Wide-Area Controller Design for Two Area Power Systems Using Robust Control

A Thesis Submitted in Partial Fulfilment

of the Requirements

for the Award of the Degree of

Master of Technology

in

Electrical Engineering

(Specialization: Control & Automation)

by

Ajay Shankar

Department of Electrical Engineering

National Institute of Technology, Rourkela

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Ajay Shankar

(Roll No- 212EE3220)

Under the Supervision of

Prof Sandip Ghosh

Department of Electrical Engineering

National Institute of Technology, Rourkela

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Department of Electrical Engineering

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Certificate

This is to certify that the Thesis entitled, **"Wide-Area Controller Design for Two Area Power Systems Using Robust Control"** submitted by ***"Ajay Shankar"*** to the National Institute of Technology, Rourkela is a bona fide research work carried out by him under my guidance and is worthy for the award of the degree of **"Master of Technology"** in **"Electrical Engineering"** with specializing in **"Control & Automation"** from this institute. The embodiment of this thesis is not submitted in any other university and/or institute for the award of any degree or diploma to the best of our knowledge and belief.

Date:

Place:

Prof Sandip Ghosh

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First and foremost, I am truly indebted to my supervisor **Prof Sandip Ghosh** for his inspiration, excellent guidance and unwavering confidence through my study, without which this thesis would not be in its present form. I also thank him for their gracious encouragement throughout the work.

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Last, but not least, I would like to dedicate this thesis to my family for their love, support, patience and blind faith into me.

Ajay Shankar

Rourkela, May 2014

Abstract

Low-area frequency oscillations are one of the major problems in the present power systems for smooth and reliable operation where power is essential to transfer from one area to another remote area through weak tie-lines. This kind of oscillations problem may result into system instability, cascade failure and even in blackouts, if they are not damp out quickly. It have been observed that local mode of oscillations can be damp out by using Power System Stabilizers (PSS) but damping inter-area mode of oscillations using PSS may not be possible always. This thesis work deals with the designing of Wide-Area Power System Stabilizers (WPSS) to damp inter-area mode of oscillations using wide-area signals. The Eigen analysis is used to verify the local and inter-area signals presented in two area power systems. H_∞ Mixed-sensitivity synthesis method for robust control is used to design Wide-Area Power System Stabilizer (WPSS). It is observed that designed WPSS is able to damp inter-area mode of oscillations presented in two area power systems.

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Symbols & Abbreviations

LFO	Low Frequency Oscillation
AVR	Automatic Voltage Regulator
PSS	Power System Stabilizer
WPSS	Wide-Area Power System Stabilizer
WADC	Wide-Area Damping Controller

Chapter 1

Introduction

In the past few decades damping in power system oscillation remains as one of the main issue for smooth and stable operation of power systems. Operation of power systems are always driven close to power system limits, because of continuous increase in power demand. This all process deals with the transmission capacity of power system. So, to boost up the power transfer capability, while maintaining the system stable, is one of the goals for power system operators.

When we transfer a huge amount of power to a long distance via a relatively weak tie lines and high exciters gain, then problem of small signal oscillation occurs. Resulting power system oscillations turned power system into instability and blackouts. In this instability problem there are different frequency components which are known as modes. In small signal stability problems local area mode of oscillation can be reduced by planting a Power System Stabilizer (PSS). These controllers use local signals e.g. Rotor Speed Deviation, voltage in tie lines as input. But the reliability of PSS to damp inter-area mode of oscillations is quiet less. PSS designing is generally based on linearizing the system model variations in generation, transmission network switching and load. So, satisfactory performances at an operating point are not always possible with PSS. However, changes in operating conditions in the power system always occur due to wide variation in system conditions. Local area controllers i.e. PSS lack the global observations, so they are not able to damp inter-area oscillations always.

So, to damp out the inter-area oscillations we need to design a Wide-Area damping controller. In the few research activities it is found that Wide-Area damping controller is able to improve transient stability also.

1.1 Problem Statement: The low frequency oscillations presented in the power systems are related to the small signal stability and it could make system unstable. Initially this problem is removed by using damper winding on turbines and generator rotors. But power system always operates close to their stability limits then problem of weak synchronizing torque was observed as the main problem of system instability. By using Automatic voltage regulators (AVRs), steady state stability of the power system is improved but it was not able to improve transient stability. Another problem in the power system was this, that it is required to transmit huge amount of power over a long distance through weak tie-lines. Power system stabilizers (PSS) are used in control loop along with automatic voltage regulators

(AVRs) to reduce the effect of low frequency oscillations. But it was able to damp only local area modes of oscillations presented in the power system while it was unable to damp inter-area mode of oscillations presented in the system.

1.2 Thesis Goals:

The goal of present thesis is to design the WPSS which is able to damp inter-area mode of oscillations presented in two-area, 4-machine power systems. Eigenanalysis methodology is used to identify *local area* and *inter-area mode* of oscillations and mixed sensitivity H_∞ based robust controller is designed to damp inter-area modes of oscillations and increase the disturbance rejection in the system.

Chapter 2

Low Frequency Oscillations

2.1 Definition: Low frequency oscillation (LFO) is the oscillation presented in generator rotor angle. They lie in the range of 0.1-3.0 Hz. By using high-gain exciters, tuning problem in generation excitation, HVDC converters or static var compensators are the few reasons of LFOs with poor damping. Such problems are known as small-signal stability problem. Solution to this problem is addressed by using power system stabilizers. LFOs includes *local mode* of oscillations, *torsional* modes (due to interaction between the mechanical and electrical modes of a turbine-generator system) [1] and *inter-area modes* of oscillation which is because of either high gain exciters or bulk amount of power transfers over long distances across weak tie-lines.

2.2 Analysis: Small disturbances are the main reasons of the LFOs in the system, such as changes in the load of the power system. These small disturbances create a steady increase or decrease in generator rotor angle which leads to lack of synchronizing torque. Lack of sufficient damping torque is one of the main problems of low frequency oscillations. With the eigenanalysis in upcoming chapters it will be clear that, eigenvectors of the system state matrix provide identification of LFOs.

Large disturbances (short circuit/loss of generator) normally lead to nonlinear oscillations of the power system in addition with the small-signal LFO modes. The LFOs (*local area* and *inter-area*) are identified by eigenanalysis.

Real Power Systems are multi machine systems so there will be many modes of oscillation and they are classified as-

1. **Local Mode Oscillation:** When dynamics of generator oscillates against the rest of the elements of the power systems or another generator in the same area then it is called Local Area Mode of Oscillations. Typical value of Local Area mode of frequency is between 0.3 to 2 Hz.
2. **Inter Area Mode of Oscillation:** When the dynamics of one area oscillates against the dynamics of the other area then this type of oscillation is called Inter-Area oscillation. Typical value of Inter-Area mode of frequency is between 0.1 to 0.8 Hz.
3. Control Mode of Oscillation

For this we should have positive torques (Synchronizing and Damping) to be stable system. If any of this torque coefficients become negative then stability gets affected.

2.3 Control: Power system stabilizer (PSS) is used with the automatic voltage regulator (AVR) of the generator in the test system to damp local area mode of oscillations. Damping of the LFOs enhances the stability limit of the system leads to higher power transfer through the system. The application of PSS to damp local area mode of oscillation by using local input signals has been verified previously. However, by using same PSS, it may not be able to damp *inter-area modes* of oscillations. Also, PSS may not able to damp all kind of frequencies presented in system. Description of the PSS and AVR related control and design is presented in upcoming chapters.

LFOs can also be controlled by the introduction of active or passive control elements other than PSSs into the power system. Thyristor-controlled series capacitors (TCSCs), Unified power controllers (UPCs) and thyristor-controlled dynamic brakes are one of them. But this thesis contains control using PSS and AVR only.

Chapter 3

Power System Stability

3.1 Power System: It is a network of electrical components used to supply, transmit and use electric power [1].

It can be broadly divided into three major parts-

1. Generator: It supplies/generate the power.

2. Transmission System: It carries power from generating centre to load centre.

3. Distribution System: It feeds power to nearby homes and industries.

3.2 Power System Stability Concepts and Definitions: Property of the power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance, is called as *power system stability*.[1].

Power system instability may be occurring in many different ways depending on the system configuration and operating mode. Initially, the stability problem has been one of maintaining synchronous operation. This aspect of stability is influenced by the dynamics of generator rotor angle and power-angle relationships [1].

Instability may also be encountered without loss of synchronism. For example, a system consisting of a synchronous generator feeding an induction motor load through a transmission line can become unstable because of collapse of load voltage. Maintenance of synchronism is not an issue in this instance; instead, the concern is stability and control of voltage.

Different forms of power system instability and concepts are given in following points.

3.3 Classification of Power System Stability:

Power system stability divided into two parts:

3.3.1 Rotor Angle Stability:

Rotor Angle Stability is the ability of the power system that its machine will be in synchronism after small perturbation [1].

This can be further be divided into four parts

a. Small Signal Stability: *Small-Signal Stability* is the ability of power system to maintain synchronism when subjected to small disturbances [1]. In this context, a disturbance is considered to be small if the equations that describe the resulting response of the system may be linearized for the purpose of analysis. Instability that may result can be of two forms: (1) Steady increase in generator rotor angle due to lack of synchronizing torque, or (2) rotor oscillations of increasing amplitude due to lack of sufficient damping torque. In today's practical power systems, the small-signal stability problem is usually one of insufficient damping of system oscillations [1].

b. Transient Stability: Ability of the power system to return to a normal operating state after disturbance, known as transient stability [1],

c. Mid Term and Long Term Stability: These terms are relatively new; They deals in the dynamic response of power system to severe upsets.

3.3.2 Voltage Stability:

This is divided into two parts-

a. Large Disturbance Voltage Stability: Ability to control voltages following large disturbances such as system fault, loss of generation and circuit contingencies [1].

b. Small Disturbance Voltage Stability: Ability to control voltages following small disturbances such as internal changes in system load [1].

Note: Voltage instability generally occur with angle stability in the system. It does not occur in pure form.

Chapter 4

Excitation System and Power System Stabilizer

This chapter provides the brief inside about power system stabilizers and excitation system. Excitation system provides direct current to the field windings of synchronous generator. For the satisfactory performance excitation system performs control and protective function for the power system by controlling field voltage, resulting field current.

Excitation system performs control of reactive power flow, voltage and improvement of system stability. Protective functions works as a limiter function.

This chapter described the modelling and characteristics of synchronous generator excitation system.

4.1 Excitation System Requirements: Different types of excitation system requirements are determined by consideration of synchronous generator and power system. In this thesis work we have used AC excitation system.

4.1.1 Generator Consideration: Main function of excitation system is the, supply and automatically adjusts the field current of synchronous generator to maintain the terminal voltage. Normally, the rating of the exciter varies from 2.0 to 3.5 kW/MVA generator rating.

The generator capabilities in this regard are limited by several factors such as rotor heating due to high field current, rotor insulation failure due to higher field voltage, stator heating due to high armature current loading, core end heating during under excited operation, and heating due to excess flux (volt/Hz) [1]. Thermal limits have time-dependent characteristics and the short-term overload capability of the generator may extend from 15 to 60 seconds. To ensure the best utilization of excitation system, it should be capable of meeting the system needs by taking full advantage of the generator's short term capability without exceeding their limits [1].

4.1.2 Power System Consideration: In the power system, the function of excitation system is to control of field voltage and improve the system stability. It should respond quickly in case of any disturbance so as to improve transient stability, also updating the generator field to improve small-signal stability hand by hand.

Excitation systems were used to control manually to maintain the machines terminal voltage and reactive power loading in early days. These days voltage control was very slow but in 1920s by using continuous and fast-acting regulators, small-signal and transient stability were enhanced. In 1960s, terminal voltage error signals were used to control the field voltage to damp LFOs.. This excitation control is called as *power system stabilizer*.

To fulfil the above roles satisfactorily, the excitation system must satisfy the following requirements:

- Meet specified response criteria
- Providing protective and limiting functions as required preventing damage to itself, the generator and other equipment.

4.2 Excitation System Elements:

Given figure shows the block diagram of a typical excitation control system for synchronous generator. It is described as follows:

4.2.1 Exciter: Exciter supplies dc power to the rotor of synchronous machine [1].

4.2.2 Regulator: Regulator process and amplifies control signal to required level and convert it into a form for control of the exciter. This includes both excitation and regulating system stabilizing function (rate feedback or lead-lag compensation) [1].

4.2.3 Terminal Voltage Transducer: It is a sensor which measure generator terminal voltage, filters and rectifies it to dc value and compares it with a reference value which represents the desired terminal voltage [1].

4.2.4 Power System Stabilizer: PSS supplies an extra input signal in form of electrical damping to the regulator to damp oscillation present in the system. Few of the commonly used input signals are rotor speed deviation, acceleration power, frequency deviation and stator voltage. The details about the power system stabilizer will be discussed in this chapter later [1].

4.2.5 Limiters and Protective Circuits: These circuits include control and protective functions which ensure that the limits of exciter and machine are not exceeded. The commonly used functions are field-current limiter, maximum excitation limiter, terminal voltage limiter, volts-per-Hertz regulator and protection and under excitation limiter [1].

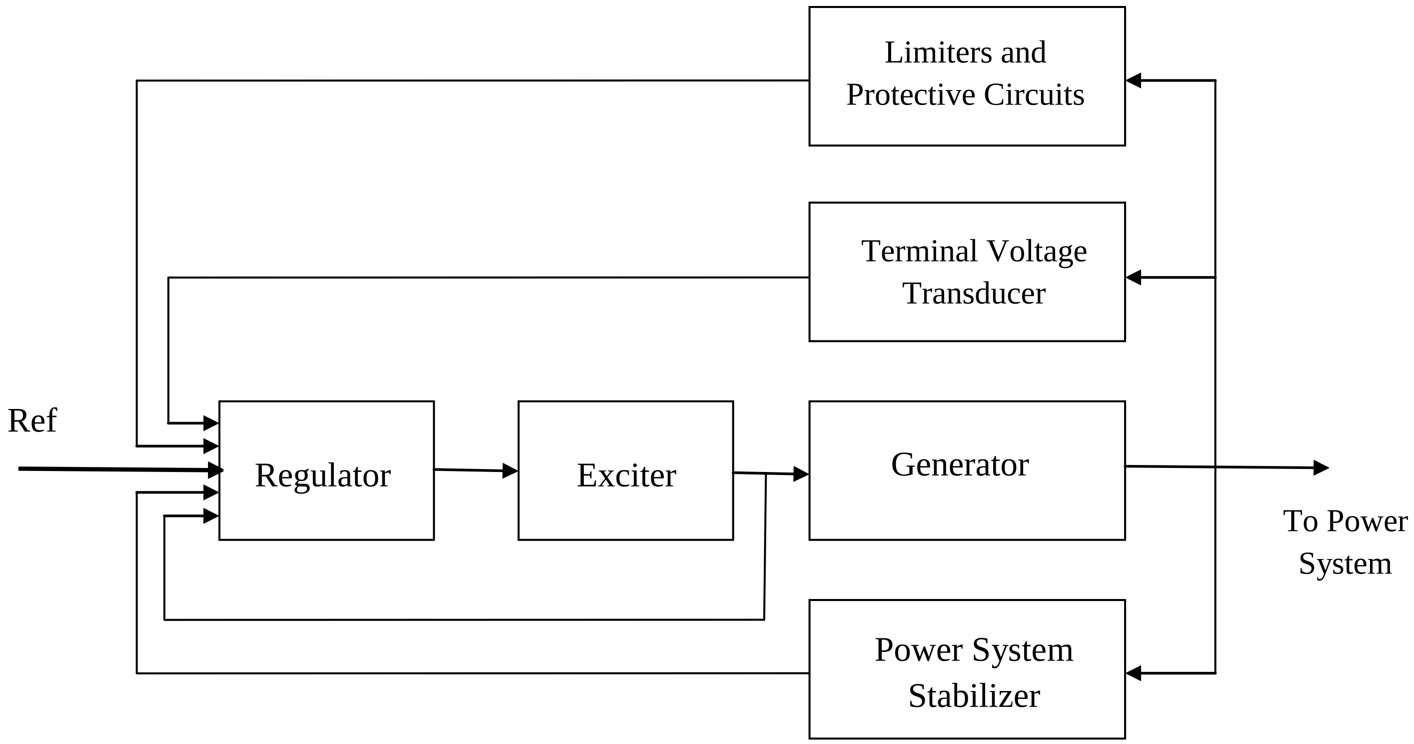

Figure 4.1: Block Diagram of Synchronous Generator Excitation Control System

4.3 Power System Stabilizer: Controller design using power system stabilizer, method of combining PSS with automatic voltage regulator (AVR), many input feedback signal to the PSS and tuning of the parameters to make system oscillation free are all parts of the PSS topic. The PSS uses auxiliary stabilizing signals to control the excitation system so as to improve the power system dynamic performance. Commonly used input signals to the power system stabilizer are shaft speed, terminal frequency and power. To provide damping, the stabilizer must produce a component of electrical torque in phase with rotor speed deviation. Power system dynamic performances are improved by damping of system oscillations. It is very effective way to enhance the small signal stability performance.

Since the purpose of PSS is to introduce a damping torque component, a logical signal to use for controlling the generator excitation is the speed deviation $\Delta\omega_r$.

4.4 PSS Design and Control Action: The function of a PSS is to provide electrical damping to a synchronous machine of the power system to upgrade the angular stability limits through the generator excitation. This electric torque applied should be in phase with rotor speed deviation. By this, local area mode oscillations are damped. This control technique is very useful during huge amount of power transfers over a remote area. Power system instabilities may occur due to negative damping effects of the PSS on the rotor.

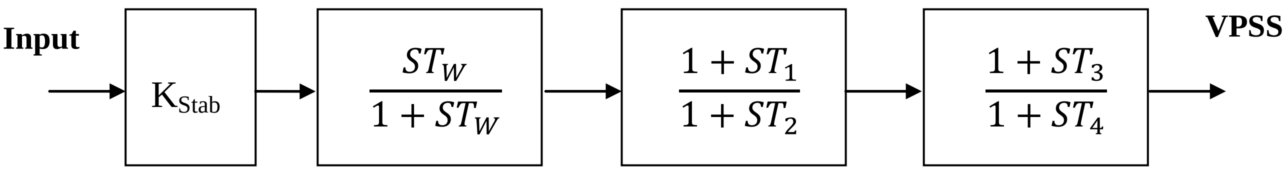

Figure 4.2: Lead-Lag PSS

The PSS comprise of a washout block which minimizes the over-response of the damping during occurrence of any fault. PSS should produce a component of electrical torque in phase with the input signal which is used as speed deviation in this thesis work, phase lead-lag compensators are used to compensate the effect of input and output signals. Damping provided by the PSS increases if gain K increases up to a certain critical gain value, after which the damping begins to decrease.

4.5 Input Signal to PSS: There are different input signals that we can use for PSS. The signals that are mostly used are identified as rotor speed deviation $\Delta\omega$, electrical power, accelerating power, rotor angle deviation and voltage in the tie line. Since the main action of PSS is to control the rotor oscillations so rotor speed deviation has been used frequently as input signal. Controllers focused around speed deviation would in a perfect world utilize a differential-sort of regulation and a high gain. Since this is unreasonable in all actuality, the beforehand said lead-lag structure is regularly utilized. Notwithstanding, one of the confinements of the speed input PSS is that it may energize torsional oscillatory modes.

A power/speed PSS configuration was proposed as an answer for the torsional communication issue endured by the speed input PSS. The power signal utilized is the generator electrical power, which has high torsional weakening. Because of this, the gain of the PSS may be expanded without the resultant loss of steadiness, which prompts more excellent oscillating damping.

4.6 Tuning and Control: The clashing requirement of local and inter-area mode damping and stability under both small signal and transient conditions have prompted numerous diverse methodologies for the control and tuning of PSS. The distinctive sorts of control and tuning techniques researched are state space/frequency domain technique, root locus of lead-lag controller, pole placement of PID controller. Every technique has its own particular benefit and weakness. This is solution for the issue of LFO damping by the provision of PSS.

In this thesis we did not provide the analysis for each of the technique rather the improvement of the oscillation damping using PSS. Through the analysis performed here it is found that PSS is able to damp local area of oscillations and WPSS has damped the inter-area mode oscillations.

Chapter 5

Modelling of Two-Area Power System & State Space Representation

This unit comprise of two area power system modelling and state space representation of the modelled system, its linearization and mode identification presented in the power system oscillation. We have chosen synchronous generator for case study.

5.1 Dynamical Modelling of Two Area Power Systems: The case study has been carried out on 4 machines, 11 buses system as give in fig. 1. The system parameters are given as follows [1].

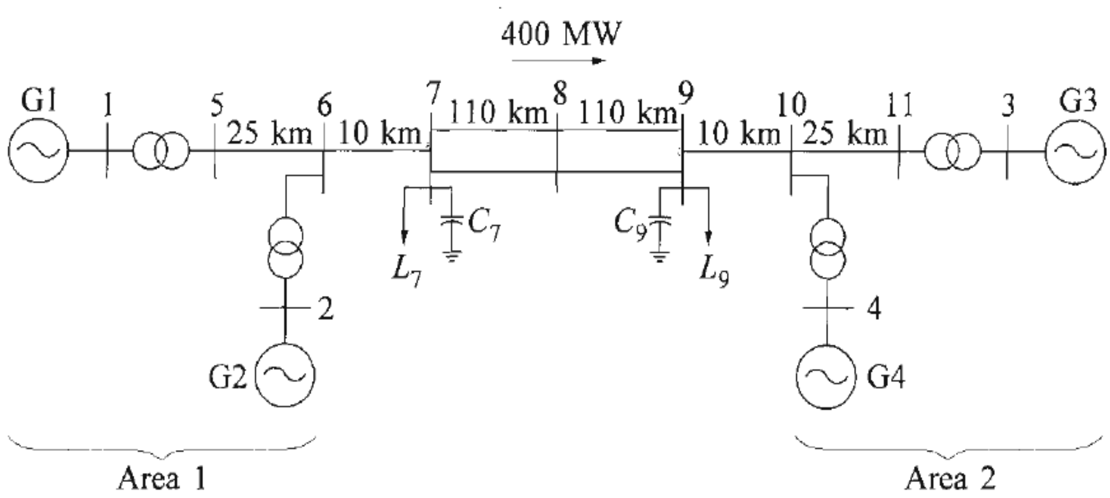

Fig. 5.1 A Simple Two-Area System

The system consists of two similar areas connected by a weak tie. Each area consists of two coupled units, each having a rating of 900 MVA and 20kV. The generator parameters in per unit on the rated MVA and kV area as follows:

$X_d = 1.8$ $\quad X_q = 1.7$ $\quad X_l = 0.2$ $\quad X_d^{'} = 0.3$ $\quad X_q^{'} = 0.55$

$X_d^{''} = 0.25$ $\quad X_q^{''} = 0.25$ $\quad R_a = 0.00125$ $\quad T_{d0}^{'} = 8\ s$ $\quad T_{q0}^{'} = 0.4\ s$

$T_{d0}^{''} = 0.03\ s$ $\quad T_{q0}^{''} = 0.05\ s$ $\quad A_{Sat} = 0.015$ $\quad B_{Sat} = 9.6$ $\quad \psi_{T1} = 0.9$

$H = 6.5\ (for\ G1\ and\ G2)$ $\quad H = 6.175\ (for\ G3\ and\ G4)$ $\quad K_D = 0$

Each step-up transformer has an impedance of $0 + j0.15$ per unit on 900 MVA and 20 kV base, and has a nominal ratio of 1.0.

The transmission system nominal voltage is 230 kV. The line lengths are identified in fig.2. The parameters of the line in per unit on 100 MVA, 230 kV base are

$$r = 0.0001\, pu/km \qquad x_l = 0.001\, pu/km \qquad b_c = 0.00175\, pu/km$$

All the generators are on manual excitation control with following dynamics:

Thyristor exciter with high transient gain:

$$K_A = 200 \qquad T_R = 0.01$$

Power System Stabilizer (PSS) Dynamics are as follows:

$$T_W = 10 \qquad T_1 = 0.05 \qquad T_2 = 0.02 \qquad T_3 = 3.0 \qquad T_4 = 5.4$$

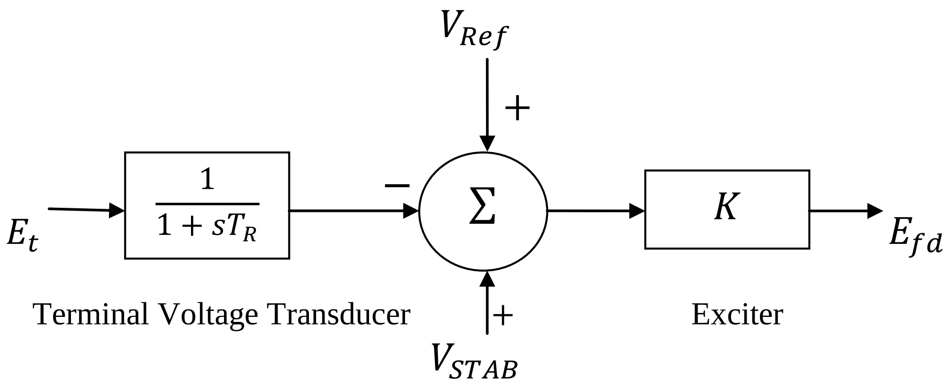

Fig. 5.2 Excitation System

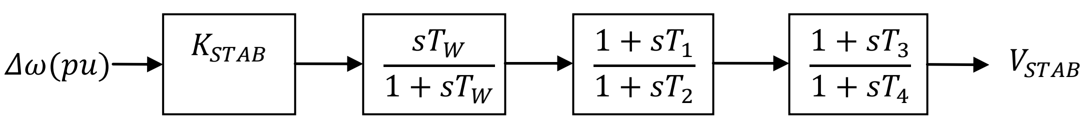

Fig. 5.3 Power System Stabilizer (PSS)

In order to simulate this problem we have simulated it once, without employed any PSS and again with PSS to calculated different modes with their corresponding frequency and damping. Since the created power system is non-linear so we have to linearize it for the concern of stability analysis.

Given system is modelled on Simulink in Matlab 2012 a using simpower system toolbox. Every element of the given system model is modelled with utmost care and then linearized around an operating point.

5.2 Model linearization without PSS: Power system is a nonlinear system. For measurement and control signal selection, a linearized model of the system is used. The system is linearized around an operating point by the command **'linearize'** in MATLAB.

lin=linearize('sys') command takes a model name sys and returns a linear time-invariant state-space model.

The dimension of state-space matrices A, B, C, and D without PSS is given:

$A = [56 \times 56]$, $B = [56 \times 4]$, $C = [8 \times 56]$, $D = [8 \times 4]$.

There are four machine sets in this model and each machine (with exciter) contains 14 states.

.

5.3 Verification of Oscillatory Modes without PSS: Eigen value analysis helps in identifying poorly damped or unstable modes in power system dynamic models. Power systems are highly nonlinear; however, under normal operating conditions, it can be assumed that these systems behave linearly, thus linearization around an operating point can be applied. Eigen value analysis is a well-established approach for studying the characteristics of inter-area modes. The approach has several attractive features: each individual mode is clearly identified by the Eigen values, and mode shapes are readily available. Eigen value analysis is commonly used to investigate the properties of inter-area oscillations in multi-machine power system models. In addition, the analysis also provides valuable information about sensitivities to parameter changes.

The eigenvector associated with a mode indicates the relative changes in the states which would be observed when that mode of oscillation is excited. It enables us to confirm that mode 43 & 44 is an inter-area mode, since generators 1 and 2 are oscillating against generators 3 and 4. However, the largest components of the eigenvector are those associated with the second exciter state. This means that the inter-area mode may be most easily observed by monitoring those states. It does not mean that these states are necessarily good for controlling the inter-area mode.

Local Area and Inter-Area modes of oscillation without PSS are given in table.

No.	Eigen Values	Frequency (Hz)	Damping Ratio	Modes/ Remark
1,2	-0.7519 ± 6.9945i	1.1132	0.1069	Local Area
3,4	-0.7479 ± 7.2177i	1.1487	0.1031	Local Area
5,6	0.0569 ± 3.9397i	0.6270	- 0.0144	Inter-Area
7,8	-19.1109 ±14.4025i	2.2922	0.7986	-
9	-32.0976	-	1	-
10,11	-19.3945 ±10.1064i	1.6085	0.8868	-
12,13	-11.8662	-	1	-

Table 5.1 System modes without PSS and manual excitation

From the table we see that system is stable. There are four Rotor Angle modes of oscillation. Their mode shapes (normalised eigenvector components corresponding to rotor angles of the four machines) are shown in figure bellow.

5.4 Plot of Rotor Angle Terms of Local-Area Mode Eigen Vector: When dynamics of generator oscillates against the rest of the elements of the power systems or another generator in the same area then it is called Local Area Mode of Oscillations. Typical value of Local-Area mode of frequency is between 0.7 to 2.0 Hz.

Eigen Value: -0.7519 ± 6.9945i

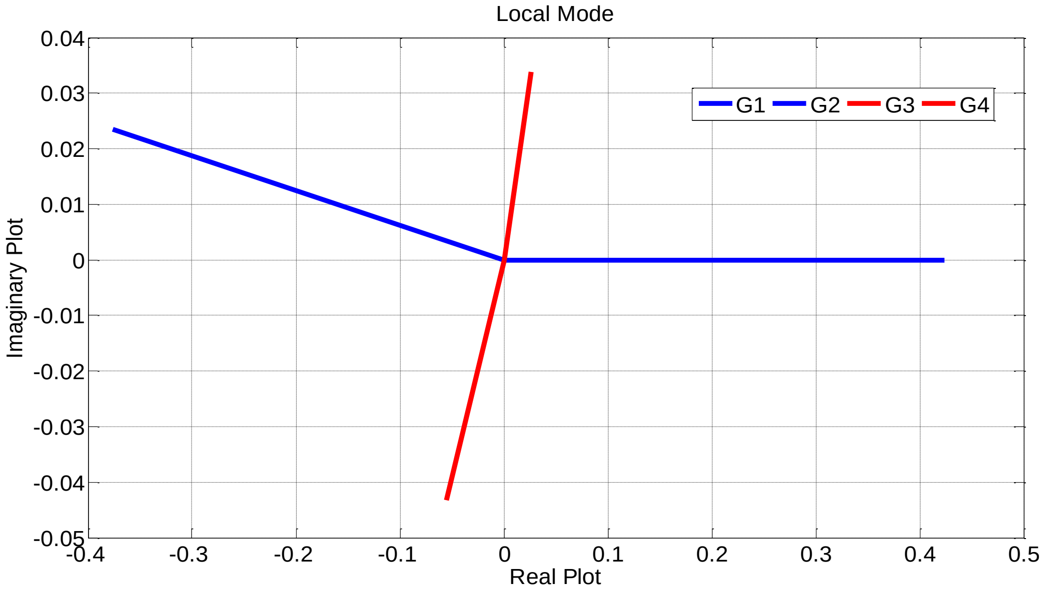

Fig 5.4 Local Area Mode Eigenvector Shape 1 (Without PSS)

Eigen Value: -0.7479 ± 7.2177i

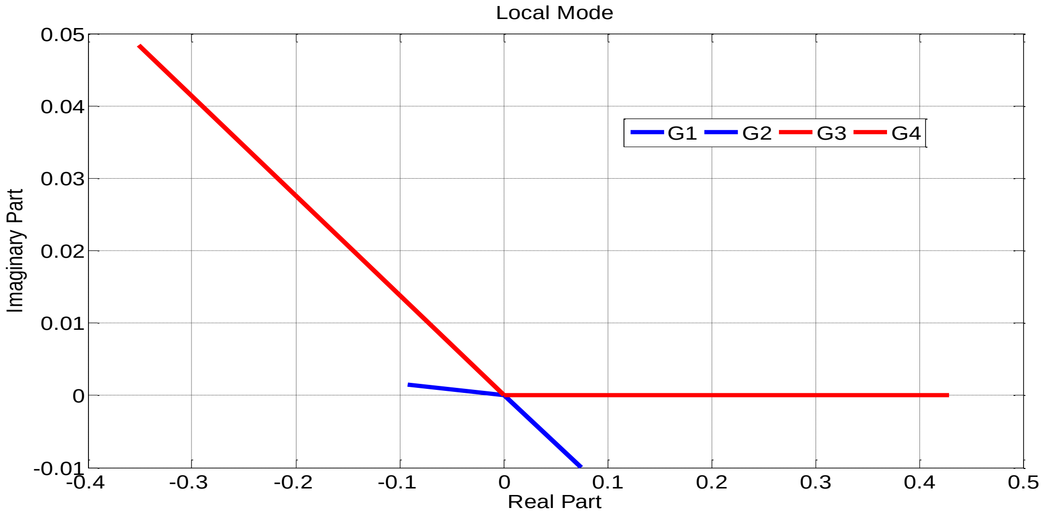

Fig 5.5 Local Area Mode Eigenvector Shape 2 (Without PSS)

5.5 Plot of Rotor Angle Term of Inter-Area Mode Eigen Vector: When the dynamics of one area oscillates against the dynamics of the other area then this type of oscillation is called Inter-Area oscillation. Typical value of Inter-Area mode of frequency is between 0.1 to 0.8 Hz.

Inter-Area modes can be identified as the Dynamics of the Generators of one area will oscillate against the dynamics of the Generator of second area at a phase difference of 180^0.

Eigen Value: 0.0569 ± 3.9397i

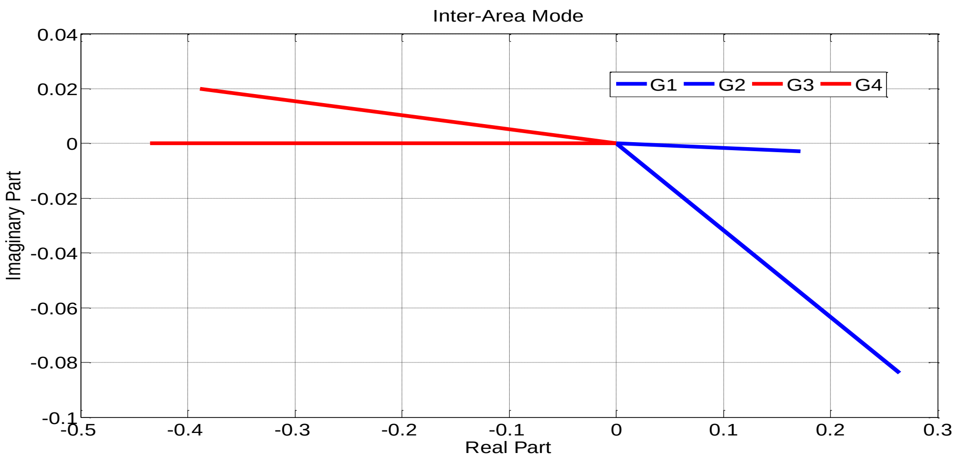

Fig 5.6 Inter-Area Mode Eigenvector Shape (Without PSS)

5.6 Model linearization with PSS: Plant consists of total 8 outputs, 4 for rotor mechanical angle and 4 for rotor speed deviation by each of the generators. We have employed rotor speed PSS in the plant as a feedback and rotor speed deviation is taken as input to the PSS. The output of PSS is stabilization signal V_{Stab} which is input of plant as feedback signal.

The system is linearized around an operating point by the command **'linearize'** in MATLAB. lin=linearize('sys') command takes a model name 'sys' and returns a linear time-invariant state-space model.

The dimension of PSS state-space matrices Apss, Bpss, Cpss, and Dpss also given:

$Apss = [12 \times 12]$, $Bpss = [12 \times 4]$, $Cpss = [4 \times 12]$, $Dpss = [4 \times 4]$

The dimension of state-space matrices A, B, C, and D with PSS is given:

$A = [68 \times 68]$, $B = [68 \times 4]$, $C = [4 \times 68]$, $D = [4 \times 4]$

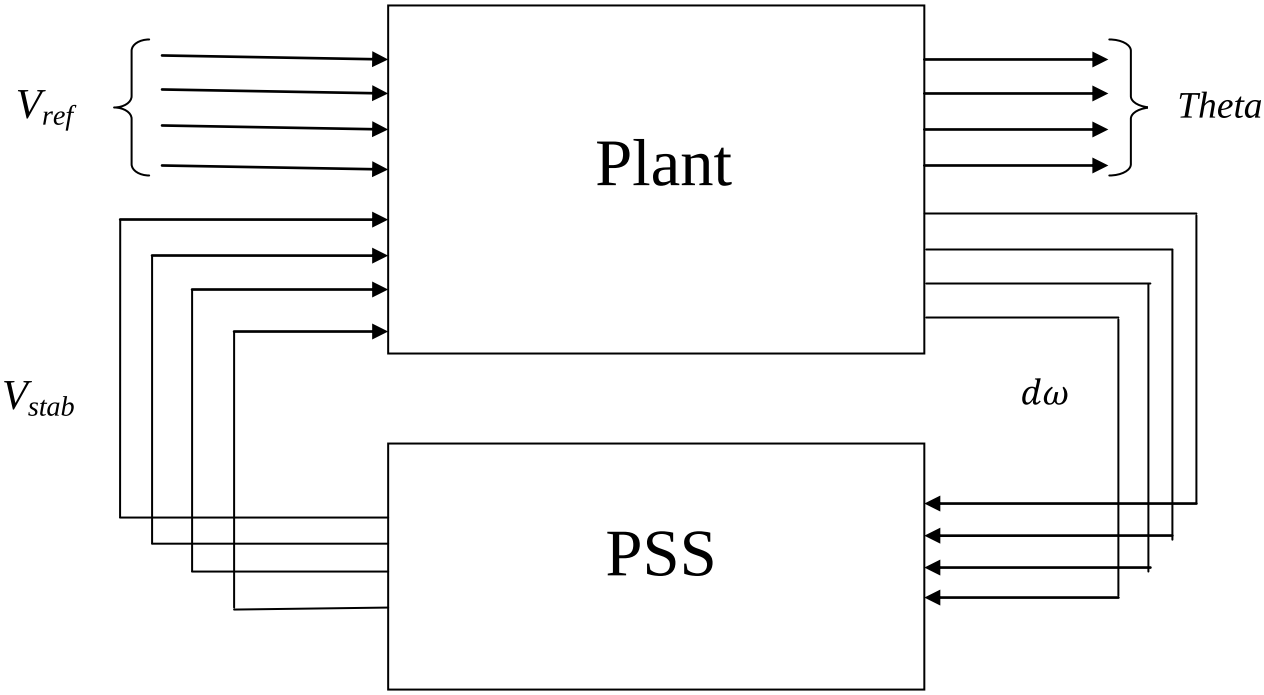

Fig. 5.7: Feedback Configuration of PSS to the Plant

5.7 Verification of Oscillatory modes with PSS: The eigenvector associated with a mode indicates the relative changes in the states which would be observed when that mode of oscillation is excited. It enables us to confirm that mode 53 & 54 is an inter-area mode, since generators 1 and 2 are oscillating against generators 3 and 4. Also states (45&46), (49&50) are identified as Local Area mode.

Local Area and Inter-Area modes of oscillation with PSS at gain 20 are given in table.

No.	Eigen Values	Frequency (Hz)	Damping Ratio	Modes/ Remark
1,2	-17.2067 ± 8.0526i	1.2816	0.9057	Local Area
3,4	-1.6745± 9.9160i	1.5782	0.1665	Local Area
5,6	-1.0654± 4.0453i	0.6438	0.2547	Inter-Area
7,8	-1.7367±9.5210i	1.5153	0.1795	-
9,10	-17.5350±12.9422i	2.0598	0.8046	-
11	-90.4950	-	1	-
12	-92.2651	-	1	-

Table 5.2: System modes with PSS and manual excitation

From the table we see that system is stable. There are four Rotor Angle modes of oscillation. Their mode shapes (normalised eigenvector components corresponding to rotor angles of the four machines) are shown in figure bellow.

5.8 Plot of Rotor Angle Terms of Local-Area Mode Eigen Vector:

Eigen Value: -17.2067 ± 8.0526i

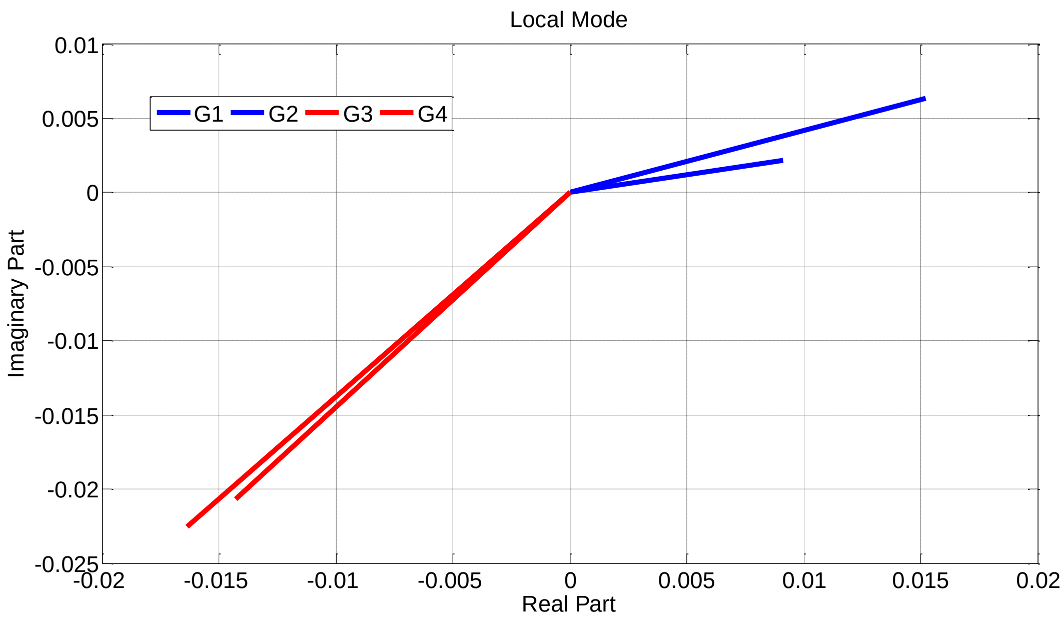

Fig 5.8 Local Area Mode Eigenvector Shape 1 (With PSS)

Eigen Value: -1.6745 ± 9.9160i

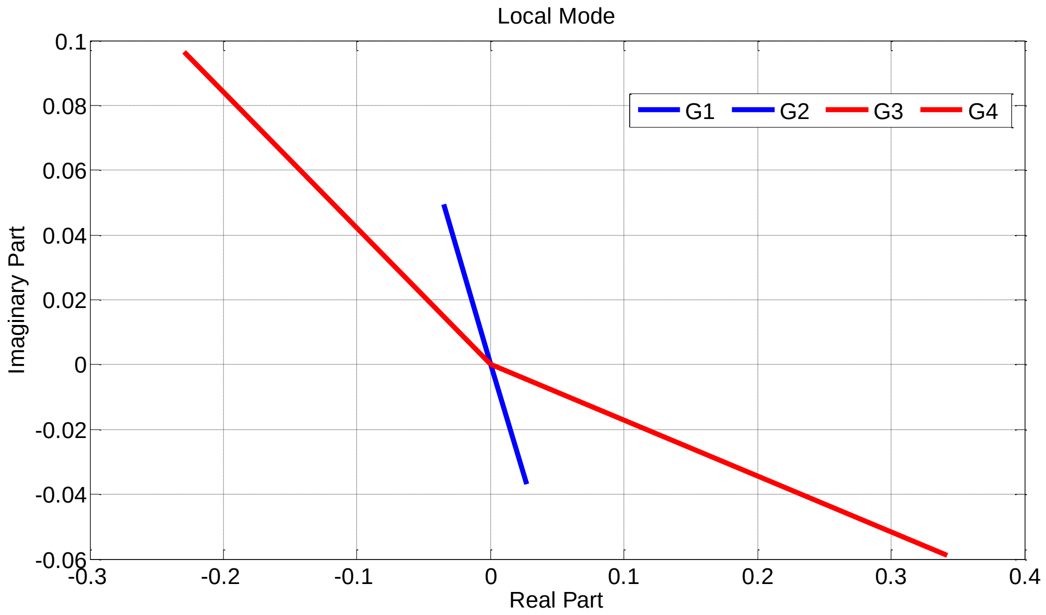

Fig 5.9 Local Area Mode Eigenvector Shape 2 (With PSS0

5.9 Plot of Rotor Angle Terms of Inter-Area Mode Eigen Vector:

Eigen Value: -1.0654± 4.0453i

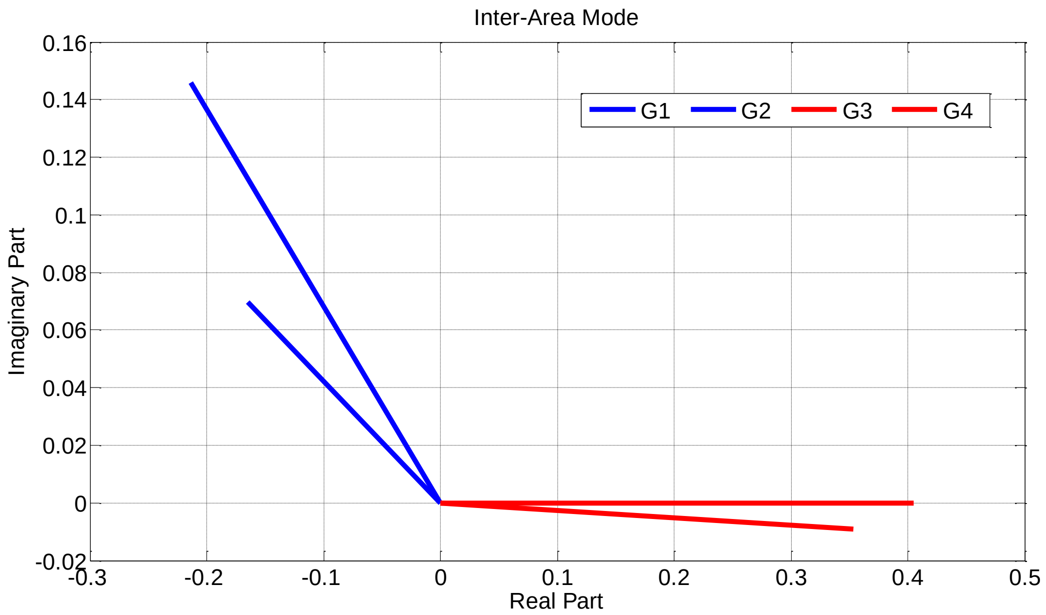

Fig 5.10 Inter-Area Mode Eigenvector Shape (With PSS)

From the above table it is confirm that PSS is able to damp the Local-Area oscillations as frequency is constant and damping is increasing on increasing the PSS gain but it is fail to remove the Inter-Area oscillations from the system even on increasing PSS gain.

Chapter 6

Wide-Area Controller Design for Two-Areas Power System

Once the system is modelled, linearized and oscillatory modes (inter-area and local area) have been identified, we could look forward to design wide-area damping controller i.e. WPSS to damp inter-area oscillations, since local area mode of oscillations has been already damped using PSS which uses local signals. This chapter comprise of wide-area control loop selection, model order reduction of plant because created model is of 68^{th} order and it could pose a formidable computation burden and a robust controller design to damp inter-area mode of oscillations.

6.1 Control Loop Selection for Wide-Area: Wide-Area control loop selection is essential for damping inter-area oscillations. For choosing wide-area control loop we need to choose best available input-output channel for efficient decentralised control unlike to centralised control in which input and output considered altogether. To choose wide-area control loop we have chosen Loop Selection Index (LSI) method base on geometric approach as it is unaffected by scaling by eigenvector. LSI approach is based on how good a combination of input and output vectors are aligned to the corresponding eigenvector for a particular mode [6].

The LSI can be calculated as given formula [6]:

$$LSI_{mn} = \frac{|b'_m v_l||c_n v_r|}{\|b_m\|\times\|v_l\|\times\|c_n\|\times\|v_r\|}$$

Where, LSI_{mn} is Loop Selection Index corresponding to m^{th} input and n^{th}output combination, b_m is the input vector corresponding to m^{th} input c_n is the output vector corresponding to n^{th} output. v_l and v_r are the left and right eigenvector corresponding to inter-area mode [6].

Loop Selection Index for the two areas, four machine system using above formula has been calculated and shown in table given bellow.

Input/output	$\Delta\omega_{13}$	$\Delta\omega_{14}$	$\Delta\omega_{23}$	$\Delta\omega_{24}$
G_1	1.0048e-004	6.3058e-005	-	-
G_2	-	-	0.0022	0.0020
G_3	5.0633e-005	-	2.2159e-006	-
G_4	-	7.2396e-007	-	5.6179e-005

Table 6.1: Loop Selection Index Corresponding to I/O Pairs

(- sign represents the I/O pairs that are not wide-area loop)

Where G_i are the generators and $\Delta\omega_{kj}$ is loop selection indices for the corresponding loops. Here from above table we can judge that LSI associated with inputs at area-1 (either at generator $G_1 or\ G_2$) is comparatively high to the inputs at area-2 (either generator ($G_3 or\ G_4$). Since area-1 is supplying electrical power to area-2, so it is very genuine as expected to have LSI associated with area-1 is high. It might likewise be noted that utilizing the WPSS at generators closer to tie-line (G_2 or G_4) enhances the LSI since they have immediate control on the buses closer to tie-line as compared to generators away from the tie-line.

Here for this case, the wide-area signal $\Delta\omega_{23}$ when utilized as input to additional controller at G_2 yields the most elevated LSI, resulting the input-output pair $\Delta\omega_{23}$used as a wide-area signal to damp the inter-area oscillations in present work.

6.2 Model Order Reduction: In electrical power systems, the order of the model may effectively arrive at around large number of state variables like control, trajectory affectability and dynamical simulation and so on. This sort of investigation brings a complex computation. Full order plant has higher number of states with limited number of input and output so they are rarely controllable and observable. To address this issue we need to reduce model order in a way such that frequency response of reduced model nearly matches with the full order model and holds critical modes of oscillation. Model order reduction is the supplanting of the original system with one of the much more diminutive dimensional order system in the accompanying way.

- The frequency response of both reduced and original system should be nearly same.
- The cost of creating the reduced model from the original model must be less than the cost of performing the analysis using the original model.

Most of the methods of model order reduction based on the linear systems which provides an exact description of the original system. The *schmr* bases model order reduction technique is used in this thesis work to obtain reduced order model from original model in MATLAB that uses schur based model order reduction technique. This function performs schur method model reduction on G(s) such that the infinity norm of the error is less or equal to smaller Hankel Singular Values [4].

Here we first reduced the 68th order original system to 10th order reduced order system and it is found that the reduced order model holds these three low-frequency oscillatory modes which were in full order model and it is also observed that reduced order plant is controllable and observable. It has also been observed that the frequency response of both original and reduced order model is found to be nearly same.

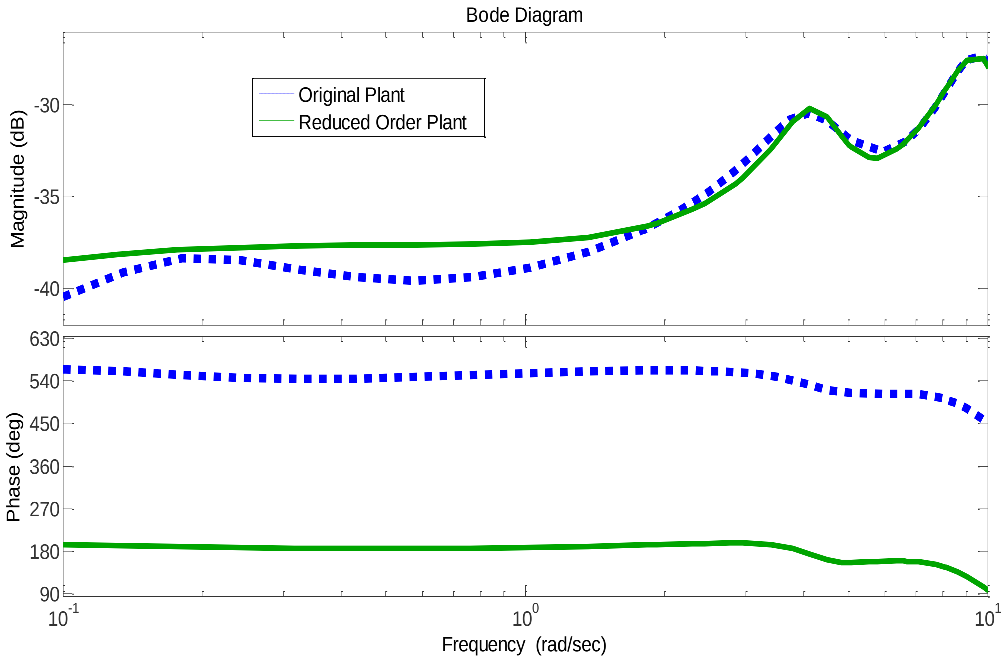

Fig. 6.1: Frequency response of full and reduced order plant

Figure given above shows the bode plot of original and reduced order plant and it is observed that frequency response of reduced 10th order model is almost matches with the original model in desired frequency range of 0.1 to 10 Hz.

T.F. of the reduced order plant $G_r(s)$ is given as:

$$G_r(s) = \frac{\begin{matrix}-0.041583(s+58.43)(s+3.497)(s+0.023)(s^2+1.772s+4.476)\\(s^2+2.751s+25.76)(s^2+3.446s+94.1)\end{matrix}}{\begin{matrix}(s+3.487)(s+3.222)(s+1.664)(s+0.06063)(s^2+1.528s+18.22)\\(s^2+3.455s+94.03)(s^2+3.311s+101.5)\end{matrix}}$$

6.3 Wide-Area Control Configuration: With the wide-area control loop selection and plant model order reduction we have applied WPSS to generator G_2 along with AVR and local PSS as shown in given figure.

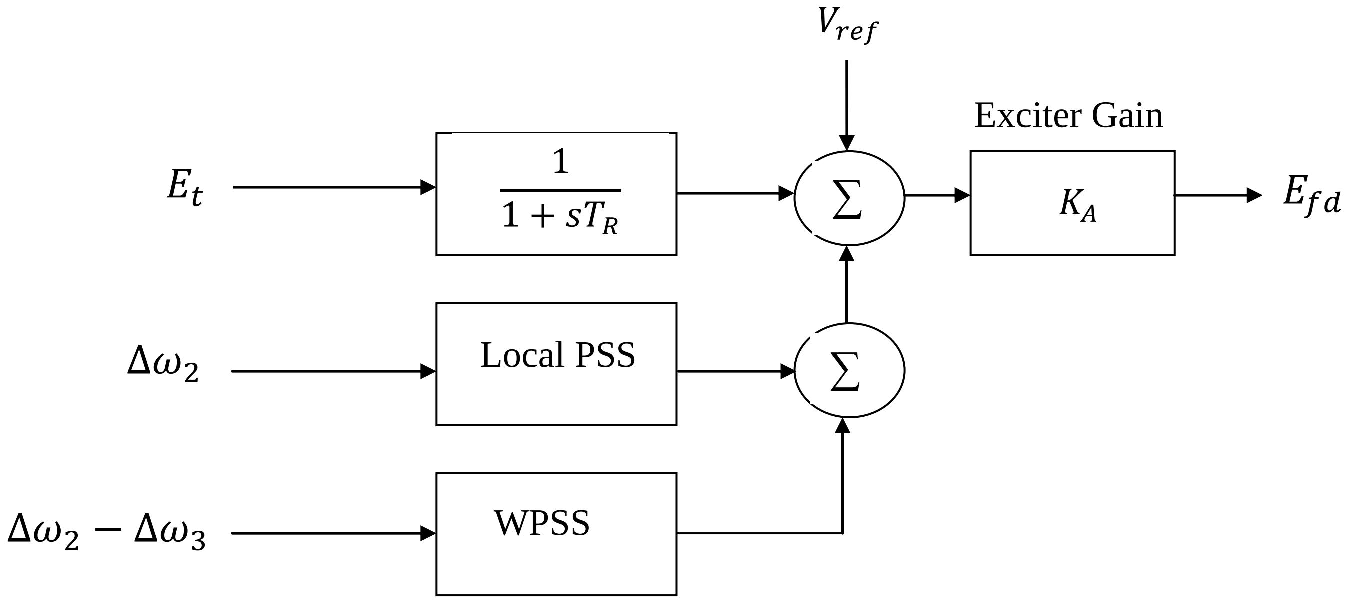

Fig. 6.2: PSS and AVR Structure at Generator G_2

WPSS is applied to AVR control loop as an additional controller through feedback to damp inter-area mode of oscillations and Local PSS is applied as a supplementary controller to the AVR loop to damp local area mode of oscillations. In this thesis work, wide-area controller design is performed using robust controller design method.

6.4 WPSS/H_∞ Controller Design: A traditional power system regularly subjected to instabilities and system transforms so it is necessary to design a robust controller that can cope with uncertainties and related problems in the model while without affecting the system performance. Robust control methodology is used to design WPSS in this thesis work.

For two areas, four machine power systems, the adapted control configuration is shown in figure.

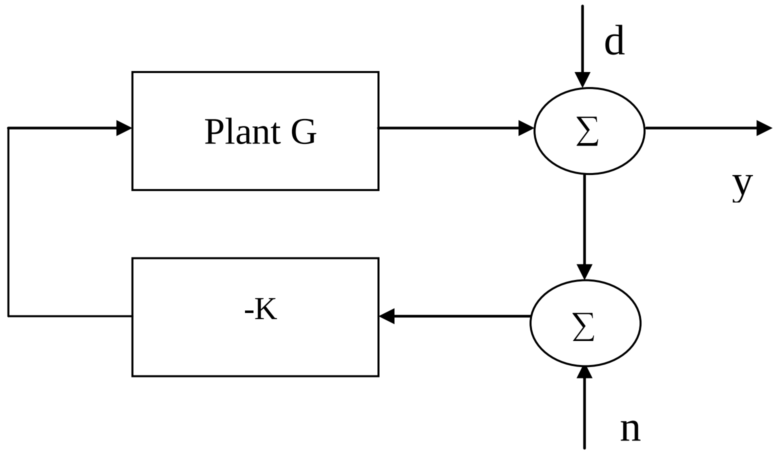

Fig.6.3: Block Diagram Representation of Close Loop System

Where G is the linearized plant, K is wide-area feedback controller (WPSS Transfer Function), *y* system is output. Another signal *d* is disturbance input to the output/system, and signal *n* is represented as noise in output measurement. The output of the system can be chosen as power in the tie-lines, rotor angle deviation and speed deviation between two generators from each area of the system [2]. By choosing these parameters from both the areas, inter-area oscillations can be identified from output measurement. We have chosen speed deviation as output in present work.

The output and input of given close loop system can be written as:

$$y = (1 + GK)^{-1}d - GK(1 + GK)^{-1}n \qquad (6.1)$$

$$u = -K(1 + GK)^{-1}d - K(1 + GK)^{-1}n \qquad (6.2)$$

Let us define: $S = (1 + GK)^{-1}$ & $T = GKS = 1 - S$ (6.3)

Where S is called sensitivity function, which represents the measure of relative change in the closed loop transfer function T to relative change in the plant model G. T is called complementary sensitivity function. It can be observed from equation (1) that S is the transfer function from disturbance to output.

Here, we need to design a robust controller in such a way that effect of disturbance and noise in the output is minimised. For disturbance and noise rejection S and T should be minimised. These kind of problem known as multi-objective problem. We have solved this problem by summing them together and made it a single objective. But, there will be trade-off to achieve the both since $S + T = 1$. Considering H_∞ performance in the sense that H_∞ norm of the function is to be minimized [3].

Hence the controller design problem is defined as:

$$\min_K \left\| \begin{matrix} S \\ T \end{matrix} \right\|_\infty \qquad (6.4)$$

Where, $\|.\|_\infty$ represents H_∞ norm of the respective function.

It has been observed that disturbance is of low frequencies and noise is of high frequencies, generally. To cope up with this problem we have considered weighted sensitivity minimization so that disturbance can be minimising at low frequencies and noise at high frequencies [16-18]. It is also beneficial if the control input can be constrained in the design so that actuator saturation does not arise and less control effort is used. We have considered this as another objective criterion, so a weighted term W_2KS is used. So the new multi-objective mixed sensitivity problem for controller design can be defined as [3]

$$\min_K \left\| \begin{matrix} W_1S \\ W_2KS \\ W_3T \end{matrix} \right\|_\infty \qquad (6.5)$$

Here, W_1, W_2 and W_3 are weight functions to minimise the effect of sensitivity function S, input sensitivity function KS and complementary sensitivity function T respectively.

Weight functions are frequency dependent and it can be chosen to meet design requirement from robust stability requirement due to unstructured uncertainties. Applying small gain criterion on (6.5) one can get necessary and sufficient condition for H_∞ design [5]. Design based on (6.5) imposes difficulty in the selection of this weight function [3]. If the combination of (i) S and KS or (ii) S and T are used for designing such H_∞ controllers then the selection of weight functions become easier. W_1 is chosen as high gain LPF, whereas other weight functions are chosen as HPF.

H_∞ Performance provides minimum gain reduction i.e. disturbance rejection. This method known as H_∞ mixed sensitivity synthesis method for robust control design. By which designed controller stabilizes the Two-Area power system and minimizes the H_∞ cost function.

With these design criteria only we may not improve damping for inter-area mode of oscillation. For this we need to place the closed loop poles in the left side of the complex plane so that damping can be improve.

The controller is designed using the performance criteria (6.5) along with pole placement in the left half of complex plane so that damping can be improved. For this we need to choose appropriate bandwidth for selecting weight function W_1.

Bandwidth is tightly defined as the frequency range within which our system is stable [3]. So it is important to select suitable weight functions for such a controller design.

Since the low frequency oscillation (local area and inter area oscillations) are bellow 10 rad/sec, so we have chosen bandwidth for the selection of W_1 and W_3 as 10 rad/sec. W_1 is chosen as LPF and W_3 is chosen as HPF and weight on control gain W_2 is chosen as BPF in the frequency range of interest.

The selected weight functions are given as follows:

$$W_1 = \frac{10}{s+10}, \quad W_2 = \frac{0.1s}{(s+1)(s+20)} \quad \text{and} \qquad W_3 = \frac{s}{s+10}$$

The *mixsyn* of robust control tool box of Matlab is used to design the WPSS controller with above design configuration [4]. Obtained controller is of the order of 14^{th} (10 order for the plant and 4 for the weights). Designed controller yields the order of the plant and order of weighting functions. High order of controller imposes difficulty in computation, implementing control gains on the system. To cope up with this problem controller order is reduced so that its frequency response matches with the full order controller in the desired frequency range and it holds the important oscillatory modes in the system.

The designed controller is further reduced 5^{th} order for ease of computation using *schmr* command in Matlab.

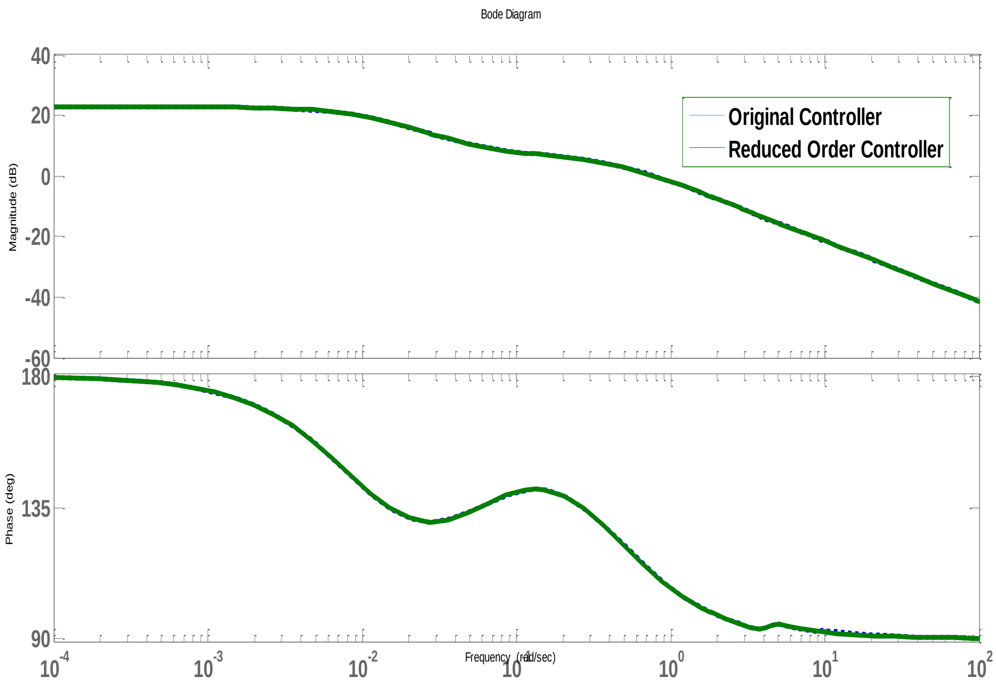

Fig. 6.4: Frequency response of full and reduced order controller

The T.F. of the reduced order controller $K_r(s)$ is given as:

$$K_r(s) = \frac{29400(s^2 - 0.07387s + 53.48)(s + 0.02287)(s - 5.881)}{(s^2 - 0.3795s + 61.13)(s + 0.01749)(s + 0.3871)(s + 1856)}$$

6.5 Simulation Result: With the designed wide-area power system stabilizer/ H_∞ mixed sensitivity robust controller low frequency oscillations in the two areas power system is studied and the simulation results are given bellow:

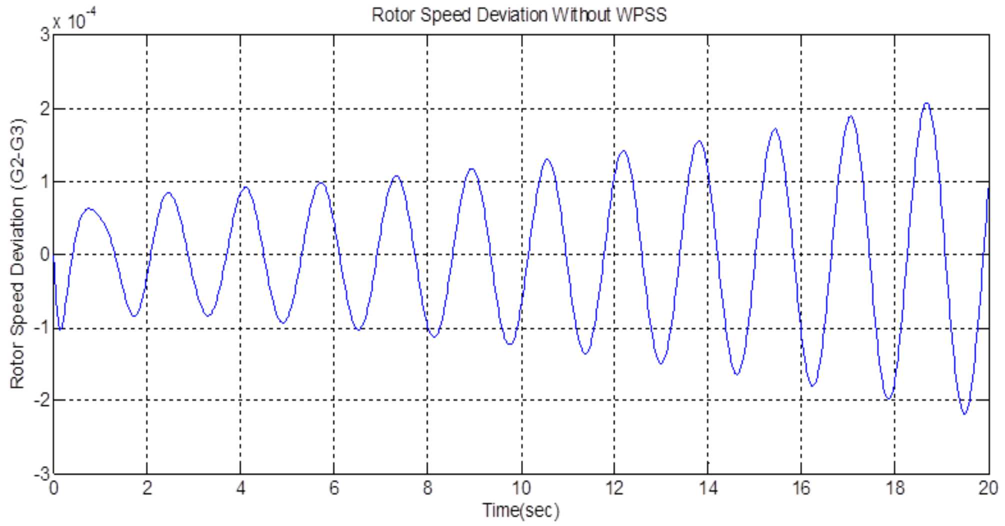

Fig. 6.5: Rotor Speed Deviation without WPSS

The above result shows the response of rotor angle deviation $\Delta\omega_2 - \Delta\omega_3$ of two area power systems without WPSS. Here rotor speed deviation is varied with respect to the V_{ref} and it is find that the rotor speed deviation $\Delta\omega_2 - \Delta\omega_3$ is increasing as time is increasing. Its response is found to be oscillatory and system is unstable because it lacks the global observation and no WPSS is used to damp inter-area mode of oscillation present in two area power system. However, local area mode of oscillations was damped out using local PSS previously.

Bellow figure present the simulation result of rotor speed deviation with WPSS.

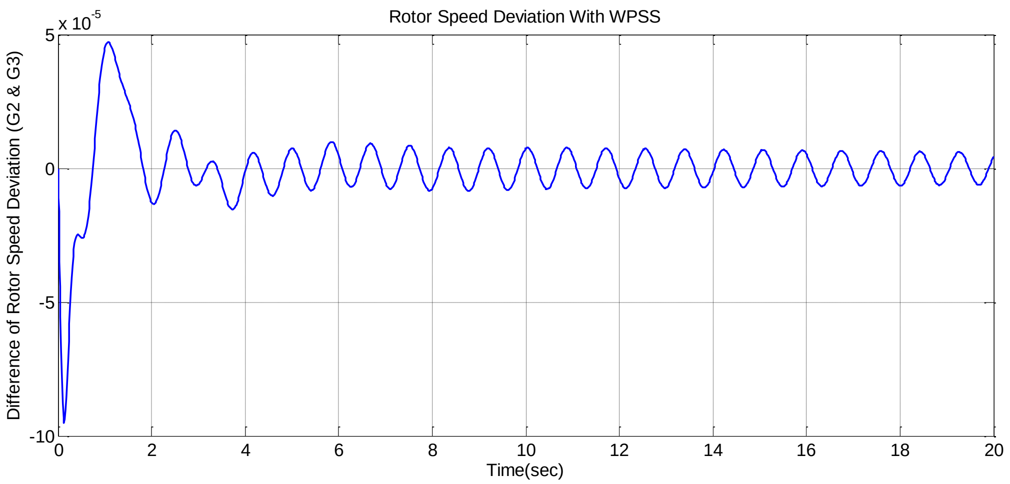

Fig. 6.6: Rotor Speed Deviation with WPSS

Above result shows the response of rotor angle deviation $\Delta\omega_2 - \Delta\omega_3$ of two area power system with WPSS. It is observed that with the use of WPSS the inter-area mode of oscillation present in two-area power system is reducing because WPSS uses global observation to damp inter-area mode of oscillations. The weight functions are selected to improve noise disturbance margin present in two area power system and mixed sensitivity H_∞ controller is designed to damp inter-area mode of oscillations.

Chapter 7

Discussion and Conclusion

In this thesis, effect of low frequency oscillations presented in two-area power system has been discussed. After modelling two area power systems it is liberalized around an operating point and local and inter-area mode of oscillations is verified, its frequency and damping has been studied. For the designing of controller it is required to reduce model order to reduce the computation effort and assure about controllability and observability. The full order model is reduced from 68th to 10th order. The designed controller order is also reduced for less computation effort and wide-area power system stabilizer (WPSS) /mixed sensitivity H_∞ controller is designed using robust control so that disturbance rejection is improved and inter-area mode of oscillations present in the two area power system has been damp out. The designed controller is able to damp the inter-area mode of oscillations presented in this two-area power system and disturbance rejection is improved. However, local area mode of oscillations was damp using PSS using local signals.

7.1 Conclusion: Mixed sensitivity H_∞ controller/WPSS for two area power system has been design to inter-area mode of oscillations present in two area power system. However, local area mode of oscillations presented in this system was damped out using PSS, which uses local signals.

7.2 Future Scope: Present work has been carried out on two areas, 4 machine power systems. The same work could be done on more than two area power systems. Also, using wide-area signals, there is some delay present in this. We can address this issue later in future.

References

[1] P. Kundur, *Power System Stability & Control* (New York, NY: McGraw-Hill, 1994).

[2] Y. Zhang & A. Bose. "Design of wide-area damping controllers for inter-area oscillations," *IEEE Trans. Power Syst.*, 23, 2008, 1136-1143.

[3] S. Skogestad & I. Postlethwaite, *Multivariable Feedback Control* (Chichester: John Wiley & Sons, 1996).

[4] G. Balas, R. Chiang, A. Packard and M. Safonov, Robust Control Toolbox 3: User's guide. (Natick, MA: The Mathworks, 2006).

[5] D. W. Gu, P. H. Petkov and M. M. Konstantinov *Robust Control Design With Matlab*, (Springer-Verlag, 2005).

[6] A. Heniche & I. Kamawa, "Assessment of two methods to select wide-area signals for power system damping control," *IEEE Trans. Power Syst.*, 23, 2008, 572—581.

[7] M. Zima, M. Larsson, P. Korba, C. Rehtanz & G. Anderson, "Design aspect for wide-area monitoring & control systems," *Proceedings of IEEE*, 93, 2005, 980-996.

[8] K. Seethalakshmi, S.N. Singh & S.C. Srivasatva, "Wide-area protection and control: present status and key challenges," *Proc, 15th National Power System Conference*, Bombay, India, 2008.

[8] M. Glavic & T.V. Cutsem, "Wide-area detection of voltage instability from synchronised phasor measurements," Part I: Principle, *IEEE Trans. Power Syst.*, 24 (3), 2009, 1408-1416.

[9] V. Terzija, G. Valverde, D. Cai, P. Reguluski, V. Madani, J. Fitch, S. Skok, M.M. Begovic & A. Phadke, Wide-area monitoring, protection and control of future electric power networks, *Proceeding of IEEE*, 99 (1), 2011, 80-93.

[10] M. Klein, G.J. Rogers & P. Kundur, A fundamental study of inter-area oscillations in power systems, *IEEE Trans. Power Syst*., 6(3), 1991, 914-921.

[11] M. Aboul-Ela, A. Sallam, J. McCalley & A. Fouad, Damping controller design for power system oscillations using global signals, *IEEE Trans. Power Syst.*, 11(2), 1996, 767-773.

[12] A. Snyder, M. Alali, N. Hadjsaid, D. Georges, T. Margotin & L. Mili, A robust damping controller for power systems using linear matrix inequalities, *Proc. Winter Meeting IEEE Power Eng. Soc.*, 1999, 519-524.

[13] I. Kamawa, R. Grondin & Y. Hebert, Wide-area measurement based stabilizing control of large power systems- a decentralised/hierarchical approach, *IEEE Trans. Power Syst.*, 16(1) 2001, 136-153.

[14] A.C. Zolotas, B. Chuadhari, I.M. Jaimoukha & P. Korba, A study on LQG/LTR control for damping inter-area oscillations in power systems, *IEEE Trans. Contr. Systems Tech.,* 15(1), 2007, 151-160.

[15] N.R. Chaudhari, A. Domahidi, R. Majumdar, B. Chaudhary, P. Korba, S. Ray & K. Uhlen, Wide-area power oscillations damping control in Nordic equivalent system, *IET Gener. Transm. Distrib.* 4, 2010, 1139-1150.

[16] D. Dotta, A.S. e Silva & I.C. Decker, Wide-area measurement based two-level control design considering signal transmission delay, *IEEE Trans Power Syst.*, 24, 2009, 208-216.

[17] Graham Rogers, *Power System Oscillations,* (Boston: Kluwer Academic Publishers, 1999).

[18] J. H. Chow and K.W. Chenug, A toolbox for power system dynamics and control engineering education and research, *IEEE Trans. on Power Syst.,* 7, 1992, 1559-1564.

[19] B.P. Padhy, S. C. Srivastava, and Nishchal k. Verma, “Robust Wide-Area TS Fuzzy Output Feedback Controller for Enhancement of Stability in Multimachine Power System,” *IEEE Systems Journal*, vol.6, no. 3, september 2012.

[20] W. Yao, L. Jiang, Q. H. Wu, J. Y. Wen and S. J. Cheng. “Delay-Dependent Stability Analysis of the Power System with a Wide-Area Damping Controller Embedded,” *IEEE Transactions on Power Systems*, vol. 26, no. 1, february 2011.