix}\begin{bmatrix}\Delta X_1\\ \vdots \\ \Delta X_n\end{bmatrix}+\begin{bmatrix} D_{31} & \cdots & 0 \\ 0 & \ddots & 0 \\ 0 & \cdots & D_{3n}\end{bmatrix}\begin{bmatrix}\Delta I_{g1}\\ \vdots \\ \Delta I_{gm}\end{bmatrix}+$$

$$\begin{bmatrix} D_{41,1} & \cdots & D_{41,n} \\ \vdots & \ddots & \vdots \\ D_{4n,1} & \cdots & D_{4n,n}\end{bmatrix}\begin{bmatrix}\Delta V_{g1}\\ \vdots \\ \Delta V_{gn}\end{bmatrix}+\begin{bmatrix} D_{51,n+1} & \cdots & D_{51,m} \\ \vdots & \ddots & \vdots \\ D_{5n,n+1} & \cdots & D_{5n,m}\end{bmatrix}\begin{bmatrix}\Delta V_{Ln+1}\\ \vdots \\ \Delta V_{Ln}\end{bmatrix} \quad (3.37)$$

Where the various sub matrices of (3.37) can be easily identified. In matrix notation, (3.37) is

$$0=C_2\Delta X+D_3\Delta I_g+D_4\Delta V_g+D_5\Delta V_L \quad (3.38)$$

Where $\Delta V_L = \begin{bmatrix} \Delta\theta_K \\ \Delta V_K \end{bmatrix}$

For the non-generator buses i=1… n.

Note that C_2, D_3 are block diagonal, where D_4, D_5 are full matrices. For load buses (3.11) and (3.12) which are written of form matrix as shown below:

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \sum_{\substack{k=1 \\ k\neq i}}^{n} V_i V_k Y_{ik} \sin(\theta_i - \theta_k - \alpha_{ik}) & -\sum_{k=1}^{n} V_k Y_{ik} \cos(\theta_i - \theta_k - \alpha_{ik}) + \frac{\partial P_{Li}(V_i)}{\partial V_i} \\ -\sum_{\substack{k=1 \\ k\neq i}}^{n} V_i V_k Y_{ik} \cos(\theta_i - \theta_k - \alpha_{ik}) & -\sum_{k=1}^{n} V_k Y_{ik} \sin(\theta_i - \theta_k - \alpha_{ik}) + \frac{\partial Q_{Li}(V_i)}{\partial V_i} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} \Delta\theta_i \\ \Delta V_i \end{bmatrix} + \begin{bmatrix} -V_i \sum_{\substack{k=1 \\ k\neq i}}^{n} V_k Y_{ik} \sin(\theta_i - \theta_k - \alpha_{ik}) & -V_i \sum_{k=1}^{n} Y_{ik} \cos(\theta_i - \theta_k - \alpha_{ik}) \\ -V_i \sum_{\substack{k=1 \\ k\neq i}}^{n} V_k Y_{ik} \sin(\theta_i - \theta_k - \alpha_{ik}) & -V_i \sum_{k=1}^{n} Y_{ik} \cos(\theta_i - \theta_k - \alpha_{ik}) \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\theta_k \\ \Delta V_k \end{bmatrix}$$

(3.39) Rewriting (3.39) we obtain

$$\begin{bmatrix} D_{6m+1,1} & \cdots & D_{6m+1,m} \\ \vdots & \ddots & \vdots \\ D_{6n,1} & \cdots & D_{6n,m} \end{bmatrix} \begin{bmatrix} \Delta V_{g1} \\ \vdots \\ \Delta V_{gm} \end{bmatrix} + \begin{bmatrix} D_{7m+1,m+1} & \cdots & D_{7m+1,n} \\ \vdots & \ddots & \vdots \\ D_{7n,m+1} & \cdots & D_{7n,n} \end{bmatrix} \begin{bmatrix} \Delta V_{Lm+1} \\ \vdots \\ \Delta V_{Ln} \end{bmatrix} \quad (3.40)$$

In matrix notation, (3.39) can be written as

$$0 = D_6 \Delta V_g + D_7 \Delta V_L \quad (3.41)$$

Where $D_6$and D_7 are full matrices.

Rewritten equations (3.30), (3.35), (3.38) and (3.41) together as follow:

$$\Delta\dot{X}_i = A_{1i}\Delta X_i + B_{1i}\Delta I_{gi} + B_{2i}\Delta V_{gi} + E_i\Delta V_i \quad (3.42)$$

$$0 = C_1\Delta X + D_1\Delta I_g + D_2\Delta V_g \quad (3.43)$$

$$0 = C_2\Delta X + D_3\Delta I_g + D_4\Delta V_g + D_5\Delta V_L \quad (3.44)$$

$$0 = D_6\Delta V_g + D_7\Delta V_L \quad (3.45)$$

From (3.34) we obtain

$$\Delta I_g = -D_1^{-1}D_1\Delta X - D_1^{-1}D_2\Delta V_g \quad (3.46)$$

Substitute (3.46) in (3.44) as shown

$$C_2\Delta X + D_3(-D_1^{-1}D_1\Delta X - D_1^{-1}D_2\Delta V_g) + D_4\Delta V_g + D_5\Delta V_L = 0 \quad (3.47)$$

Let

$$K_1 = [D_4 - D_3D_1^{-1}D_2] \quad , \quad K_2 = [D_2 - D_3D_1^{-1}D_1]$$

Then

$$K_2\Delta X + K_1\Delta V_g + D_5\Delta V_L = 0 \quad (3.48)$$

Substitute (3.46) in (3.42) we find

$$\Delta\dot{X} = (A_1 - B_1D_1^{-1}C_1)\Delta X + (-B_1D_1^{-1}D_2 + B_2)\Delta V_g + E_1\Delta U \quad (3.49)$$

$$K_2\Delta X + K_1\Delta V_g + D_5\Delta V_L = 0 \quad (3.50)$$

$$0 = D_6\Delta V_g + D_7\Delta V_L \quad (3.51)$$

Equations (3.49)-(3.51) can be put in a form of matrix shown below

$$\begin{bmatrix} \Delta\dot{X} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} A_1 - B_1 D_1^{-1} C_1 & -B_1 D_1^{-1} D_2 + B_2 & 0 \\ K_2 & K_1 & D_5 \\ 0 & D_6 & D_7 \end{bmatrix} \begin{bmatrix} \Delta X \\ \Delta V_g \\ \Delta V_L \end{bmatrix} + \begin{bmatrix} E_1 \\ 0 \\ 0 \end{bmatrix} \Delta U \qquad (3.52)$$

Let

$A' = A_1 - B_1 D_1^{-1} C_1$, $B' = -B_1 D_1^{-1} D_2 + B_2$

So

$$\Delta\dot{X} = A'\Delta X + B'\Delta V_g + E_1 \Delta U \qquad (3.53)$$

$$K_2 \Delta X + K_1 \Delta V_g + D_5 \Delta V_L = 0 \qquad (3.54)$$

$$0 = D_6 \Delta V_g + D_7 \Delta V_L \qquad (3.55)$$

From (3.55)

$$\Delta V_L = -D_7^{-1} D_6 \Delta V_g \qquad (3.56)$$

Substitute (3.56) in (3.54) we find

$$K_2 \Delta X + F \Delta V_g = 0 \qquad (3.57)$$

Where

$$F = K_1 - D_5 D_7^{-1} D_6 \qquad (3.58)$$

From (3.57)

$$\Delta V_g = -F^{-1} K_2 \Delta X \qquad (3.59)$$

Substitute (3.59) in (3.53) we find

$$\Delta\dot{X} = A_{SYS} \Delta X + E_1 \Delta U \qquad (3.60)$$

Where

$$A_{SYS} = A' - B' F^{-1} K_2 \qquad (3.61)$$

This model can be used to examine the effect of small-signal disturbance on the eigenvalues of the multi-machine power system. When a PSS are installed at any machine, the extra state variables corresponding to this controller will be added with the system matrix [4].

3.4 Design and Tuning of PSS Damping Controller

There are three kind of signals are considered for PSS input: machine speed, terminal frequency, or power. One of these signals is fed into the PSS to produce a signal that is fed into the excitation system to increase the damping torque component. The general form of the PSS transfer function is given by (3.62) where k is the order of the PSS; typically the order is one or two.

$$G(s) = K_{pss}\left(\frac{1+sT_1}{1+sT_2}\right)^2 \frac{sT_W}{1+sT_W} \qquad (3.62)$$

The gain, K_{pss} determines the amount of added damping, while the last term in the above transfer function represents the washout filter. This filter is added such that there is no steady state voltage reference error due to the speed deviation.

There are different types of tuning techniques have been successfully utilized with power system stabilizer applications:

- Phase compensation method**:** This method consists of adjusting the stabilizer to compensate for the phase lag through the generator, excitation system, and power system such that the stabilizer path provides torque changes which are in phase with speed changes.
- Root locus method: Synthesis by root locus involves shifting the eigenvalues associated with the power system modes of oscillation by adjusting the stabilizer pole and zero locations in the s-plane. It gives additional insight to performance by working directly with the closed-loop characteristics of the system, as opposed to the open-loop nature of the phase compensation technique.

3.5 Determination the Optimal Location of PSS

During the application of PSS in multi-machine power system to achieve the largest improvement in damping of electromechanical mode of oscillations. Firstly, the best location of PSS must be identified among a number of interconnected machines. PSS must be placed at the generators should be able to stabilize all of the electromechanical modes. The selection of PSS location is generally carried out using participation factor, sensitivity of PSS effect, and optimum PSS location index.

3.5.1 Participation factor

PF analysis method has been applied to find the best location of a PSS in a multi-machine power system. The PF is a quantitative measure of how a particular mode (eigenvalue) is affected by the various state variables in the system. In a multi-machine system, the PF (PF_i) for the ith machine considering speed deviation ($\Delta\omega_i$) as the respective state variable is defined by

$$PF_i = \phi_{j,\Delta\omega_i}\psi_{j,\Delta\omega_i} \tag{3.63}$$

Where $\phi_{j,\Delta\omega_i}$ is the right-eigenvector entry and $\psi_{j,\Delta\omega_i}$is the left eigenvector entry of the $j$thelectromechanical swing mode corresponding to the state variable $\Delta\omega_i$ of the ith machine. The machine having the highest PF for the most poorly damped swing mode signifies the most effective location of stabilizer application

PF provides an initial screening of locations [4]. In this work, the following procedure is employed to decide the location of PSS.

1. List all swing modes whose damping factor is less than 0.05.
2. List participation factor for slip-signal for each of the selected swing mode.
3. Location of PSS is decided for the machine whose slip participation is the highest in that mode.

3.5.2 Sensitivity of PSS

In order to take into consideration the effect of both the PSS input and the PSS control in selecting the PSS location, SPE for the ith machine has been considered as

$$SPE_i = \phi_{j,\Delta\omega_i}\psi_{j,\Delta E_{fd_i}} \quad (3.64)$$

for i =1, 2, . . .,m (the number of machines) where $\phi_{j,\Delta\omega_i}$ is the right-eigenvector entry and $\psi_{j,\Delta E_{fd_i}}$ is the left-eigenvector entry of the jth mode corresponding to the state $\Delta\omega_i$ and ΔE_{fd_i} of the ith machine. SPE measures both the activity of PSS input ($\Delta\omega_i$) participating in a certain oscillatory mode and the control effect of PSS, on this mode. The larger the magnitude of the SPE, the better is the overall performance of the PSS.

3.5.3 Optimum PSS location index

Optimum PSS location index (OPLI) is based on the change of exciter transfer function with respect to the PSS transfer function in a certain swing mode. The change of response of the excitation system with respect to the PSS response for a swing mode λ' is determined by the proposed index OPLI and is defined by:

$$|OPLI_i| = \frac{\left|(G_{ex_i}(\lambda') - G_{ex_i}(\lambda^o))\right|}{|G_{pss}(\lambda')|} \quad (3.65)$$

For i=1, 2. . . m (the number of machines).

Here, $\lambda^o$and $\lambda'$are the critical swing modes before and after the installation of PSS, respectively. The magnitude of OPLI measures the effect of PSS on the exciter response in a swing mode λ' of interest. The larger the value of the OPLI, the larger is the control effect of PSS on the exciter and the better is the overall performance of PSS in the power system [4].

CHAPTER FOUR
SIMULATION AND RESULTS

In the previous chapter the power system stabilizer (PSS) was designed. This chapter is an important part of project. In this chapter the eigenvalue analysis and time-domain simulation have been represented for the multi-machines system. The results are obtained through simulations of the system response for different operating conditions: the system with PSS and without PSS.

4.1 Case Study

3 machines, 9-buses power system has been used to demonstrate the modal analysis of a power system. The single line diagram of the system is shown in Figure (4.1) the data of system is shown in Appendix (A.1) and (A.2).

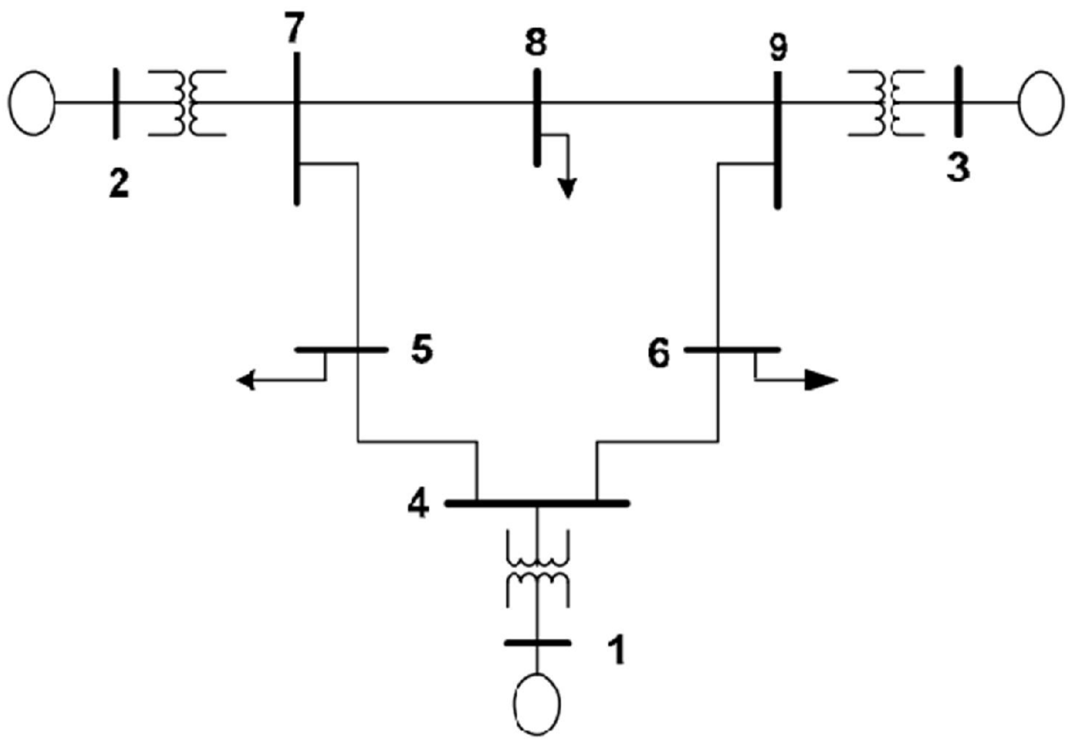

Figure 4.1: 3machine-9bus System

4.2 Eigenvalue Analysis

In this section eigenvalue method has been used to analyze the stability problem of the system in two cases.

4.2.1 Base case

Table 4.1: The eigenvalues of the system without PSS at normal operation.

SL_ Number	Eigenvalue	Damping Ratio	Frequency (Hz)	Nature of mode
1	-0.6856 +12.7756i	0.0536	2.0333	Local area
2	-0.6856 -12.7756i	0.0536	2.0333	Local area
3	-0.1229 + 8.2867i	0.0148	1.3189	Local area
4	-0.1229 - 8.2867i	0.0148	1.3189	Local area
5	-2.3791 + 2.6172i	0.6726	0.4165	Non swing
6	-2.3791 - 2.6172i	0.6726	0.4165	Non swing
7	-4.6706 + 1.3750i	0.9593	0.2188	Non swing
8	-4.6706 - 1.3750i	0.9593	0.2188	Non swing
9	-3.5199 + 1.0156i	0.9608	0.1616	Non swing
10	-3.5199 - 1.0156i	0.9608	0.1616	Non swing
11	-2.2008 + 0.0000i	1.0000	0	Non swing
12	-0.8845 + 0.0000i	1.0000	0	Non swing
13	0.0000 + 0.0000i	-0.0000	0.0000	Non swing
14	0.0000 - 0.0000i	-0.0000	0.0000	Non swing
15	-3.2258 + 0.0000i	1.0000	0	Non swing

Table 4.2: The eigenvalues of the system without PSS at light load condition.

SL_ Number	Eigenvalue	Damping Ratio	Frequency (Hz)	Nature of mode
1	-0.5632 +12.8797i	0.0437	2.0499	Local area
2	-0.5632 -12.8797i	0.0437	2.0499	Local area
3	-0.0918 + 8.0362i	0.0114	1.2790	Local area
4	-0.0918 - 8.0362i	0.0114	1.2790	Local area
5	-2.2524 + 2.8443i	0.6208	0.4527	Non swing
6	-2.2524 - 2.8443i	0.6208	0.4527	Non swing
7	-4.8698 + 1.2413i	0.9690	0.1976	Non swing
8	-4.8698 - 1.2413i	0.9690	0.1976	Non swing
9	-3.6321 + 0.8351i	0.9746	0.1329	Non swing
10	-3.6321 - 0.8351i	0.9746	0.1329	Non swing
11	0.0000 + 0.0000i	-1.0000	0	Non swing
12	-0.0000 + 0.0000i	1.0000	0	Non swing
13	-2.0897 + 0.0000i	1.0000	0	Non swing
14	-0.7327 + 0.0000i	1.0000	0	Non swing
15	-3.2258 + 0.0000i	1.0000	0	Non swing

Table 4.3: The eigenvalues of the system without PSS at heavy load condition.

SL_ Number	Eigenvalue	Damping Ratio	Frequency (Hz)	Nature of mode
1	-0.9403 +12.5445i	0.0747	1.9965	Local area
2	-0.9403 -12.5445i	0.0747	1.9965	Local area
3	-0.2454 + 8.1631i	0.0301	1.2992	Local area
4	-0.2454 - 8.1631i	0.0301	1.2992	Local area
5	-2.5874 + 2.2604i	0.7531	0.3598	Non swing
6	-2.5874 - 2.2604i	0.7531	0.3598	Non swing
7	-4.0310 + 1.3952i	0.9450	0.2221	Non swing
8	-4.0310 - 1.3952i	0.9450	0.2221	Non swing
9	-2.8585 + 1.5510i	0.8790	0.2468	Non swing
10	-2.8585 - 1.5510i	0.8790	0.2468	Non swing
11	-3.4033 + 0.0000i	1.0000	0	Non swing
12	-1.7412 + 0.0000i	1.0000	0	Non swing
13	0.0000 + 0.0000i	-0.0000	0.0000	Non swing
14	0.0000 - 0.0000i	-0.0000	0.0000	Non swing
15	-3.2258 + 0.0000i	1.0000	0	Non swing

In this case generators are provided with static exciter with no PSS. Further, constant impedance type load modal has been employed for both real and reactive components of loads. The eigenvalues, damping ratio, frequency of oscillations, and the type of mode of oscillations are shown in Table (4.1), (4.2) and (4.3).

All of the real parts are negative which mean the system is stable but it observed that the real parts and damping ratio of the system at light load are decreased which mean the system became poorly damped, but at heavy load the real parts and damping ratio increased.

4.2.2 Controlled case

Here the PSS controller has been added to the system however, before adding it the optimal location of PSS has been determined. From the method of design the PSS; which represented in the previous section the PSSs have been designed and added to machine 2 and machine 3 and Table (4.4) showing system response.

Table 4.4: The eigenvalues of the system with PSS at normal operation.

SL_ Number	Eigenvalue	Damping Ratio	Frequency (Hz)	Nature of mode
1	-62.1948 + 0.0000i	1.0000	0	Non Swing
2	-54.1848 + 0.0000i	1.0000	0	Non Swing
3	-23.5775 + 0.0000i	1.0000	0	Non Swing
4	-4.6746 +13.7283i	0.3223	2.1849	Local Area
5	-4.6746 -13.7283i	0.3223	2.1849	Local Area
6	-13.7865 + 0.0000i	1.0000	0	Non Swing
7	-4.4773 + 7.8970i	0.4932	1.2569	Local Area
8	-4.4773 - 7.8970i	0.4932	1.2569	Local Area
9	-3.8843 + 2.9517i	0.7962	0.4698	Non Swing
10	-3.8843 - 2.9517i	0.7962	0.4698	Non Swing
11	-3.8724 + 2.2456i	0.8651	0.3574	Non Swing
12	-3.8724 - 2.2456i	0.8651	0.3574	Non Swing
13	-3.8797 + 2.0749i	0.8818	0.3302	Non Swing
14	-3.8797 - 2.0749i	0.8818	0.3302	Non Swing
15	-2.1369 + 0.0000i	1.0000	0	Non Swing
16	-0.8870 + 0.0000i	1.0000	0	Non Swing
17	-0.2227 + 0.0000i	1.0000	0	Non Swing
18	0.0000 + 0.0000i	-1.0000	0	Non Swing

19	-0.0000 + 0.0000i	1.0000	0	Non Swing
20	-0.1002 + 0.0000i	1.0000	0	Non Swing
21	-3.2258 + 0.0000i	1.0000	0	Non Swing

In this case generators are provided with static exciter with PSS, all of the real parts are negative which mean the system is stable and observed that the PSSs raise the damping ratio from (1.48%) and(5.36%) to (32.23%) and (49.32%) for local area mode as shown in Figure (4.2).

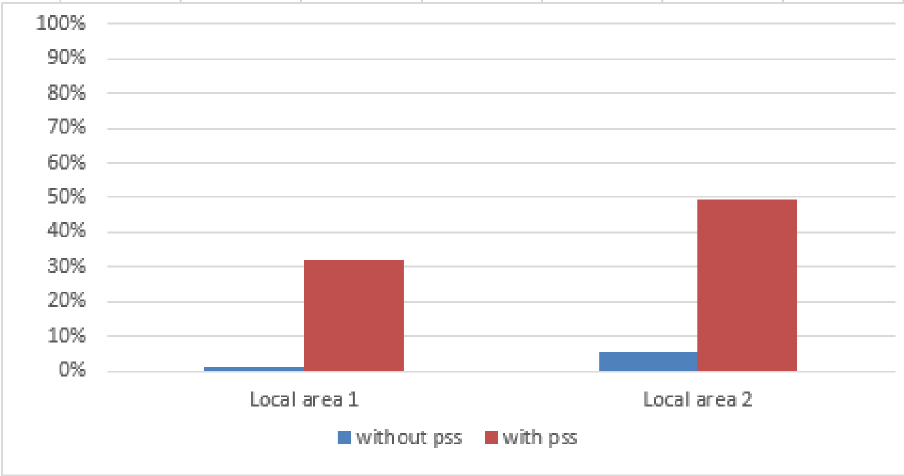

Figure 4.2: Compression of damping ratio between base case and controlled case during normal operation

Table 4.5: The eigenvalues of the system with PSS at light load condition

SL_ Number	Eigenvalue	Damping Ratio	Frequency (Hz)	Nature of mode
1	-62.1988 + 0.0000i	1.0000	0	Non Swing
2	-54.0760 + 0.0000i	1.0000	0	Non Swing
3	-24.4580 + 0.0000i	1.0000	0	Non Swing
4	-5.0416 +14.1434i	0.3358	2.2510	Local Area
5	-5.0416 -14.1434i	0.3358	2.2510	Local Area
6	-13.9577 + 0.0000i	1.0000	0	Non Swing
7	-4.0785 + 8.1202i	0.4488	1.2924	Local Area
8	-4.0785 - 8.1202i	0.4488	1.2924	Local Area
9	-4.9056 + 2.2572i	0.9084	0.3592	Non Swing
10	-4.9056 - 2.2572i	0.9084	0.3592	Non Swing
11	-2.4835 + 3.3720i	0.5930	0.5367	Non Swing
12	-2.4835 - 3.3720i	0.5930	0.5367	Non Swing
13	-3.8515 + 1.2860i	0.9485	0.2047	Non Swing
14	-3.8515 - 1.2860i	0.9485	0.2047	Non Swing
15	-2.0565 + 0.0000i	1.0000	0	Non Swing
16	-0.7334 + 0.0000i	1.0000	0	Non Swing
17	-0.1650 + 0.0000i	1.0000	0	Non Swing
18	-0.1002 + 0.0000i	1.0000	0	Non Swing
19	-0.0000 + 0.0000i	1.0000	0	Non Swing
20	0.0000 + 0.0000i	-1.0000	0	Non Swing
21	-3.2258 + 0.0000i	1.0000	0	Non Swing

Table 4.6: The eigenvalues of the system with PSS at heavy load condition.

SL_ Number	Eigenvalue	Damping Ratio	Frequency (Hz)	Nature of mode
1	-61.8456 + 0.0000i	1.0000	0	Non Swing
2	-53.6573 + 0.0000i	1.0000	0	Non Swing
3	-24.3436 + 0.0000i	1.0000	0	Non Swing
4	-3.3678 +13.1730i	0.2477	2.0965	Local Area
5	-3.3678 -13.1730i	0.2477	2.0965	Local Area
6	-9.9099 + 4.0856i	0.9245	0.6503	Local Area
7	-9.9099 - 4.0856i	0.9245	0.6503	Local Area
8	-8.0400 + 0.0000i	1.0000	0	Non Swing
9	-3.3208 + 5.6758i	0.5050	0.9033	Non Swing

10	-3.3208 - 5.6758i	0.5050	0.9033	Non Swing
11	-3.8480 + 1.8600i	0.9003	0.2960	Non Swing
12	-3.8480 - 1.8600i	0.9003	0.2960	Non Swing
13	-2.6940 + 1.7539i	0.8380	0.2791	Non Swing
14	-2.6940 - 1.7539i	0.8380	0.2791	Non Swing
15	-2.9949 + 0.0000i	1.0000	0	Non Swing
16	-1.7353 + 0.0000i	1.0000	0	Non Swing
17	-0.2976 + 0.0000i	1.0000	0	Non Swing
18	-0.1001 + 0.0000i	1.0000	0	Non Swing
19	0.0000 + 0.0000i	-1.0000	0	Non Swing
20	-0.0000 + 0.0000i	1.0000	0	Non Swing
21	-3.2258 + 0.0000i	1.0000	0	Non Swing

Also in this case when light load added to the system the damping ratio increase from (4.37%), (1.14%) to (33.58%), (44.88%) for the two modes, when heavy load added to the system the damping ratio increase from (7.47%), (3.01) to (24.77%), (92.45%) for the two modes.

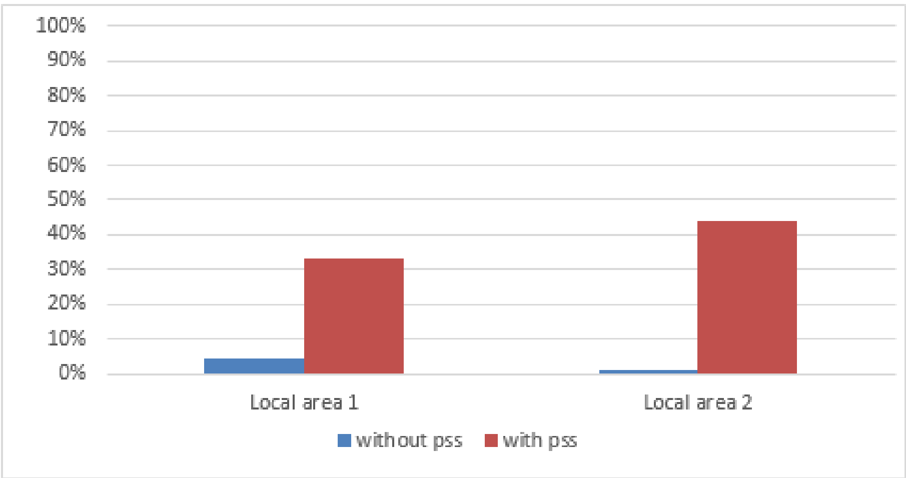

Figure 4.3: Compression of damping ratio between base case and controlled case during light load operation

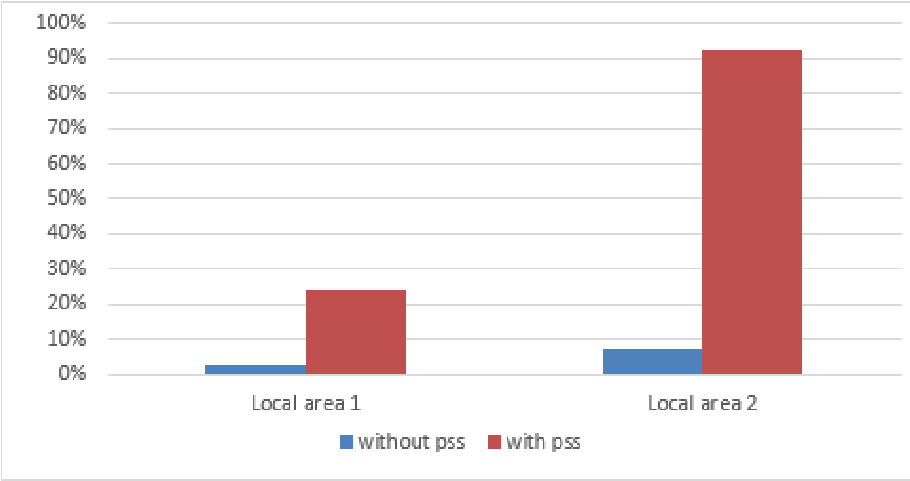

Figure 4.4: Compression of damping ratio between base case and controlled case during heavy load operation

4.3 Time Domain Simulation

The time domain simulations were performed to validate the results of modal analysis. The effectiveness of the PSSs is assessed by their ability to damp low frequency oscillations under various operating conditions. These types of time domain simulation were performed under various types of faults (change in references, symmetrical three phase fault and load changes) [1].

4.3.1 The system without PSS

The response of the rotor speed deviation, the rotor angle deviation and electrical power output at normal operation in Figure (4.5), (4.6) and (4.7).

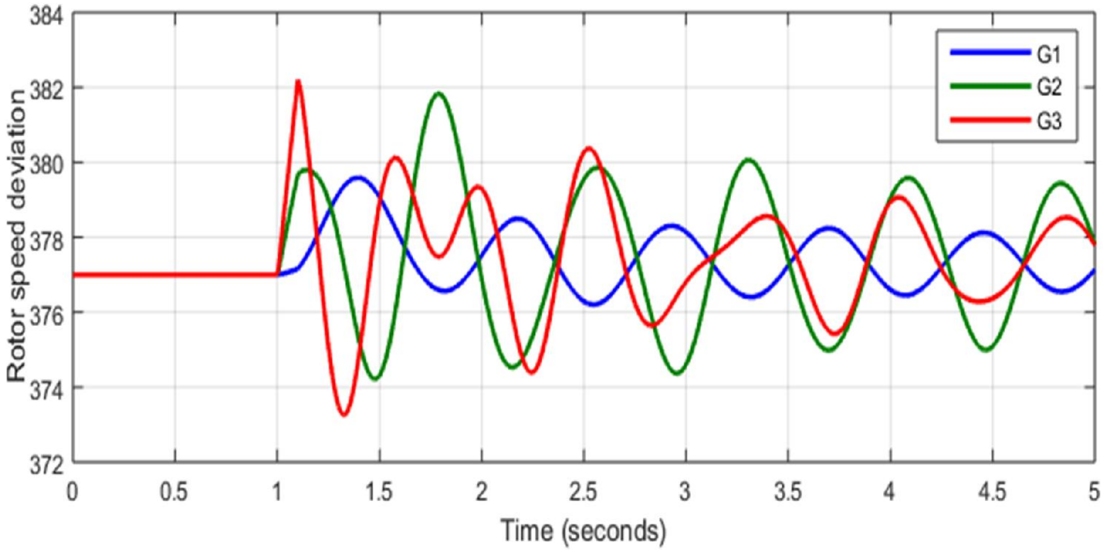

Figure 4.5: Response of rotor speed deviation without PSS at normal operation

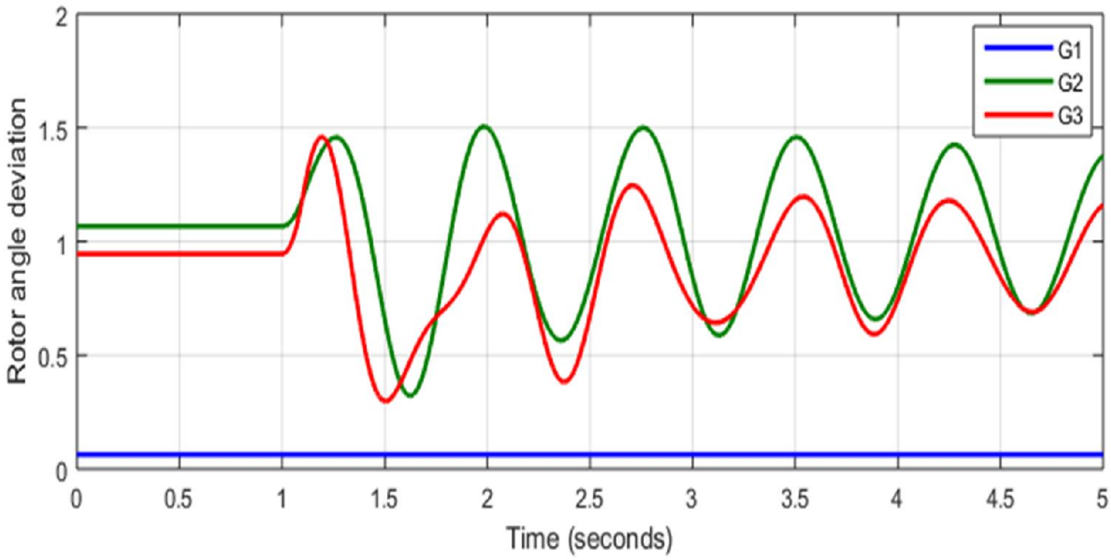

Figure 4.6: Response of rotor angle deviation without PSS at normal operation

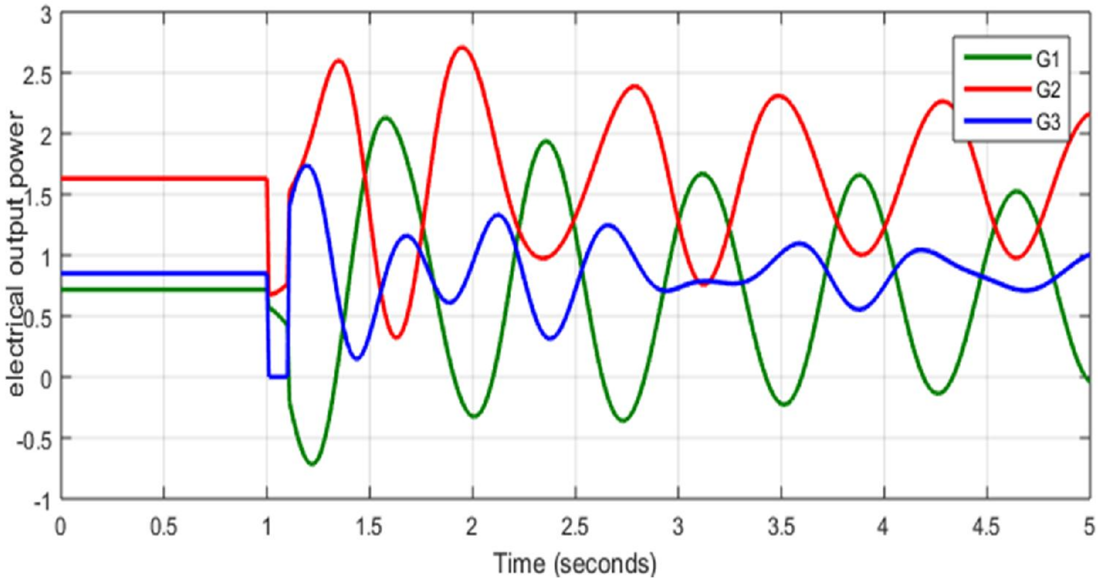

Figure 4.7: Response of electrical power output without PSS at normal operation

The response of the rotor speed deviation, the rotor angle deviation and electrical power output at light load in Figure (4.8), (4.9) and (4.10).

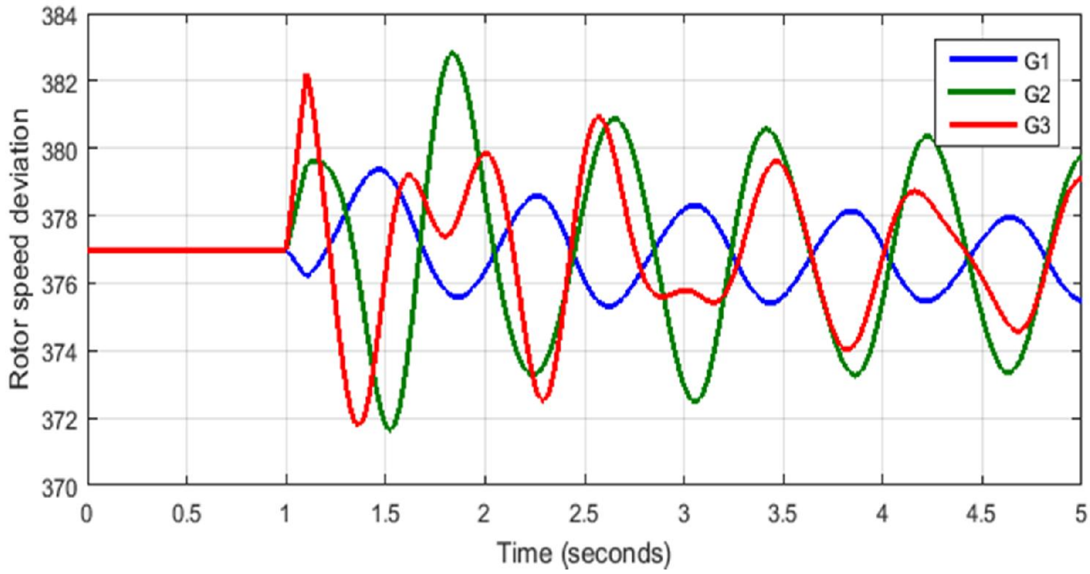

Figure 4.8: Response of rotor speed deviation without PSS at light load

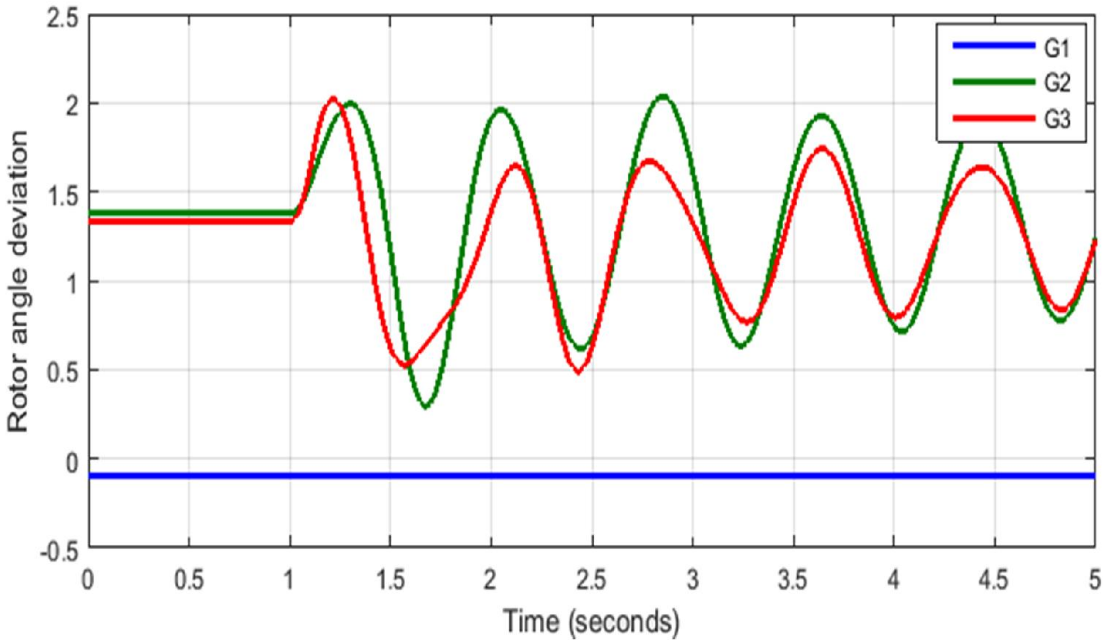

Figure 4.9: Response of rotor angle deviation without PSS at light load

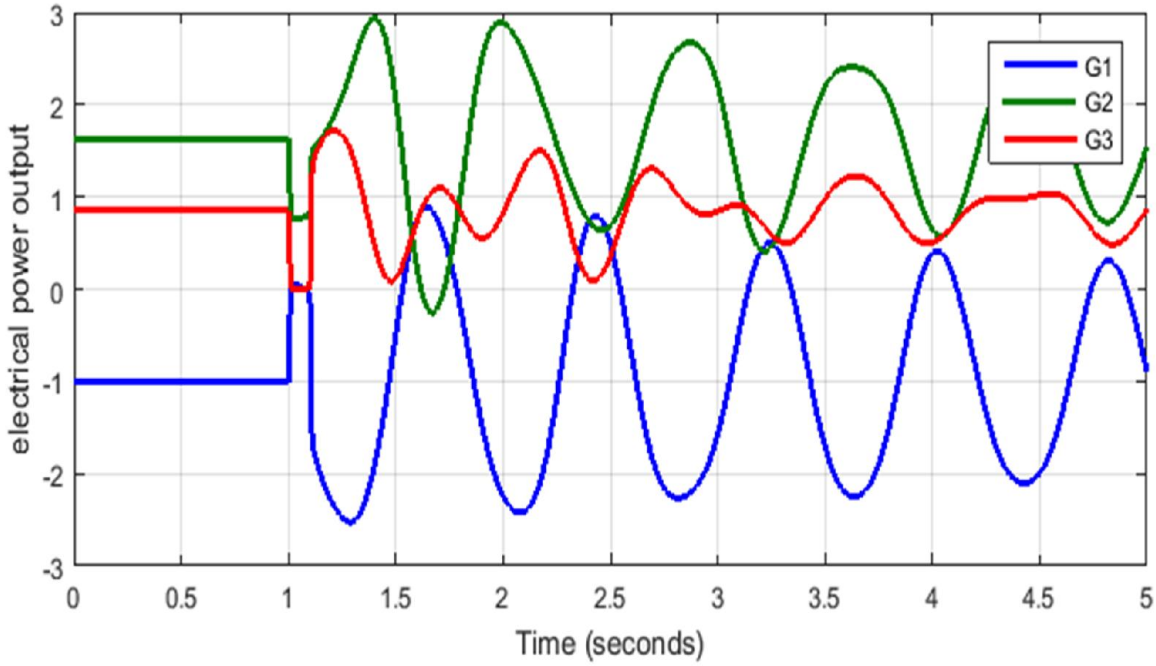

Figure 4.10: Response of electrical power output without PSS at light load

The response of the rotor speed deviation, the rotor angle deviation and electrical power output at heavy load in Figure (4.11), (4.12) and (4.13).

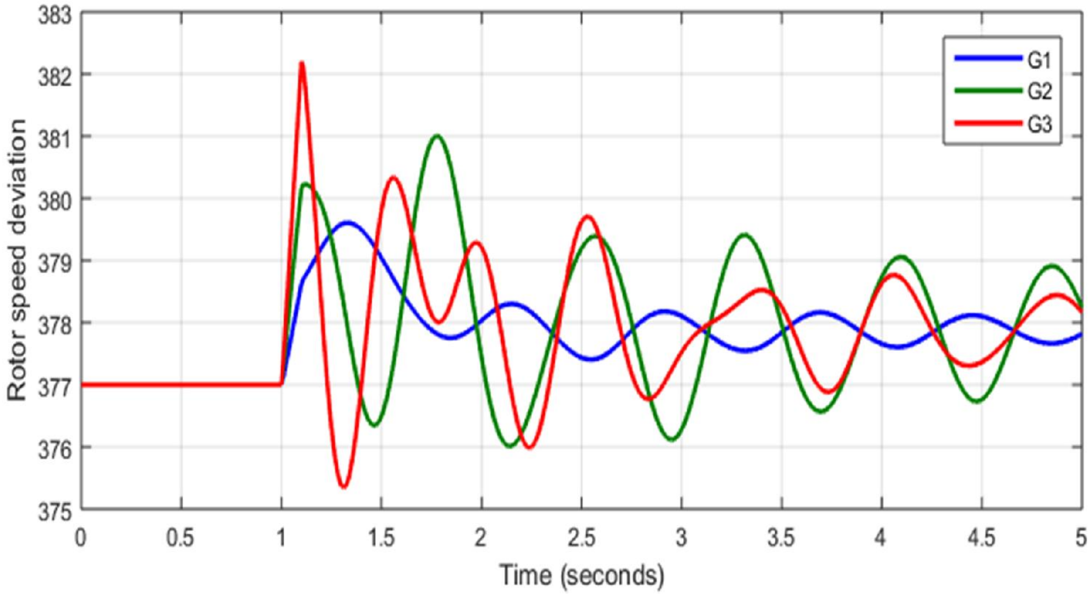

Figure 4.11: Response of rotor speed deviation without PSS at heavy load

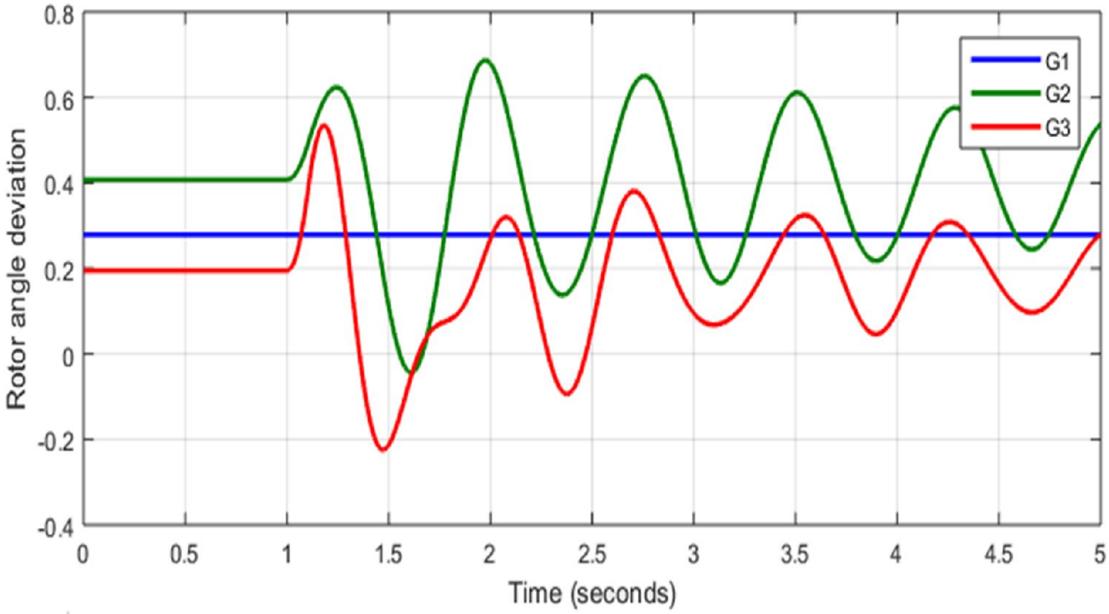

Figure 4.12: Response of rotor angle deviation at heavy load

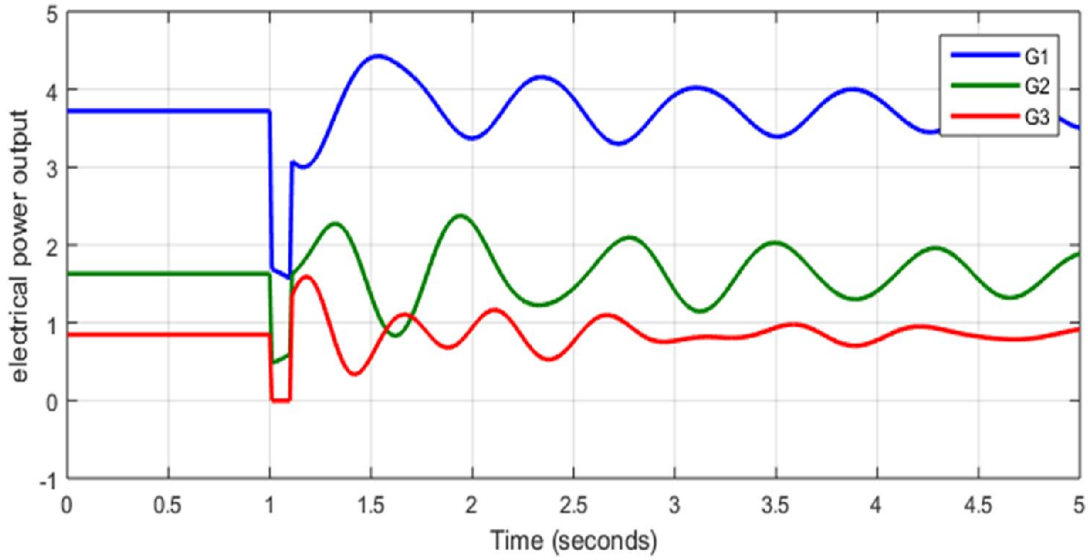

Figure 4.13: Response of electrical power output without PSS at heavy load

4.3.2 The system with PSS

The response of the rotor speed deviation, the rotor angle deviation and electrical power output, The PSS was located in generator 2 and 3.in Figure (4.14), (4.15) and (4.16).

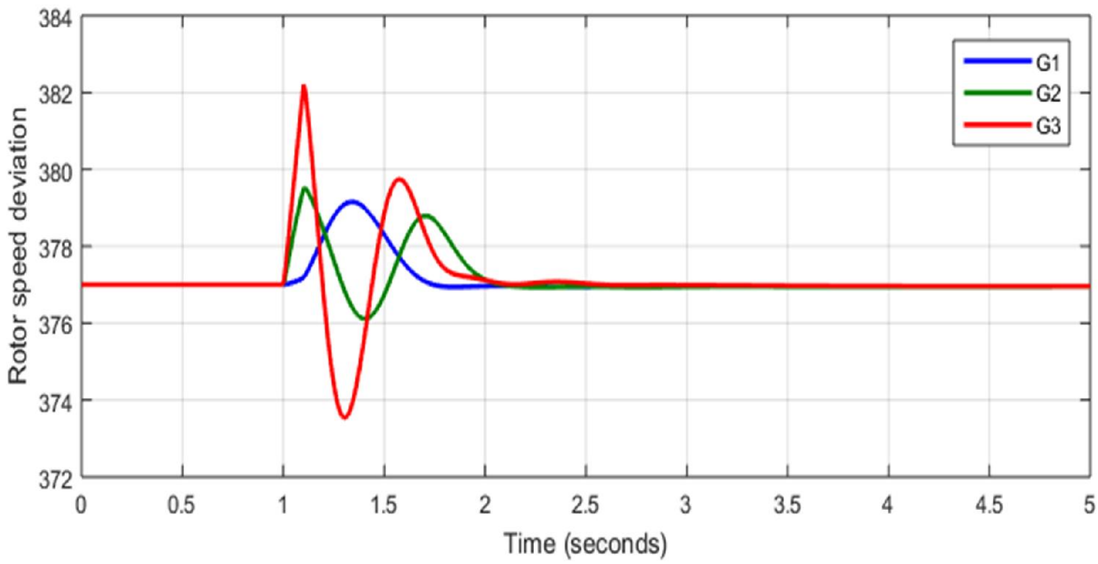

Figure 4.14: Response of rotor speed deviation with PSS at normal operation

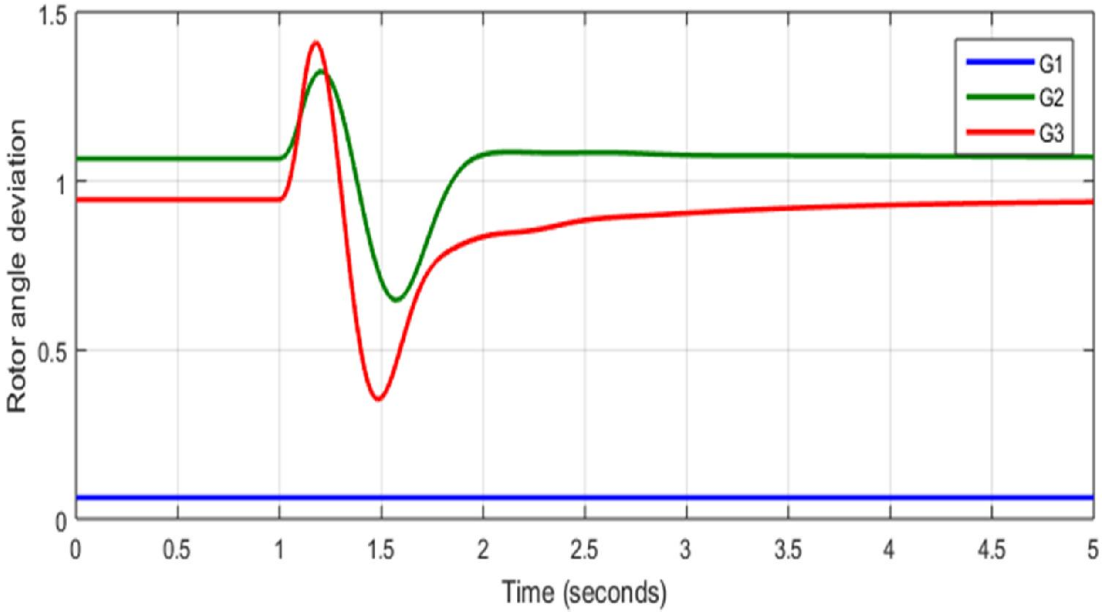

Figure 4.15: Response of rotor angle deviation with PSS at normal operation

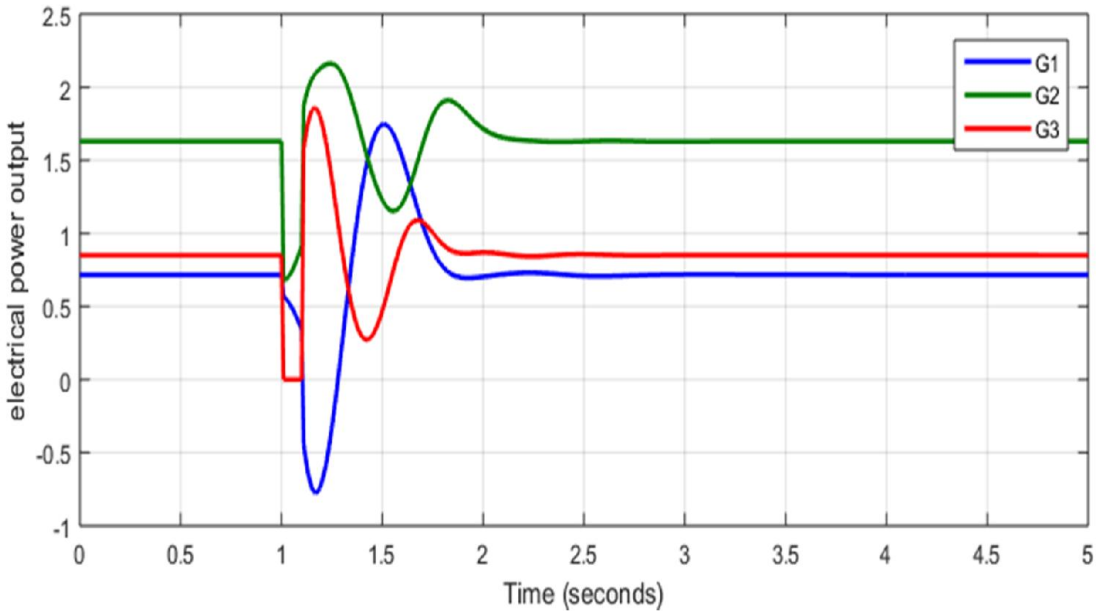

Figure 4.16: Response of electrical power output with PSS at normal operation

The response of the rotor speed deviation, the rotor angle deviation and electrical power output at light load in Figure (4.17), (4.18) and (4.19).

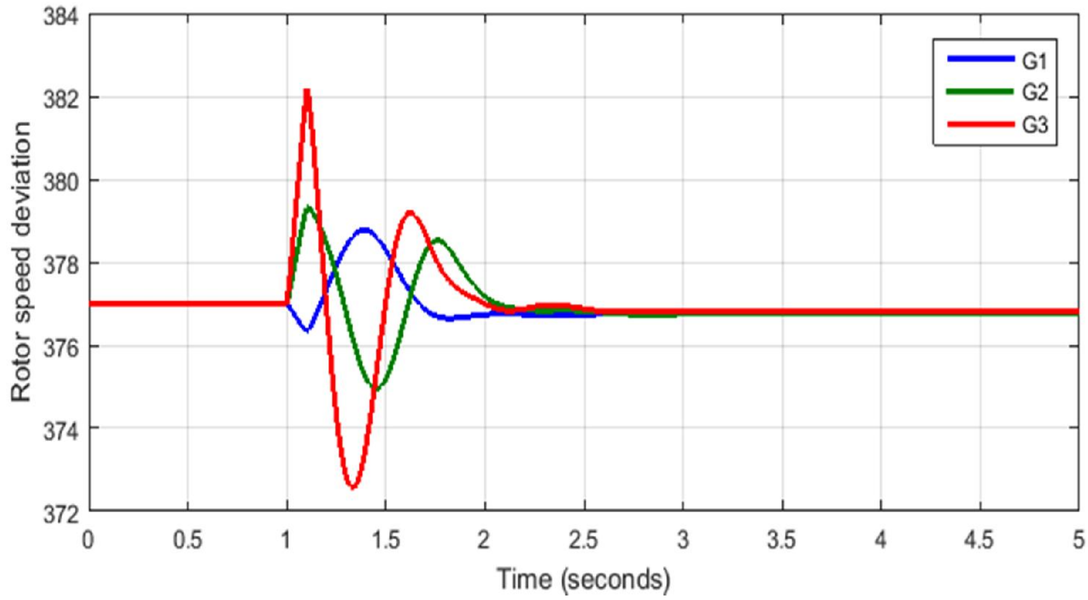

Figure 4.17: Response of rotor speed deviation with PSS at light load

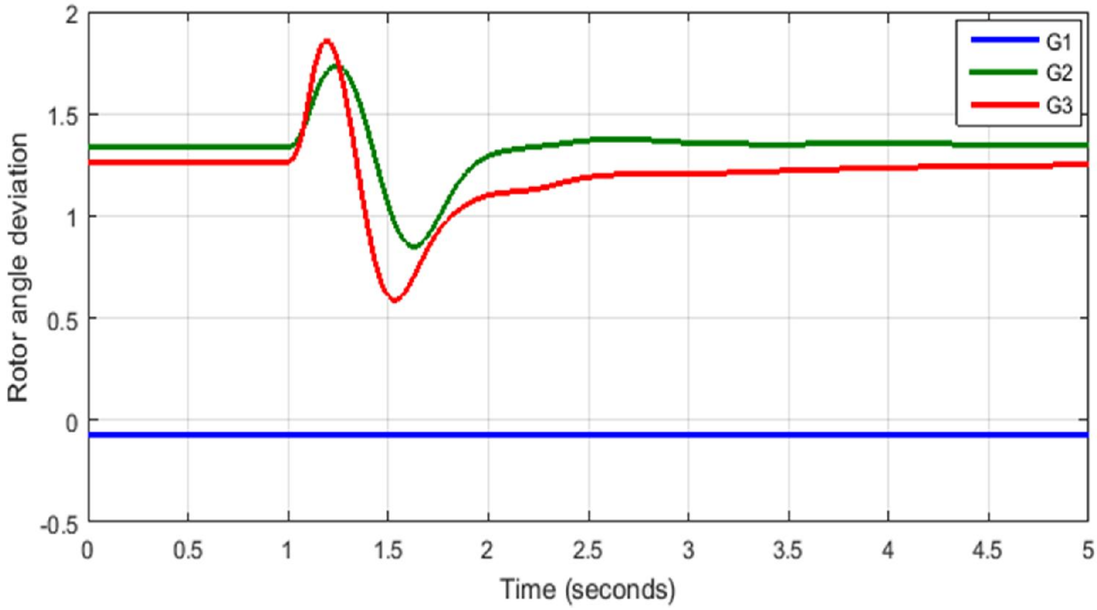

Figure 4.18: Response of rotor angle deviation with PSS at light load

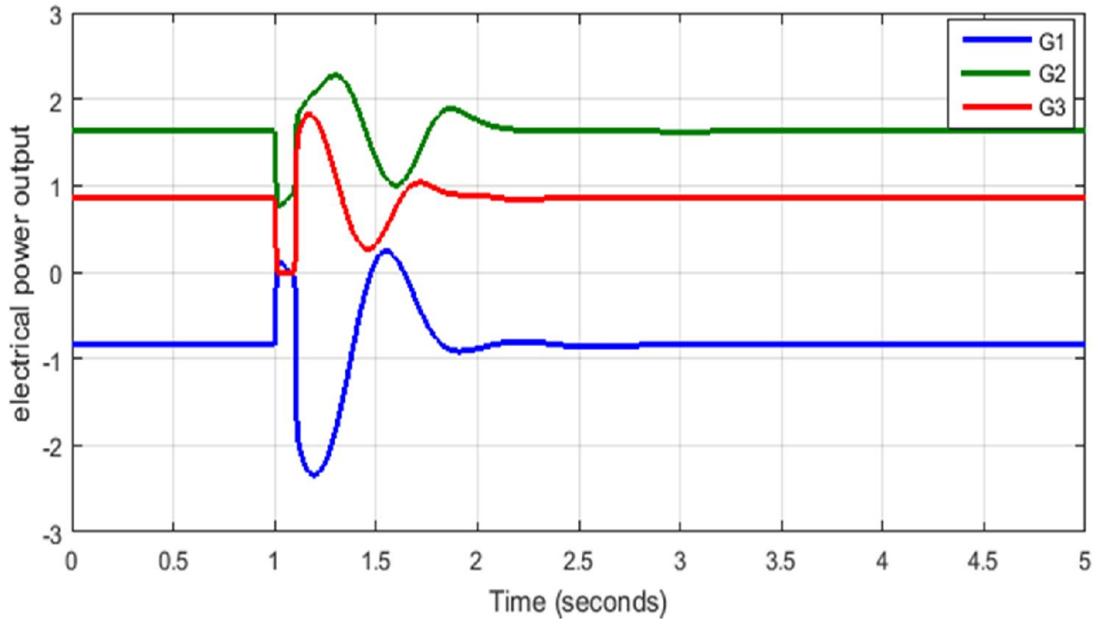

Figure 4.19: Response of electrical power output with PSS at light load

The response of the rotor speed deviation, the rotor angle deviation and electrical power output at heavy load in Figure (4.20), (4.21) and (4.22).

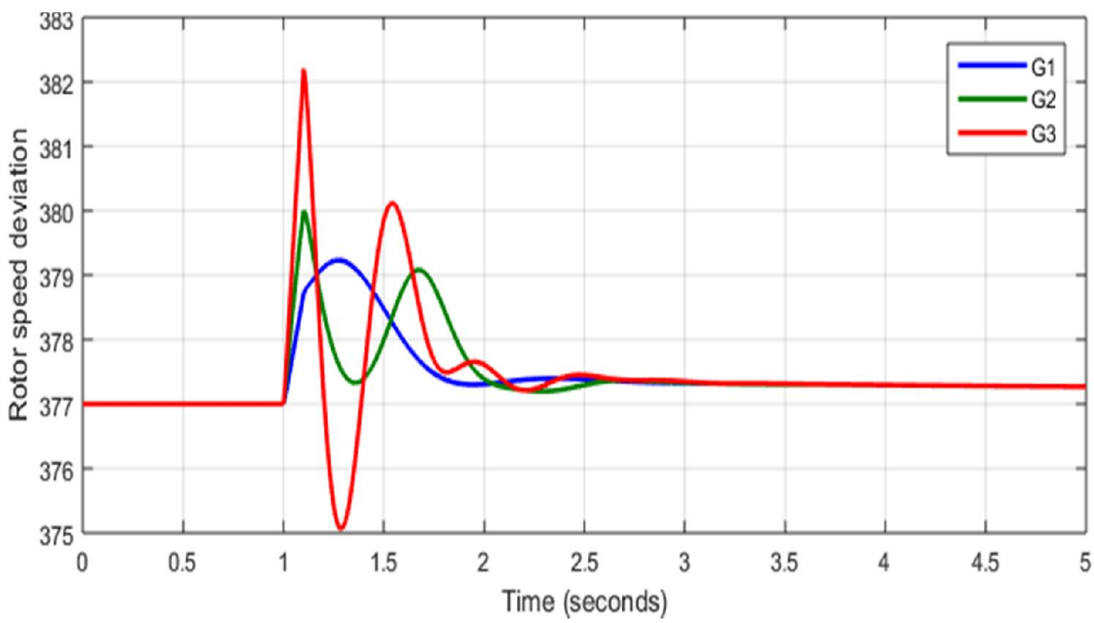

Figure 4.20: Response of rotor speed deviation with PSS at heavy load

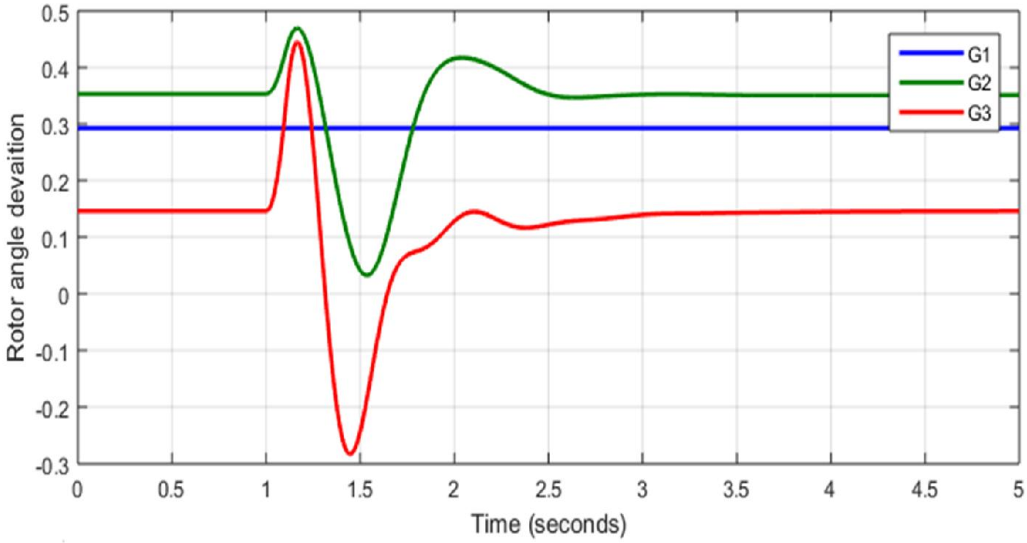

Figure 4.21: Response of rotor angle deviation with PSS at heavy load

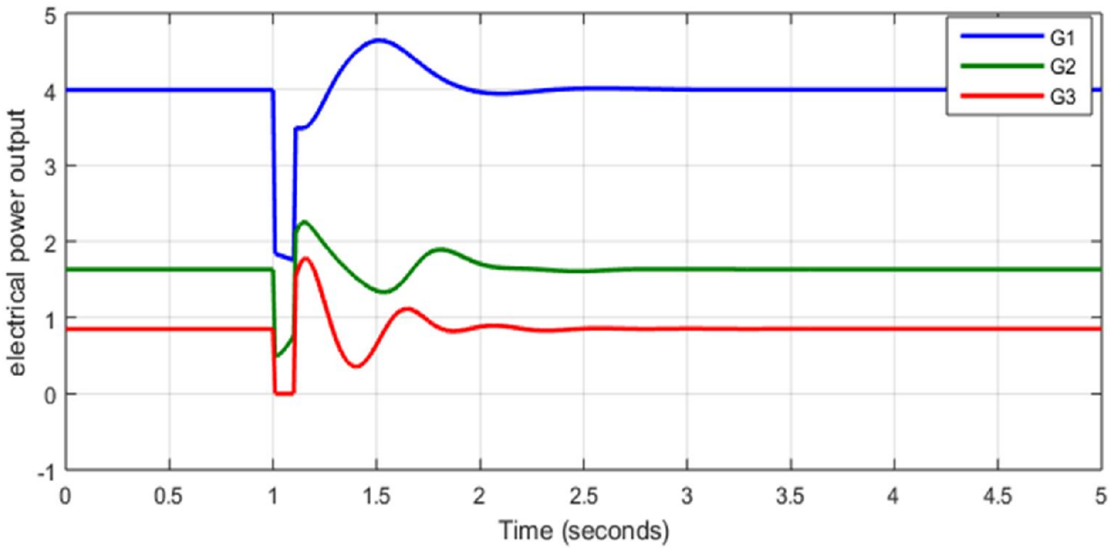

Figure 4.22: Response of electrical power output with PSS at heavy load

4.4 Results Analysis

- Implementation of PSSs reduces the settling time at the moment of disturbance as shown in time domain figures.
- Implementation of PSSs decreases the maximum overshoot.
- Also PSSs increase the damping ratio as shown in Figures (4.2), (4.3) and (4.4).

CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The problem of low frequency oscillations in power systems has been addressed in this thesis by using eigenvalue method, and time domain simulation. The system in base case (without PSS) was stable at normal condition but has poor damping of electromechanical low frequency oscillation of local modes. To provide adequate damping ratio, the power system stabilizer has been designed by using phase compensation technique. The optimal location of multi PSS controllers is important issue to avoid the destabilizing effect of them. Participation factors which represent the contribution of machines in specific modes is used to identifying the optimal locations. After that the effect of PSS has been discussed for small and large disturbances.

Finally the power system stabilizer (PSS) is a cost effective way of improving the damping of electromechanical oscillations of rotor and return the stability to the system.

5.2 Recommendations

In this thesis, design and optimal location of PSSs' to improve the overall

stability were determined and the speed deviation was taken as the input signal of damping controllers. The coming points can be used in the future:

- Change the input signal of PSS such as terminal bus frequency or electrical power output, although dual input power system stabilizer signals such as speed and electrical power output are could be used.
- Use other methods to specify the optimal location of PSS such as Genetic Algorithm (GA) method.
- Improve the stability by using another controller addition to PSS such as one of the Flexible AC transmission system (FACTS) family.

REFERECES

[1] P.Kunder," Power system stability and control", McGraw-Hill companies, university of Toronto, 1994.

[2] D P Kothari, I J nagrath, "Modern Power System Analysis", third edition. McGraw-Hill companies, New Delhi, 2003.

[3] Chapman Stephen. Electric machinery and power system fundamentals. McGraw hill, Boston 2001.

[4] Debasish Mondal, Abhijit Chakrabarti, Aparajita Senguta, "Power System Small Signal Stability Analysis and Control". Amsterdam, Elsevier Inc.2014.

[5] K.R. Padiyar, Power System Dynamics Stability and Control, second edition ,BS Publications, Hyderabad, India, 2002.

[6] P.M. Anderson, A.A.Fouad "Power System Stability and Control", second edition, John Wiley & Sons, Inc. New York, 2003.

APPENDIX (A)

3 MACHINE 9 BUS DATA

APPENDIX (A.1)

3-Machines Data

Parameters	Machine 1	Machine 2	Machine 3
$R_s(pu)$	0.089	0.089	0.089
$H(s)$	23.64	6.4	3.01
$D(pu)$	0.2	0.2	0.2
$X_d(pu)$	0.269	0.8958	1.998
$X'_d(pu)$	0.0608	0.1198	0.1813
$X_q(pu)$	0.0969	0.8645	1.2578
$X'_q(pu)$	0.0969	0.8645	1.2578
$T'_{do}(s)$	8.96	6.0	5.89
$T'_{qo}(s)$	0.31	0.535	0.6

APPENDIX (A.2)

Lines Data

From Bus No.	To Bus No.	Series Resistance $R_s(pu)$	Series Reactance $X_s(pu)$Suscep	Shunt Susceptance $B\ (pu)$
1	4	0	0.0576	0
2	7	0	0.0625	0
3	9	0	0.0586	0
4	5	0.01	0.85	0.176
4	6	0.017	0.092	0.158
5	7	0.032	0.161	0.306
6	9	0.039	0.17	0.358
7	8	0.0085	0.072	0.149
8	9	0.0119	0.1008	0.209

APPENDIX (A.3)

Exciters Data

Parameters	Exciter 1	Exciter 2	Exciter 3
K_A	20	20	20
$T_A(s)$	0.2	0.2	0.2
K_E	1.0	1.0	1.0
$T_E(s)$	0.314	0.314	0.314
K_F	0.063	0.063	0.063
$T_F(s)$	0.35	0.35	0.35

APPENDIX (A.4)

PSSs parameters

No. of PSS	T_W	K_G	T_1	T_2	T_3	T_4	K_{PSS}
PSS 1	10	4.415	0.6581	0.0211	0.6737	0.0230	4033.47
PSS 2	10	0.8845	0.7403	0.0299	0.9705	0.0207	1026.74