Chapter One

Introduction

1.1 Background

The power system is a dynamic system and it is constantly being subjected to disturbances, which cause the generator voltage angle to change. When these disturbances die out, a new acceptable steady state operating condition is reached. It is important that these disturbances do not drive the system to unstable condition. The disturbances may be of local mode having frequency range of 0.7 to 2 Hz or of inter area modes having frequency range in 0.1 to 0.8 Hz, these swings are due to the poor damping characteristics caused by modern voltage regulators with high gain. A high gain regulator through excitation control has an important effect of eliminating synchronizing torque but it affects the damping torque negatively. In order to compensate the unwanted effect of these voltage regulators, additional signal is introduced in feedback loop of voltage regulators. The additional signals are mostly derived from speed deviation, excitation deviation or accelerating power. This is achieved by injecting a stabilizing signal into the excitation system voltage reference summing point junction. The device is providing this signal is called “power system stabilizer”. Excitation control is well known as one of the effective means to enhance the overall stability of electrical power systems. Present day excitation systems predominantly constitute the fast acting AVRs. A high response exciter is beneficial in increasing the synchronizing torque, thus enhancing the transient stability that is to hold the generator in synchronism with power system during large transient fault condition. However, it produces a negative damping especially at high values of external system reactance and high generator outputs.

Stability of synchronous generators depends upon number of factors such as setting of automatic voltage regulators (AVR).The AVR and generator field dynamics introduces a phase lag so that resulting torque is out of phase with both rotor angle and speed deviation. Positive synchronizing torque and negative damping torque often result, which can cancel the small inherent positive damping torque available, leading to instability. Generator excitation controls have been installed and made faster to improve stability. The Power System Stabilizer has been added to the excitation systems to improve the oscillatory instability and it used to provide a supplementary signal to excitation system. The basic function of the PSS is to extend the stability limit by modulating generator excitation to provide the positive damping torque to power swing modes. The application of power system stabilizer (PSS) is to generate a supplementary signal, which is applied to control loop of the generating unit to produce a positive damping. The most widely used conventional PSS is lead-lag PSS where the gain settings are fixed under certain value which are determined under particular operating conditions to result in optimal performance for a specific condition. However, they give poor performance under different synchronous generator loading conditions. The PSS, while damping the rotor oscillations can cause instability of turbine generator shaft torsional modes. Selection of shaft speed pick-up location and torsional notch filters are used to attenuate the torsional mode frequency signals. The PSS gain and torsional filter however, adversely affect the exciter mode damping ratio. The use of accelerating power as input signal for the PSS attenuates the shaft torsional modes inherently and mitigates the requirements of the filtering in main stabilizing path [1].

1.2 Power System Stability

Power system stability is the tendency of a power system to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium. Since power systems rely on synchronous machines for generation of electrical power, a necessary condition for satisfactory system operation is that all synchronous machines remain in synchronism [1].

1.2.1 Steady-state stability

Steady-state stability analysis is the study of power system and its generators in strictly steady state conditions and trying to answer the question of what is the maximum possible generator load that can be transmitted without loss of synchronism of any generator. The maximum power is called the steady-state stability limit [2].

1.2.2 Transient stability

Transient stability is the ability of the power system to maintain synchronism when subjected to a sudden and large disturbance within a small time such as a fault on transmission facilities, loss of generation or loss of a large load. The system response to such disturbances involves large excursions of generator rotor angles, power flows, bus voltages [3].

1.2.3 Dynamic Stability

A system is said to be dynamically stable if the oscillations do not acquire more than certain amplitude and die out quickly. Dynamic stability is a concept used in the study of transient conditions in power systems. Any electrical disturbances in a power system will cause electromechanical transient processes. Besides the electrical transient phenomena produced, the power balance of the generating units is always disturbed, and thereby mechanical oscillations of machine rotors follow the disturbance [3].

1.3 Power System Stabilizers

Power system stabilizer is control device that used to enhance damping of power system oscillations in order to extend power transfer limits of the system and maintain reliable operation of the grid. It can be proved that a voltage regulator in the forward path of the exciter generator systems will introduce a damping torque and under heavy loading conditions this damping torque becomes negative. This is a situation where dynamic instability may cause concern. Further, it has been also pointed out that in the forward path of excitation control loop, the three time constants introduce a large phase at low frequencies just above the natural frequency of the excitation systems. To overcome this effect and improve damping compensating network called “power system stabilizer (PSS)” can be introduced [4].

1.4 Problem Statement

Some of the earliest power system stability problems included spontaneous power system oscillations at low frequencies. These low frequency oscillations (LFOs) are related to the small signal stability of a power system and are detrimental to the goals of maximum power transfer and power system security. Once the solution of using damper windings on the generator rotors and turbines to control these oscillations is found to be satisfactory, the stability problem is thereby disregarded for some time. However, as power systems began to be operated closer to their stability limits, the weakness of a synchronizing torque among the generators is recognized as a major cause of system instability. Automatic voltage regulators (AVRs) helped to improve the steady-state stability of the power systems. But with the creation of large, interconnected power systems, another concern is the transfer of large amounts of power across extremely long transmission lines. The addition of a supplementary controller into the control loop, such as the introduction of conventional power system stabilizers (CPSSs) to the AVRs on the generators, provides the means to reduce the inhibiting effects of low frequency oscillations.

1.5 Solution Methodology

To overcome the drawbacks of conventional power system stabilizer (CPSS), numerous techniques have been proposed in the literature. In this Dissertation work, the conventional PSS's effect on the system damping is compared with a fuzzy logic based PSS while applied to a single machine infinite bus (SMIB) power system. For the conventional design state space representation is used here.

1.6 Objectives of the Dissertation

The objectives of the dissertation are:

- To study the nature of power system stability, excitation system, automatic voltage regulator for synchronous generator and power system stabilizer.
- To develop a fuzzy logic based power system stabilizer which will make the system quickly stable when fault occurred in the system.
- Simulation is used to validate fuzzy logic based power system stabilizer and its performance is compared with conventional power system stabilizer and without power system stabilizer.

1.7 Dissertation layouts

In addition to chapter one this dissertation consists of five chapters. Chapter two gives the mathematical model of single machine infinite bus and Excitation system (AVR & Exciter) and type of oscillations in power system. Chapter three presents the structure and analyzes the power system stabilizers (PSSs) and Fuzzy logic controller (FLC).Chapter four discuses the simulation and results. Finally chapter five gives conclusions and recommendations of the work.

Chapter Two

Mathematical Model of Single Machine Infinite Bus

2.1 Introduction

Small-signal oscillations in a synchronous generator, particularly when it is connected to the power system through a long transmission line, are a matter of concern since before. As long transmission lines interconnect geographically vast areas, it is becoming difficult to maintain synchronism between different parts of the power system. Moreover, long lines reduce load ability of the power system and make the system weak, which is associated with Interarea oscillations during heavy loading. The phenomenon of small signal or small disturbance stability of a synchronous machine connected to an infinite bus through external reactance has been studied in by means of block diagrams and frequency response analysis. The objective of this analysis is to develop insights into the effects of excitation systems, voltage regulator gain, and stabilizing functions derived from generator speed and working through the voltage reference of the voltage regulator. The analysis based on linearization technique is ideally suitable for investigating problems associated with the small-signal oscillations. In this technique, the characteristics of a power system can be determined through a specific operating point and the stability of the system is clearly examined by the system eigenvalues. This chapter describes the linearized model of a single-machine infinite bus (SMIB) system given by Heffron and Philips that investigates the local mode of oscillations in the range of frequency 1-3 Hz. Voltage stability or dynamic voltage stability can be analyzed by monitoring the eigenvalues of the linearized power system with progressive loading. Instability occurs when a pair of complex conjugate eigenvalues crosses the right half of s-plane. This is referred to as dynamic voltage instability, and mathematically, this phenomenon is called Hopf bifurcation. The following steps have been adopted sequentially to analyze the small-signal stability performance of an SMIB system [5].

1. The differential equations of the flux-decay model of the synchronous machine are linearized and a state-space model is constructed considering exciter output Efd as input.

2. From the resulting linearized model, certain constants known as the K constants

(K_1–K_6) are derived. They are evaluated by small-perturbation analysis on the fundamental synchronous machine equations and hence are functions of machine and system impedances and operating point.

3. The model obtained is put in a block diagram form and a fast-acting exciter between terminal voltage ΔV_t and exciter output ΔEfd is introduced in the block diagram.

4. The real parts of the electromechanical modes are associated with the damping torque and the imaginary parts contribute to the synchronizing torque.

The following assumptions are generally made to analyze the small-signal stability problem in SMIB power system:

1- The mechanical power input remains constant during the period of transient.
2- Damping or asynchronous power is negligible.
3- Stator resistance is equal to zero.
4- The synchronous machine can be represented by a constant voltage source (electrically) behind the transient reactance.
5- The mechanical angle of the synchronous machine rotor coincides with the electric phase angle of the voltage behind transient reactance.
6- No local load is assumed at the generator bus; if a local load is fed at the terminal of the machine, it is to be represented by constant impedance (or admittance)

2.2 Fundamental Equations

The differential algebraic equations of the synchronous machine of the flux-decay model with fast exciter as show in Figure 2.1 can be represented as follows [5].

$$\frac{dE'_q}{dt} = -\frac{1}{T'_{do}}\left(E'_q + (X_d - X'_d)I_d - E_{fd}\right) \quad (2.1)$$

$$\frac{d\delta}{dt} = \omega - \omega_o \quad (2.2)$$

$$\frac{d\delta}{dt} = \frac{\omega_s}{2H}[T_M - \left(E'_q I_q + \left((X_q - X'_d\right)I_d I_q + D(\omega - \omega_o)\right)] \quad (2.3)$$

$$\frac{dE_{fd}}{dt} = -\frac{E_{fd}}{T_A} + \frac{K_A}{T_A}\left(V_{ref} - V_t\right) \quad (2.4)$$

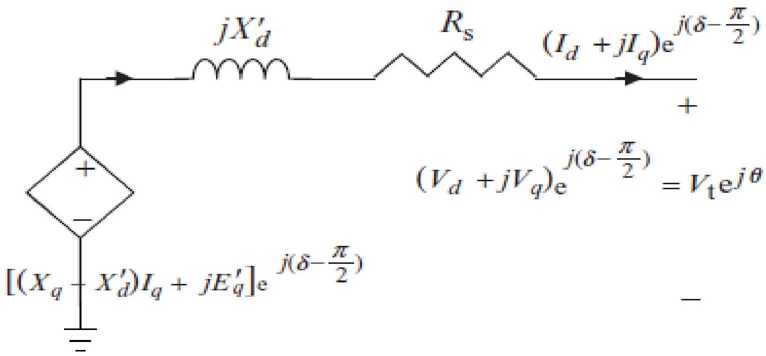

Figure 2.1 Dynamic circuits for the flux decay model of the machine.

2.3 Stator Equation

The synchronous stator equation is written as below [5]

$$V_t \sin(\delta - \theta) + R_s I_s - X_q I_q = 0 \quad (2.5)$$

$$E'_q - V_t \cos(\delta - \theta) - R_s I_s - X'_q I_q = 0 \quad (2.6)$$

As it is assumed stator resistance Rs=0 and V_t denote the magnitude of the generator terminal voltage, the earlier-mentioned equations are reduced to

$$X_q I_q - V_t \sin(\delta - \theta) = 0 \quad (2.7)$$

$$E'_q - V_t \cos(\delta - \theta) - X'_q I_q = 0 \quad (2.8)$$

Now

$$\left(V_d + jV_q\right)e^{j\left(\delta - \frac{\pi}{2}\right)} = V_t e^{j\theta}$$

Hence

$$V_d + jV_q = V_t e^{j\theta} . e^{-j\left(\delta - \frac{\pi}{2}\right)} \quad (2.9)$$

Expansion of the right-hand side results in

$$V_d + jV_q = V_t \sin(\delta - \theta) + jV_t \cos(\delta - \theta)$$

Therefore

$$V_d = V_t \sin(\delta - \theta) \ \ \& \ \ V_q = V_t \cos(\delta - \theta)$$

Substitution of V_d and V_q in (2.7) and (2.8) gives

$$X_q I_q + V_d = 0 \quad (2.10)$$

$$E'_q - V_q - X'_d I_d = 0 \quad (2.11)$$

2.4 Network Equation

The equation of the power system network is given as below [5]

$$\left(I_d + I_q\right)e^{j\left(\delta - \frac{\pi}{2}\right)} = \frac{V_t \angle \theta^{\circ} - V_{\infty} \angle \theta^{\circ}}{R_e + jX_e} \quad (2.12)$$

$$\left(I_d + I_q\right)e^{j\left(\delta - \frac{\pi}{2}\right)} = \frac{\left(V_d + V_q\right)e^{j\left(\delta - \frac{\pi}{2}\right)} - V_{\infty} \angle \theta^{\circ}}{R_e + jX_e} \quad (2.13)$$

$$I_d R_e + jI_q R_e + jI_d X_e - I_q X_e = \left(V_d + jV_q\right) - V_{\infty} e^{-j\left(\delta - \frac{\pi}{2}\right)} \quad (2.14)$$

$$\left(I_d R_e - I_q X_e\right) + j\left(I_q R_e + I_d X_e\right) = (V_d - V_{\infty} \sin \delta) + j(V_q - V_{\infty} \cos \delta) \quad (2.15)$$

$$\left(I_d R_e - I_q X_e\right) = V_d - V_{\infty} \sin \delta \quad (2.16)$$

$$\left(I_q R_e + I_d X_e\right) = V_q - V_{\infty} \cos \delta \quad (2.17)$$

2.5 Linearization Process and State-space Model

The linearization model of SMIB is obtained using the following steps:

Step I: The linearization of the stator algebraic (2.10) and (2.11) given

$$X_q\Delta I_q + \Delta V_d = 0 \tag{2.18}$$

$$\Delta E'_q - \Delta V_q - X'_d\Delta I_d = 0 \tag{2.19}$$

Rearranging (2.18) and (2.19) gives

$$\Delta V_d = X_q\Delta I_q \tag{2.20}$$

$$\Delta V_q = -X'_d\Delta I_d + \Delta E'_q \tag{2.21}$$

Writing (2.20) and (2.21) in matrix form gives

$$\begin{bmatrix}\Delta V_d\\ \Delta V_q\end{bmatrix} = \begin{bmatrix}0 & X_q\\ -X'_d & 0\end{bmatrix}\begin{bmatrix}\Delta I_d\\ \Delta I_q\end{bmatrix} + \begin{bmatrix}0\\ \Delta E'_q\end{bmatrix} \tag{2.22}$$

Step II: The linearization of the load-flow (2.16) and (2.17) results in

$$\left(\Delta I_d R_e - \Delta I_q X_e\right) = \Delta V_d - V_\infty \cos\delta\Delta\delta \tag{2.23}$$

$$\left(\Delta I_q R_e + \Delta I_d X_e\right) = \Delta V_q - V_\infty sin\delta\Delta\delta \tag{2.24}$$

Rearranging (2.23) and (2.24) given

$$\Delta V_d = \Delta I_d R_e - \Delta I_q X_e + V_\infty \cos\delta\Delta\delta \tag{2.25}$$

$$\Delta V_q = \Delta I_d R_e + \Delta I_q R_e - V_\infty sin\delta\Delta\delta \tag{2.26}$$

Writing (2.25) and (2.26) in matrix form given

$$\begin{bmatrix}\Delta V_d\\ \Delta V_q\end{bmatrix} = \begin{bmatrix}R_e & -X_e\\ X_e & R_e\end{bmatrix}\begin{bmatrix}\Delta I_d\\ \Delta I_q\end{bmatrix} + \begin{bmatrix}V_\infty\cos\delta\\ -V_\infty sin\delta\end{bmatrix}\Delta\delta \tag{2.27}$$

Step III: Equating the right-hand side of (2.22) and (2.27) given

$$\begin{bmatrix}R_e & -X_e\\ X_e & R_e\end{bmatrix}\begin{bmatrix}\Delta I_d\\ \Delta I_q\end{bmatrix} + \begin{bmatrix}V_\infty\cos\delta\\ -V_\infty sin\delta\end{bmatrix}\Delta\delta = \begin{bmatrix}0 & X_q\\ -X'_d & 0\end{bmatrix}\begin{bmatrix}\Delta I_d\\ \Delta I_q\end{bmatrix} + \begin{bmatrix}0\\ \Delta E'_q\end{bmatrix} \tag{2.28}$$

$$\left(\begin{bmatrix}R_e & -X_e\\ X_e & R_e\end{bmatrix} + \begin{bmatrix}0 & X_q\\ -X'_d & 0\end{bmatrix}\right)\begin{bmatrix}\Delta I_d\\ \Delta I_q\end{bmatrix} = \begin{bmatrix}0\\ \Delta E'_q\end{bmatrix}\begin{bmatrix}V_\infty\cos\delta\\ -V_\infty sin\delta\end{bmatrix}\Delta\delta \tag{2.29}$$

$$\begin{bmatrix}R_e & -(X_e + X_q)\\ (X_e + X'_d) & R_e\end{bmatrix}\begin{bmatrix}\Delta I_d\\ \Delta I_q\end{bmatrix} = \begin{bmatrix}0\\ \Delta E'_q\end{bmatrix} + \begin{bmatrix}V_\infty\cos\delta\\ -V_\infty sin\delta\end{bmatrix}\Delta\delta \tag{2.30}$$

$$\begin{bmatrix} R_e & -(X_e+X_q) \\ (X_e+X'_d) & R_e \end{bmatrix}^{-1} = \frac{1}{\Delta_e}\begin{bmatrix} R_e & (X_e+X_q) \\ -(X_e+X'_d) & R_e \end{bmatrix} \tag{2.31}$$

Where

$\Delta_e = R_e{}^2 + \left(X_e + X_q\right)(X_e + X'_d)$

Solving for ΔI_d andΔI_q from (2.30) results in

$$\begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} = \begin{bmatrix} 0 \\ \Delta E'_q \end{bmatrix}\begin{bmatrix} R_e & -(X_e+X_q) \\ (X_e+X'_d) & R_e \end{bmatrix}^{-1} + \begin{bmatrix} -V_\infty \cos\delta \\ V_\infty sin\delta \end{bmatrix}\Delta\delta.\begin{bmatrix} R_e & -(X_e+X_q) \\ (X_e+X'_d) & R_e \end{bmatrix}^{-1} \tag{2.32}$$

$$\begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} = \frac{1}{\Delta_e}\begin{bmatrix} 0 \\ \Delta E'_q \end{bmatrix}\begin{bmatrix} R_e & (X_e+X_q) \\ -(X_e+X'_d) & R_e \end{bmatrix} + \frac{1}{\Delta_e}\begin{bmatrix} -V_\infty \cos\delta \\ V_\infty sin\delta \end{bmatrix}\Delta\delta.\begin{bmatrix} R_e & (X_e+X_q) \\ -(X_e+X'_d) & R_e \end{bmatrix} \tag{2.33}$$

That is

$$\begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} = \frac{1}{\Delta_e}\begin{bmatrix} (X_e+X_q)\Delta E'_q \\ R_e \Delta E'_q \end{bmatrix} + \frac{1}{\Delta_e}\begin{bmatrix} -R_e V_\infty cos\delta + V_\infty sin\delta(X_e+X_q) \\ R_e V_\infty sin\delta + V_\infty cos\delta(X_e+X'_d) \end{bmatrix}\Delta\delta \tag{2.34}$$

Therefore:

$$\begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} = \frac{1}{\Delta_e}\begin{bmatrix} (X_e+X_q) & -R_e V_\infty cos\delta + V_\infty sin\delta(X_e+X_q) \\ R_e & R_e V_\infty sin\delta + V_\infty cos\delta(X_e+X'_d) \end{bmatrix}\begin{bmatrix} \Delta E'_q \\ \Delta\delta \end{bmatrix} \tag{2.35}$$

Step IV: The linearizations of (2.1)–(2.4) are as follows. Here, the frequency is normalized as $v = \frac{\omega}{\omega_s}$throughout our study:

$$\Delta \dot{E}'_q = -\frac{1}{T`_{do}}\Delta E'_q - \frac{1}{T`_{do}}(X_d + X'_d)\Delta I_d + \frac{1}{T`_{do}}\Delta E'_{fd} \tag{2.36}$$

$$\Delta\dot{\delta} = \omega_s \Delta V \tag{2.37}$$

$$\Delta\dot{V} = \frac{2}{H}\Delta T_M - \frac{2}{H}\Delta E'_q.I_q - \frac{2}{H}E'_q.I_q - \frac{\left(X_q - X'_d\right)}{2H}\Delta I_d I_q - \frac{\left(X_q - X'_d\right)}{2H}I_d\Delta I_q - \frac{D\omega_s}{2H} \quad (2.38)$$

$$T_A\,\Delta\dot{E}'_q = -\Delta E'_{fd} + K_A\left(\Delta V_{ref} - \Delta V_t\right) \quad (2.39)$$

$$\begin{bmatrix} \Delta\dot{E}'_q \\ \Delta\dot{\delta} \\ \Delta\dot{V} \end{bmatrix} = \begin{bmatrix} \frac{1}{T`_{do}} & 0 & 0 \\ 0 & 0 & \omega_s \\ \frac{I_q}{2H} & 0 & \frac{D\omega_s}{2H} \end{bmatrix}\begin{bmatrix} \Delta E'_q \\ \Delta\delta \\ \Delta V \end{bmatrix} + \begin{bmatrix} -\frac{(X_d - X'_d)}{T`_{do}} & 0 \\ 0 & 0 \\ \frac{I_q(X`_d - X_q)}{2H} & \frac{(X`_d - X_q)}{2H} - \frac{E`_q}{2H} \end{bmatrix}\begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} + \begin{bmatrix} \frac{1}{T`_{do}} & 0 \\ 0 & 0 \\ 0 & \frac{1}{2H} \end{bmatrix}\begin{bmatrix} \Delta E_{fd} \\ \Delta T_M \end{bmatrix} \quad (2.40)$$

Step V: Obtain the linearized equations in terms of the K constants. The expressions for ΔI_d and ΔI_q obtained from Equation (2.35) are

$$\Delta I_d = \frac{\mathbf{1}}{\boldsymbol{\Delta_e}}\left[(X_e - X_q)\Delta E`_q + \{-R_e V_\infty cos\delta + (X_e - X`_d)V_\infty sin\delta\}\Delta\delta\right] \quad (2.41)$$

$$\Delta I_q = \frac{1}{\boldsymbol{\Delta_e}}\left[R_e\Delta E`_q + \{R_e V_\infty sin\delta + (X_e - X`_d)V_\infty cos\delta\}\Delta\delta\right] \quad (2.42)$$

On substitution of I_d and I_q in (2.40), the resultant equations relating the constants K1, K2, K3, and K4 can be expressed as

$$\Delta E'_q = -\frac{1}{K_3 T`_{do}}\,\Delta E'_q - \frac{K_4}{T`_{do}}\Delta\delta + \frac{1}{T`_{do}}\Delta E_{fd} \quad (2.43)$$

$$\Delta\dot{\delta} = \omega_s\Delta V \quad (2.44)$$

$$\Delta\dot{V} = -\frac{K_2}{2H}\,\Delta E'_q - \frac{D\omega_s}{2H}\Delta V + \frac{1}{2H}\Delta T_M \quad (2.45)$$

Step VI: The linearization of generator terminal voltage is as follows: The magnitude of the generator terminal voltage is

$$V_t = \sqrt{{V_d}^2 + {V_q}^2}$$

$$V_t{}^2 = V_d{}^2 + V_q{}^2 \quad (2.46)$$

The linearization of (2.46) gives

$$2V_t\Delta V_t = 2V_d\Delta V_d + 2V_q\Delta V_q \quad (2.47)$$

Therefore

$$\Delta V_t = \frac{V_d}{V_t}\Delta V_d + \frac{V_q}{V_t}\Delta V_q \quad (2.48)$$

Now, substituting (2.35) into (2.22),

$$\begin{bmatrix}\Delta V_d\\ \Delta V_q\end{bmatrix} = \frac{1}{\Delta_e}\begin{bmatrix}0 & X_q\\ X`_d & 0\end{bmatrix}\begin{bmatrix}(X_e + X_q) & -R_eV_\infty cos\delta + V_\infty sin\delta(X_e + X_q)\\ R_e & R_eV_\infty sin\delta + V_\infty cos\delta(X_e + X'_d)\end{bmatrix}\begin{bmatrix}\Delta E'_q\\ \Delta\delta\end{bmatrix} + \begin{bmatrix}0\\ \Delta E'_q\end{bmatrix} \quad (2.49)$$

Or

$$\begin{bmatrix}\Delta V_d\\ \Delta V_q\end{bmatrix} = \frac{1}{\Delta_e}\begin{bmatrix}R_eX_q & X_q(R_eV_\infty sin\delta + V_\infty(X_e + X'_d)cos\delta)\\ -(X_e + X_q) & -X`_d(-R_eV_\infty cos\delta + V_\infty(X_e + X_q)sin\delta)\end{bmatrix}\begin{bmatrix}\Delta E'_q\\ \Delta\delta\end{bmatrix} + \begin{bmatrix}0\\ \Delta E'_q\end{bmatrix}$$

Therefore

$$\Delta V_d = \frac{1}{\Delta_e}[R_eX_q\Delta E'_q + X_qR_eV_\infty sin\delta + X_qV_\infty(X_e + X'_d)cos\delta\Delta\delta] \quad (2.50)$$

$$\Delta V_q = [-X`_d(X_e + X_q)\Delta E'_q + (X`_dR_eV_\infty cos\delta + X`_dV_\infty(X_e + X_q)sin\delta\Delta\delta] + \Delta E'_q \quad (2.51)$$

Replacing and ΔVq from (2.50) and (2.51) in (2.48) results in

$$\Delta V_t = K_5 \Delta\delta + K_6 \Delta E'_q \quad (2.52)$$

2.6 Derivation of K Constants

From (2.36), the expression of $\Delta E'_q$ on substitution of ΔI_d is [5].

$$\Delta \dot{E}'_q = -\frac{1}{T`_{do}}\Delta E'_q - \frac{1}{T`_{do}}(X_d + X'_d)\left(\frac{\mathbf{1}}{\Delta_{\boldsymbol{e}}}[(X_e - X_q)\Delta E`_q + \{-R_e V_\infty cos\delta + (X_e - X`_d)V_\infty sin\delta\}\Delta\delta]\right) + \frac{1}{T`_{do}}\Delta E_{fd} \quad (2.53)$$

$$\Delta \dot{E}'_q = -\frac{1}{T`_{do}}\left[1 + \frac{(X_d - X`_d)(X_e + X_q)}{\Delta_{\boldsymbol{e}}}\right]\Delta E'_q - \frac{1}{T`_{do}}\frac{V_\infty(X_d + X'_d)}{\Delta_{\boldsymbol{e}}}\{(X_e - X_q)sin\delta - R_e cos\delta\}\Delta\delta + \frac{1}{T`_{do}}\Delta E_{fd} \quad (2.54)$$

$$\Delta \dot{E}'_q = -\frac{1}{K_3 T`_{do}}\Delta E'_q - \frac{K_4}{T`_{do}}\Delta\delta + \frac{1}{T`_{do}}\Delta E_{fd} \quad (2.55)$$

$$\frac{1}{K_4} = 1 + \frac{(X_d - X`_d)(X_e + X_q)}{\Delta_e} \quad (2.56)$$

$$K_4 = \frac{V_\infty(X_d - X`_d)}{\Delta_e}[(X_e + X_q)sin\delta - R_e cos\delta] \quad (2.57)$$

Again from (2.38), the expression of $\Delta\dot{V}$ on substitution of ΔI_d and ΔI_q is

$$\Delta\dot{V} = -\frac{1}{2H}\Delta E'_q . I_q - \frac{\left(X_q - X'_d\right)I_q}{2H}\frac{1}{\Delta_e}\left[(X_e + X_q)\Delta E'_q + \{-R_e V_\infty cos\delta + \left[(X_e + X_q\right)V_\infty sin\delta\}\Delta\delta\right] + \left(\frac{\left(X`_d - X_q\right)}{2H} I_d - \frac{1}{2H}E'_q\right)\frac{1}{\Delta_e}[R_e\Delta E'_q + \{R_e V_\infty sin\delta + (X_e + X_q)V_\infty cos\delta\}\Delta\delta - \frac{D\omega_s}{2H}\Delta V + \frac{1}{2H}\Delta T_M \qquad (2.58)$$

$$\Delta\dot{V} = -\frac{1}{2H}\frac{1}{\Delta_e}\left[I_q\Delta_e - I_q\left(X`_d - X_q\right)\left(X_e - X_q\right) - R_e I_d\left(X`_d - X_q\right) + R_e E'_q\right]\Delta E'_q + \frac{V_\infty I_q}{2H\Delta_e}\left(X`_d - X_q\right)\left[(X_e + X_q)sin\delta - R_e cos\delta\right]\Delta\delta + \frac{V_\infty}{\Delta_e}\left[\left\{I_d\left(X`_d - X_q\right) - E'_q\right\}\{(X_e + X`_d)cos\delta + R_e sin\delta\}\right] - \frac{D\omega_s}{2H}\Delta V + \frac{1}{2H}\Delta T_M \qquad (2.59)$$

This can be written in terms of K constants as

$$\Delta\dot{V} = \frac{K_2}{2H}\Delta E'_q - \frac{K_1}{2H}\Delta\delta - \frac{D\omega_s}{2H}\Delta V + \frac{1}{2H}\Delta T_M \qquad (2.60)$$

$$K_2 = \frac{1}{\Delta_e}\left[I_q\Delta_e - I_q\left(X`_d - X_q\right)\left(X_e - X_q\right) - R_e I_d\left(X`_d - X_q\right) + R_e E'_q\right] \qquad (2.61)$$

$$K_1 = \frac{1}{\Delta_e}\left[V_\infty I_q\left(X`_d - X_q\right)\left[(X_e + X_q)sin\delta - R_e cos\delta\right] + V_\infty\left[\left(X`_d - X_q\right)I_d - E'_q\right]\left[(X_e + X`_d)cos\delta + R_e sin\delta\right]\right] \quad (2.62)$$

On substitution of ΔV_d and ΔV_q in (2.46), it reduces to

$$\Delta V_t = \frac{V_d}{V_q}\left[\frac{1}{\Delta_e}\left\{R_e X_q E`_q + R_e X_q V_\infty sin\delta + X_q V_\infty\left(X`_d + X_q\right)cos\delta\Delta\delta\right\}\right] + \frac{V_q}{V_t}\left[\frac{1}{\Delta_e}\left\{-X`_d\left(X_e + X_q\right)\Delta E'_q + R_e X`_d V_\infty cos\delta + X`_d V_\infty\left(X_e + X_q\right)sin\delta\Delta\delta\right\} + \Delta E'_q\right]$$

Or

$$\Delta V_t = \left[\frac{1}{\Delta_e}\left\{\frac{V_d}{V_t}R_e X_q - \frac{V_d}{V_t}X`_d\left(X_e + X_q\right)\right\} + \frac{V_d}{V_t}\right]\Delta E'_q + \left[\frac{1}{\Delta_e}\left\{\frac{V_d}{V_t}X_q\left(R_e V_\infty sin\delta + V_\infty cos\delta\left(X`_d + X_q\right)\right) + \frac{V_q}{V_t}X`_d\left(R_e V_\infty cos\delta - V_\infty\left(X`_d + X_q\right)sin\delta\right)\right\}\right]\Delta\delta \quad (2.63)$$

Therefore, (2.63) can be written in terms of K constants as

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E'_q \quad (2.64)$$

$$K_5 = \frac{1}{\Delta_e}\left\{\frac{V_d}{V_t}X_q\left(R_e V_\infty sin\delta + V_\infty cos\delta\left(X`_d + X_q\right)\right) + \frac{V_q}{V_t}X`_d\left(R_e V_\infty cos\delta - V_\infty\left(X`_d + X_q\right)sin\delta\right)\right\} \quad (2.65)$$

$$K_6 = \frac{1}{\Delta_e}\left\{\frac{V_d}{V_t}R_eX_q - \frac{V_d}{V_t}X`_d\left(X_e + X_q\right)\right\} + \frac{V_d}{V_t} \quad (2.66)$$

Now, the overall linearized machine differential equations (2.43)–(2.45) and the linearized exciter equation (2.39) together can be put in a block diagram shown in Figure 2.2 In this representation, the dynamic characteristics of the system can be expressed in terms of the K constants. These constants (K_1–K_6) and the block diagram representation were developed first by Heffron–Phillips and later by de Mello to study the synchronous machine stability as affected by local low-frequency oscillations and its control through excitation system [5].

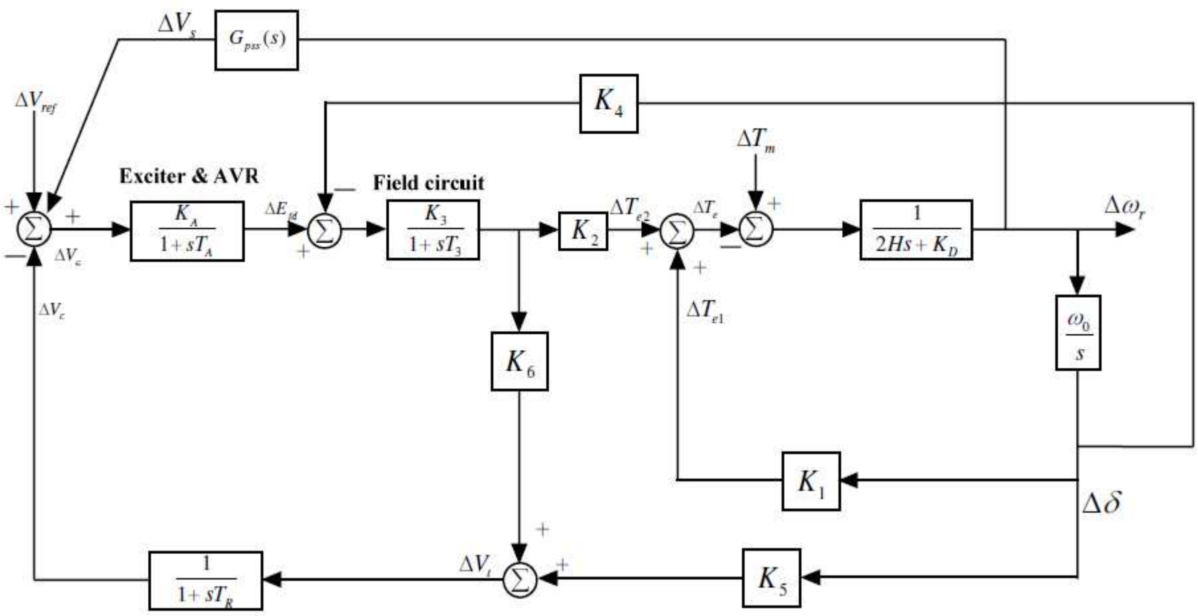

Figure 2.2 Block diagram of the synchronous Machine flux decay model

The K constants presented in the block diagram Figure 2.2 are defined as follows:

$K_1 = \frac{\Delta T_e}{\Delta \delta}\Big| E`_q$ Change in electric torque for a change in rotor angle with constant flux linkages in the d-axis.

$K_2 = \frac{\Delta T_e}{\Delta E`_q}\Big| \delta$ Change in electric torque for a change in d-axis flux linkages with constant rotor angle.

$K_3 = \frac{X`_d + X_e}{X_d + X_e}$ For the case where the external impedance is a pure reactanceX_e.

$K_4 = \frac{1}{K_3} \frac{\Delta E`_q}{\Delta \delta}$ Demagnetizing effect of a change in rotor angle.

$K_5 = \frac{\Delta V_t}{\Delta \delta}\Big| E`_q$ Change in terminal voltage with change in rotor angle for constant $E`_q$

$K_6 = \frac{\Delta V_t}{\Delta E`_q}\Big| \delta$ Change in terminal voltage with change in $E`_q$ for constant rotor angle.

It is evident that the K constants are dependent on various system parameters such as system loading and the external network resistance (Re) and reactance (Xe). Generally, the value of the K constants is greater than zero (>0), but under heavy loading condition (high generator output) and for high value of external system reactance, K5 might be negative, contributing to negative damping and causing system instability. This phenomenon has been discussed in the following sections based on state space model [5].

The state-space representation of the synchronous machine can be obtained when (2.43)–(2.45) and (2.52) are written together in matrix form. Assuming $\Delta T_M = 0$, the state-space model of the SMIB system without exciter is therefore:

$$\begin{bmatrix} \Delta E`_q \\ \Delta \dot{\delta} \\ \Delta \dot{V} \end{bmatrix} = \begin{bmatrix} -\frac{1}{K_3 T`_{do}} & -\frac{K_4}{T`_{do}} & 0 \\ 0 & 0 & \omega_s \\ -\frac{K_2}{2H} & -\frac{K_1}{2H} & \frac{D\omega S}{2H} \end{bmatrix} \begin{bmatrix} \Delta E`_q \\ \Delta \delta \\ \Delta V \end{bmatrix} + \begin{bmatrix} \frac{1}{T`_{do}} \\ 0 \\ 0 \end{bmatrix} \Delta E`_{fd} \tag{2.67}$$

$$\Delta V_t = \begin{bmatrix} K_6 & K_5 & 0 \end{bmatrix} \begin{bmatrix} \Delta E`_q \\ \Delta \delta \\ \Delta V \end{bmatrix} \tag{2.68}$$

$$T_A \Delta \dot{E}`_{fd} = -\Delta E_{fd} + K_A(\Delta V_{ref} + \Delta V_t) \quad (2.69)$$

$$\Delta \dot{E}`_{fd} = \frac{1}{T_A}\Delta E_{fd} - \frac{K_A K_5}{T_A}\Delta\delta - \frac{K_A K_6}{T_A}\Delta E`_q + \frac{K_A}{T_A}\Delta V_{ref} \quad (2.70)$$

$$\begin{bmatrix} \Delta \dot{E}`_q \\ \Delta\dot{\delta} \\ \Delta\dot{V} \\ \Delta\dot{E}_{fd} \end{bmatrix} = \begin{bmatrix} -\frac{1}{K_3 T`_{do}} & -\frac{K_4}{T`_{do}} & 0 & \frac{1}{T`_{do}} \\ 0 & 0 & \omega_s & 0 \\ -\frac{K_2}{2H} & -\frac{K_1}{2H} & \frac{D\omega S}{2H} & 0 \\ -\frac{K_A K_6}{T_A} & -\frac{K_A K_5}{T_A} & 0 & -\frac{1}{T_A} \end{bmatrix} \begin{bmatrix} \Delta E`_q \\ \Delta\delta \\ \Delta V \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{K_A}{T_A} \end{bmatrix} \Delta V_{ref} \quad (2.71)$$

2.7 The Power System Stabilizer in State Matrix

Assume that the damping D in the torque loop is zero. The input to the stabilizer is ΔV. An extra state equation will add. The washout filter stage is omitted since its objective is to offset only the DC steady state error, hence is dose not play any role in the design. The added stage equation due to PSS is

$$\Delta \dot{V_{PSS}} = -\frac{1}{T_2}\Delta V_{PSS} + \frac{K_{PSS}}{T_2}\Delta V + K_{PSS}\frac{T_1}{T_2}\Delta\dot{V} \quad (2.72)$$

$$\Delta\dot{V} = -\frac{K_2}{2H}\Delta E_{fd} - \frac{K_2}{2H}\Delta\delta \quad (2.73)$$

By substitute (2.73) in (2.72) is gives

$$\Delta \dot{V_{PSS}} = -\frac{1}{T_2}\Delta V_{PSS} + \frac{K_{PSS}}{T_2}\Delta V + K_{PSS}\frac{T_1}{T_2}\left(-\frac{K_2}{2H}\Delta E_{fd} - \frac{K_2}{2H}\Delta\delta\right) \quad (2.74)$$

Therefore

$$\Delta \dot{V_{PSS}} = -\frac{1}{T_2}\Delta V_{PSS} + \frac{K_{PSS}}{T_2}\Delta V - \frac{\boldsymbol{K_2 T_1}}{\boldsymbol{T_2}}\left(\frac{\boldsymbol{K_{PSS}}}{\boldsymbol{2H}}\right)\Delta E_{fd} - \frac{\boldsymbol{K_1 T_1}}{\boldsymbol{T_2}}\left(\frac{\boldsymbol{K_{PSS}}}{\boldsymbol{2H}}\right)\Delta\delta \quad (2.75)$$

The state matrix of the system model is

$$\begin{bmatrix} \Delta \dot{E}`_q \\ \Delta\dot{\delta} \\ \Delta\dot{V} \\ \Delta\dot{E}_{fd} \\ \Delta\dot{V}_{PSS} \end{bmatrix} = \begin{bmatrix} -\frac{1}{K_3 T`_{do}} & -\frac{K_4}{T`_{do}} & 0 & \frac{1}{T`_{do}} & 0 \\ 0 & 0 & \omega_s & 0 & 0 \\ -\frac{K_2}{2H} & -\frac{K_1}{2H} & \frac{D\omega S}{2H} & 0 & 0 \\ -\frac{K_A K_6}{T_A} & -\frac{K_A K_5}{T_A} & 0 & -\frac{1}{T_A} & \frac{K_A}{T_A} \\ -\frac{K_2 T_1}{T_2}\left(\frac{K_{PSS}}{2H}\right) & -\frac{K_1 T_1}{T_2}\left(\frac{K_{PSS}}{2H}\right) & \frac{K_{PSS}}{T_2} & 0 & -\frac{1}{T_2} \end{bmatrix} \begin{bmatrix} \Delta E`_q \\ \Delta\delta \\ \Delta V \\ \Delta E_{fd} \\ \Delta V_{PSS} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_A}{T_A} \\ \frac{K_{PSS}}{T_2} \end{bmatrix} \Delta V_{ref} \tag{76}$$

Chapter Three

Tuning Method of power System Stabilizer

3.1 Power System Stabilizer

The basic function of a power system stabilizer is damping the generator rotor oscillations by controlling its excitation using auxiliary stabilizing signal(s). To provide damping, the stabilizer must produce a component of electrical torque in phase with the rotor speed deviations. It is well established that fast acting exciters with high gain AVR can contribute to oscillatory instability in power systems. This type of instability is characterized by low frequency (0.2 to 2.0 Hz) oscillations which can persist (or even grow in magnitude) for no apparent reason. A cost efficient and satisfactory solution to the problem of oscillatory instability is to provide damping for generator rotor oscillations.

This is conveniently performed by providing Power System Stabilizers (PSS) which are supplementary controllers in the excitation systems. The objective of designing PSS is to provide additional damping torque without affecting the synchronizing torque at critical oscillation frequencies. It can be generally said that need for PSS will be felt in situations when power has to be transmitted over long distances with weak AC ties. Even when PSS may not be required under normal operating conditions, they allow satisfactory operation under unusual or abnormal conditions which may be encountered at times [6].

Thus, PSS has become a standard option with modern static exciters and it is essential for power engineers to use these effectively. Retrofitting of existing excitation systems with PSS may also be required to improve system stability. If the exciter transfer function and the generator transfer function between ΔE_{fd} and ΔT_e are pure gains, a direct feedback of Δw_r would result in a damping torque component. However, in practice both the generator and the exciter exhibit frequency dependent gain and phase characteristics.

Therefore, the PSS transfer function CPSS should have appropriate phase compensation circuits to compensate for the phase lag between the exciter input and the electrical torque. In the ideal case, with the phase characteristic of CPSS being an exact inverse of the exciter and generator phase characteristics to be compensated, the PSS would result in a pure damping torque at all oscillating frequencies. The phase compensation block provides the appropriate phase lead characteristic to compensate for the phase lag between the exciter input and the generator electrical (air-gap) torque [6].

The figure 3.1 shows a single first-order block. In practice, two or more first-order blocks may be used to achieve the desired phase compensation. In some cases, second-order blocks with complex roots have been used. Normally, the frequency range of interest is 0.1 to 2.0 Hz and the phase- lead network should provide compensation over this entire frequency range.

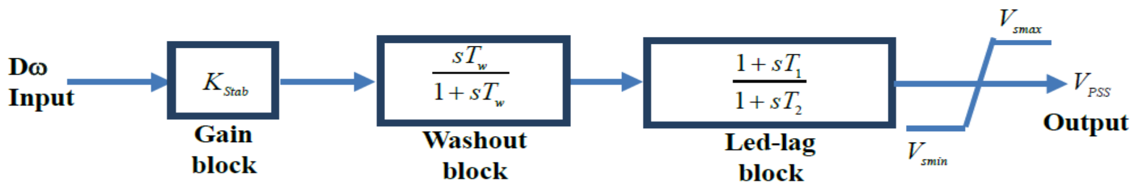

Figure 3.1 Block diagram of PSS

The phase characteristic to be compensated changes with system conditions; therefore a compromise is made and a characteristic is acceptable for different system conditions is selected. Generally some under compensation is desirable so that the PSS, in addition to significantly increase the damping torque, results in a slight increase of the synchronizing torque. The signal washout block serves as a high-pass filter, with the time constant T_w high enough to allow signals associated with oscillations in w_r to pass unchanged. Without it, steady changes in speed would modify the terminal voltage. It allows the PSS to respond only to changes in speed. From the view point of the washout function, the value of T_w is not critical and may be in the range of 1 to 20 seconds.

The main consideration is that it is long enough to pass stabilizing signals at the frequencies of interest unchanged, but not so long that it leads to undesirable generator voltage excursions during system-islanding conditions. The stabilizer gain determines the amount of damping introduced by the PSS.

The PSS parameters should be such that the control system results into the following. [6].

1- Maximize the damping of the local plant mode as well as inter-area mode oscillations without compromising stability of other modes.
2- Enhance system transient stability.
3- Not adversely affect system performance during major system upsets which cause large frequency excursions
4- Minimize the consequences of excitation system malfunction due to component failure.

3.2 Power System Stabilizer Design

The basic function of a PSS is to add damping to the generator rotor oscillations by controlling its excitation using auxiliary stabilizing signal. To provide damping, the stabilizer must produce a component of electrical torque in phase with the rotor speed deviation. For the simplicity a conventional PSS is modeled by two stage (identical), lead/lag network which is represented by a gain K_{STAB} and two time constants T_1 and T_2. This network is connected with a washout circuit of a time constant T_w.

In Figure 3.1 the phase compensation block provides the appropriate phase lead characteristics to compensate for the phase lag between exciter input and generator electrical torque. The phase compensation may be a single first order block as shown in Figure 3.1 or having two or more first order blocks or second order blocks with complex roots.

3.3 Power System Stabilizer Control Methods

The tuning of PSS differs based on the type of input. However, in general tuning of PSS consists of the following [4].

3.3.1 Power System Stabilizer Output Limiter

Set output limits so that PSS cannot move generator terminal voltage beyond a predetermined value. Typical range of settings is from ±5% to ±10% of rated generator terminal voltage. Asymmetrical limits may be employed.

3.3.2 Protection and Alarms

The PSS output protection should be coordinated with the output limiter. Since the output limiter provides a wider range of signals than can be tolerated in steady-state operation, several methods may be used to obtain security from driving the excitation system beyond the normal operating limits. These methods include voltage-sensitive switches, auxiliary timing circuits and limiter meters. The voltage sensitive switch usually measures generator terminal voltage and disconnects the PSS signal from the excitation system when the terminal voltage exceeds a preset limit. The auxiliary timer method uses a circuit to monitor the PSS output level, and if the level exceeds a preset limit for a given time, the PSS signal is removed from the excitation system. If protection removes the PSS from service an alarm should actuate.

3.3.3 Washout Filter

There is an interrelationship between the phase compensation and the washout time constant. Short washout time constants provide additional phase compensation in frequency-based PSS at the lower frequencies while dramatically reducing the gain. A washout time constant of 10 seconds or less is recommended to quickly remove low frequency components (below 0.1 Hz) from the PSS output.

3.3.4 Phase Compensation

Identify inter-area modes of oscillation. Measure generator and excitation system response without PSS. Tune PSS to provide as close to zero degrees of phase shift as possible at the inter-area frequency or frequencies. If local stability concerns require PSS settings resulting in an inter-area phase shift other than zero, the setting shall in no case result in a phase shift in excess of 30 degrees at inter-area modes. The PSS provides substantial phase shift so that the electrical torque provided by the generator is approximately in phase with speed. The goal is to eliminate phase lag as possible throughout a wide range of frequencies of interest, and then adjust gain as outlined below.

3.3.5 Gain Test

A gain as high as practicable is required for best contribution to system damping.Since the maximum gain that is safely usable depends upon many factors, it is best determined by test. The gain test shall be performed under operating conditions that result in maximum overall system gain so that the true gain margin is identified. Generally, this occurs with the unit loaded to at least 80% of full load. If shaft torsionals are of concern, the torsionals shall be monitored during the gain test.

3.3.6 Commissioning Tests

Perform an impulse response by injecting a large signal into the AVR (5-10%) and identify local mode damping. Verify local mode oscillation damping has improved, or, at a minimum, has not been degraded.

3.4 Power System Stabilizer Tuning Methods

The conflicting requirements of local and inter-area mode damping and stability under both small signal and transient conditions have led to many different approaches for the tuning of PSSs. Methods investigated for the tuning include

1- Fuzzy logic controller based PSS
2- State-space/frequency domain techniques ,

3- Residue compensation,
4- Phase compensation/root locus of a lead-lag PSS controller,
5- Desensitization of a robust controller,
6- Pole-placement for a PID-type controller,
7- Sparsity techniques for a lead-lag controller
8- Strict linearization technique for a linear quadratic controller.

The diversity of the approaches can be accounted for by the difficulty of satisfying the conflicting design goals, and each method having its own advantages and disadvantages. This is the crux of the problem of low frequency oscillation damping by the application of power system stabilizers. This Dissertation is not intended to provide a qualitative analysis of each of these techniques, using Fuzzy logic controller based power system stabilizer [6, 7].

3.5 Fuzzy Logic Controller

Fuzzy logic is a derivative from classical Boolean logic and implements soft linguistic variables on a continuous range of truth values to be defined between conventional binary that is [0, 1]. It can often be considered a subset of conventional set theory. The fuzzy logic is capable to handle approximate information in a systematic way and therefore it is suited for controlling non-linear systems and for modeling complex systems where an inexact model exists or systems where ambiguity or vagueness is common. It is advantageous to use fuzzy logic in controller design due to the following reasons:

1- A Simpler and faster Methodology.
2- It reduces the design development cycle.
3- It simplifies design complexity.
4- An alternative solution to non-linear control.
5- Improves the control performance.
6- Simple to implement.
7- Reduces hardware cost.

FLCs are very useful when an exact mathematical model of the plant is not available; however, experienced human operators are available for providing qualitative rules to control the system. Fuzzy logic, which is the logic on which fuzzy logic control is based, is much closer in spirit to human thinking and natural language than the traditional logic systems. Basically, it provides an effective mean of capturing the approximate, inexact nature of our knowledge about the real world. Viewed in this perspective, the essential part of the fuzzy logic controller (FLC) is a set of linguistic control rules related by dual concepts of fuzzy implication and the compositional rule of inference. In essence, the FLC provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. The methodology of the FLC appears very useful when the processes are too complex for analysis by conventional quantitative techniques. The importance of fuzzy logic derives from the fact that most modes of human reasoning and especially common sense reasoning are approximate in nature. In doing so, the fuzzy logic approach allows the designer to handle efficiently very complex closed-loop control problems. There are many artificial intelligence techniques that have been employed in modern power systems, but fuzzy logic has emerged as the powerful tool for solving challenging problems [8].

3.6 Fuzzy controller Sets

Fuzzy set, as the name implies, is a set without a crisp boundary. The transition from "belong to a set" to "not belong to a set" is gradual, and this smooth transition is characterized by membership functions. The fuzzy set theory is based on fuzzy logic, where a particular object has a degree of membership in a given set that may be anywhere in the range of 0 to 1. On the other hand, classical set theory is based on Boolean logic, where a particular object or variable is either a member of a given set (logic 1), or it is not (logic 0) [9].

3.7 Membership Functions

A membership function is a curve that defines how the values of a fuzzy variable in a certain region are mapped to a membership value [1] (or degree of membership) between 0 and 1. The MF maps each element of *X* to a membership degree between 0 and 1 (included). Obviously, the definition of a fuzzy set is a simple extension of the definition of a classical (crisp) set in which the characteristic function is permitted to have any value between 0 and 1.

If the value of the membership function is restricted to either 0 or 1, then *A* is reduced to a classical set. For clarity, we shall also refer to classical sets as ordinary sets, crisp sets, non-fuzzy sets, or just sets. Usually, *X* is referred to as the universe of discourse, or simply the universe, and it may consist of discrete (ordered or non-ordered) objects or it can be a continuous space. In practice, when the universe of discourse *X* is a continuous space, we usually partition it into several fuzzy sets whose MFs cover X in a more or less uniform manner.

These fuzzy sets, which usually carry names that conform to adjectives appearing in our daily linguistic usage, such as "large," "medium," or "small," are called linguistic values or linguistic labels. Thus, the universe of discourse X is often called the linguistic variable.

The fuzzy membership not only provides for a meaningful and powerful representation of measurement of uncertainties, but also provides the meaningful representation of vague concepts expressed in natural language [8].

3.8 Types of Membership Functions

The various types of membership functions are given below:

1- Triangular Membership Function.

2- Gaussian Membership Function.

3- Trapezoidal Membership Function.

4- Sigmoidal Membership Function.

5- Generalized bell Membership Function.

3.9 Fuzzy Inference Systems (FIS)

The fuzzy inference system or fuzzy system is a popular computing frame-work based on the concept of fuzzy set theory, fuzzy if-then rules, and fuzzy reasoning [6].

The fuzzy inference system basically consists of a formulation of the mapping from a given input set to an output set using FL as shown in Figure 3.2. The mapping process provides the basis from which the inference or conclusion can be made. The basic structure of fuzzy inference system consists of three conceptual components: a rule base, which contains a selection of fuzzy rules; a data base, which defines the membership functions used in the fuzzy rules; and a reasoning mechanism which performs the inference procedure upon the rules and given facts to derive a reasonable output or conclusion.

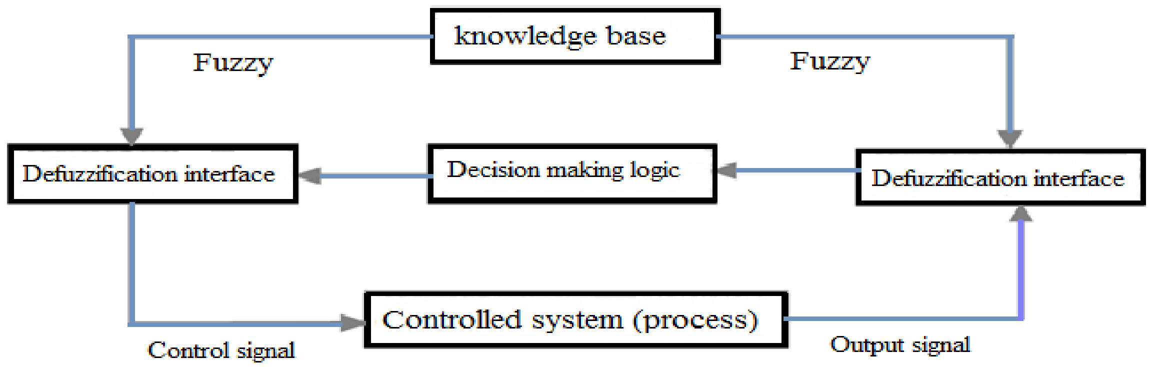

Figure 3.2 Block diagram of Fuzzy logic controller

The fuzzy logic controller comprises of four principle components: fuzzification interface, knowledge base, decision making logic, and defuzzification interface [9].

1- Fuzzification: In fuzzification, the values of input variables are measured that is converts the input data into suitable linguistic values.
2- Knowledge base: The knowledge base consists of a database and linguistic control rule base. The database provides the necessary

definitions, which are used to define the linguistic control rules and fuzzy data manipulation in an FLC. The rule base characterizes the control policy of domain experts by means of set of linguistic control rules.

3- Decision making logic: The decision making logic has the capability of stimulating human decision making based on fuzzy concepts.

4- Defuzzification: The defuzzification performs scale mapping, which converts the range of values of output variables into corresponding universe of discourse. If the output from the defuzzifier is a control action for a process, then the system is a non-fuzzy logic decision system. There are different techniques for defuzzification such as maximum method, height method, and centroid method.

3.10 Design of Fuzzy Logic Based Power System Stabilizer

The basic structure of the fuzzy logic controller is shown in Figure 3.3 Here the inputs to the fuzzy logic controller are the normalized values of error 'e' and change of error 'ce'. Normalization is done to limit the universe of discourse of the inputs between -1 to 1 such that the controller can be successfully operated within a wide range of input variation. Here K_e and K_{ce} are the normalization factors for error input and change of error input respectively. For this fuzzy logic controller design, the normalization factors are taken as constants. The output of the fuzzy logic controller is then multiplied with a gain K_O to give the appropriate control signal U. The output gain is also taken as a constant for this fuzzy logic controller [8].

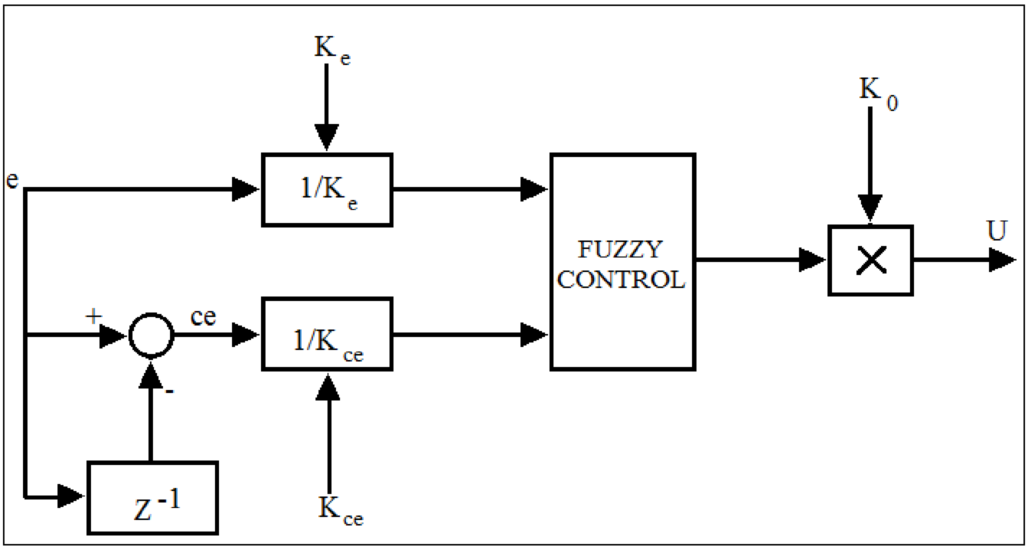

Figure 3.3 Basic Structure of Fuzzy Logic Controller

The fuzzy controller used in power system stabilizer is normally a two- input and a single-output component. The two inputs are change in angular speed and rate of change of angular speed whereas output of fuzzy logic controller is a voltage signal.

3.11 Controller Design Procedure

The fuzzy logic controller (FLC) design consists of the following steps.

1- Identification of input and output variables.

2- Construction of control rules.

3- Establishing the approach for describing system state in terms of fuzzy sets, that is establishing fuzzification method and fuzzy membership functions.

4- Selection of the compositional rule of inference.

5- Defuzzification method, that is., transformation of the fuzzy control statement into specific control actions.

The above steps are explained with reference to fuzzy logic based power system stabilizer in the following section. Thus helps understand these steps more objectively.

3.12 Input/output Variables

The design starts with assigning the mapped variables inputs/output of the fuzzy logic controller (FLC). The first input variable to the FLC is the generator speed deviation and the second is acceleration. The output variable to the FLC is the voltage. After choosing proper variables as input and output of fuzzy controller, it is required to decide on the linguistic variables. These variables transform the numerical values of the input of the fuzzy controller to fuzzy quantities. The number of linguistic variables describing the fuzzy subsets of a variable varies according to the application. Here seven linguistic variables for each of the input and output variables are used to describe them. Table 3.1 shows the Membership functions for fuzzy variables [8].

Table 3.1 Membership functions for fuzzy variables

NB	Negative Big
NM	Negative Medium
NS	Negative Small
ZE	Zero
PS	Positive Small
PM	Positive Medium
PB	Positive Big

The triangular membership functions are used to define the degree of membership. Here for each input variable, seven labels are defined namely, NB, NM, NS, ZE as shown in Figure 3.4, Figure 3.5 and Figure 3.6, PS, PM and PB. Each subset is associated with a triangular membership function to form a set of seven membership functions for each fuzzy variable.

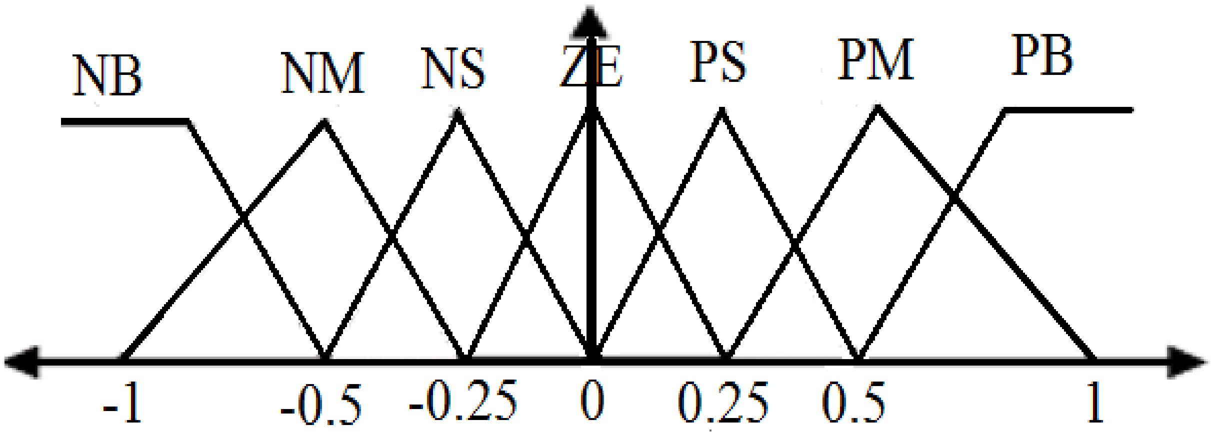

Figure 3.4 Membership function for speed deviation

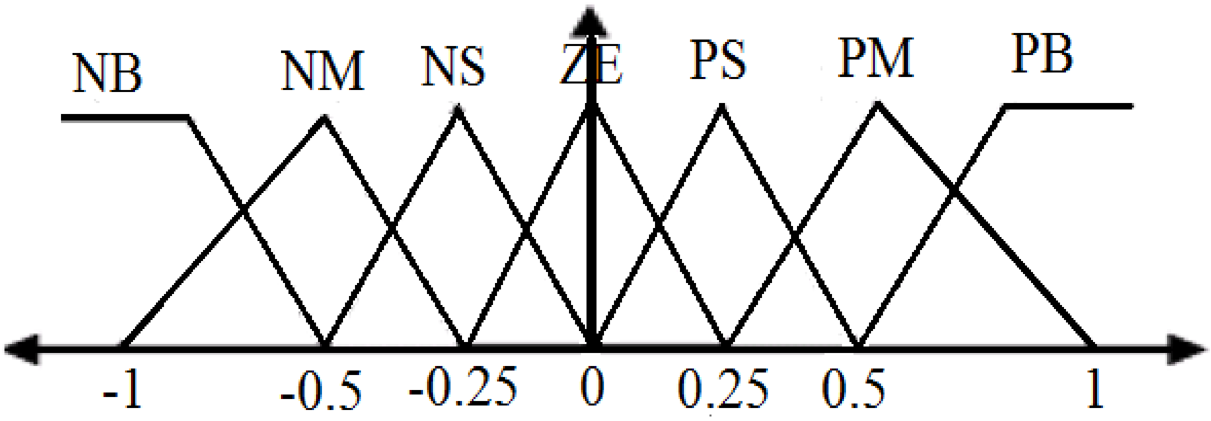

Figure 3.5 Membership function for acceleration

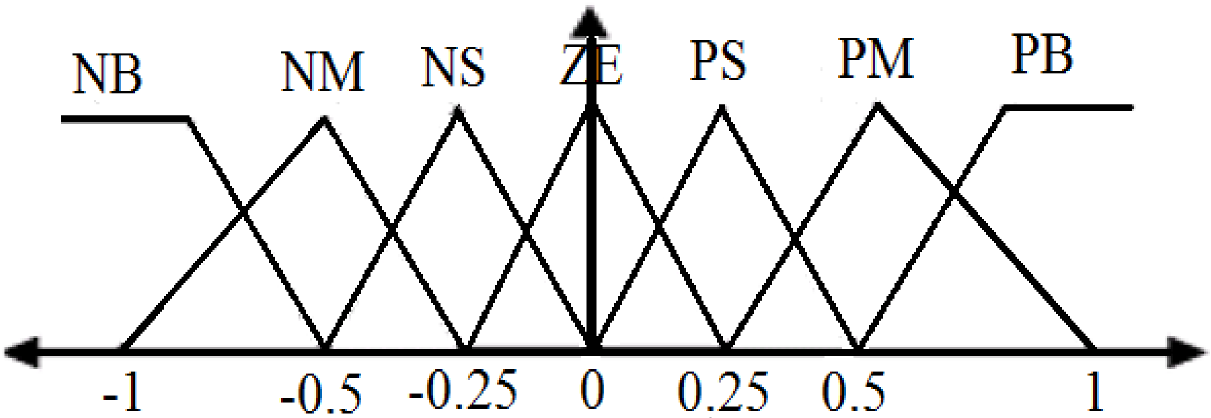

Figure 3.6 Membership function for voltage

The variables are normalized by multiplying with respective gains $K_e; K_{ce}; K_0$ so that their values lie between -1 and +1. In this stage the input variables speed deviation and acceleration are processed by the inference engine that executes 7*7 rules represented in rule Table 3.2 each entity shown in Table 3.2 represent a rule. The antecedent of each rule conjuncts speed deviation (Δω) and acceleration (Δ*a*) fuzzy set values.

Table 3.2 Rule base of fuzzy logic controller

Speed deviation	Acceleration						
	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NM	NS
NM	NB	NM	NM	NM	NS	NS	ZE
NS	NM	NM	NS	NS	ZE	ZE	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NS	ZE	ZE	PS	PS	PM	PM
PM	ZE	PS	PS	PM	PM	PM	PB
PB	PS	PM	PM	PB	PB	PB	PB

The knowledge required to generate the fuzzy rules can be derived from an offline simulation. Some knowledge can be based on the understanding of the behavior of the dynamic system under control. For monotonic systems, a symmetrical rule table is very appropriate, although sometimes it may need slight adjustment based on the behavior of the specific system. If the system dynamics are not known or are highly nonlinear, trial and error procedures and experience play an important role in defining the rules. An example of the rule is: If Δω is NS and Δ*a* is NM then U is NB which means that if the speed deviation is negative small and acceleration is negative medium then the output of fuzzy controller should be negative big. The procedure for calculating the crisp output of the Fuzzy Logic Controller (FLC) for some values of input variables is based on the following three steps [6,8].

Step 1: Determination of degree of firing (DOF) of the rules:

The DOF of the rule consequent is a scalar value which equals the minimum of two antecedent membership degrees. For example if ¢*!* is PS with a membership degree of 0.6 and ¢*a* is PM with a membership degree of 0.4 then the degree of firing of this rule is 0.4.

Step2: Inference Mechanism:

The inference mechanism consists of two processes called fuzzy implication and aggregation. The degree of firing of a rule interacts with its consequent to provide the output of the rule, which is a fuzzy subset. The formulation used to determine how the DOF and the consequent fuzzy set interact to form the rule output is called a fuzzy implication. In fuzzy logic control the most commonly used method for inferring the rule output is Mamdani method.

Step3: a mechanism called defuzzification is used.

In this example output U is defuzzified according to the membership functions shown in Figure 4.10. Here center of gravity (COA) or centroid method is used to calculate the final fuzzy value.

3.13 Selection of Input and Output Variable

Define input and control variables, that is, determine which states of the process should be observed and which control actions arc to be considered. For FLPSS design, generator speed deviation and acceleration can be observed and have been chosen as the input signal of the fuzzy PSS. The dynamic performance of the system could be evaluated by examining the response curve of these two variables. The voltage is taken as the output from the fuzzy logic controller.

Chapter Four

Simulation and Results

4.1 Introduction

Power system operation is characterized by the random variation of the load condition, continuous change in generation schedule and network interconnection. Moreover, power systems are subject to different exogenous disturbances such as actions of different controllers, switching of lines or increasing such loads in the system. Such disturbances will initiate low frequency power system oscillations which should be consequently endangering the overall stability of the system. Ones the low frequency oscillations started, they would continue for a while and disappear, or continue to grow causing system separation. In modern power system operation, the low frequency power system oscillations initiated by disturbance have been one of the major concerns. The oscillations may sustain and grow to cause system separation if adequate damping is not available [4].

4.2 System Layout

Power system oscillations are a characteristic of the system and they are inevitable. Power system oscillations are initiated by normal small changes in system loads and they become much worse following a large disturbance. The AVR can inject negative damping into the system at high power loading, leading power factors and large tie-line reactance. This so-called negative damping may be eliminated by introducing a supplementary control loop known as the power system stabilizer. The basic function of a PSS is to extend the stability limits by modulating the generator excitation to provide damping for the rotor oscillations of synchronous machines. The PSS can enhance the damping of power system, increase the static stability and improve the transmission capability. Two distinct types of oscillations are already identified: local mode oscillation and inter-area mode oscillation [3]. The system lay-out is shown in Figure 4.1.

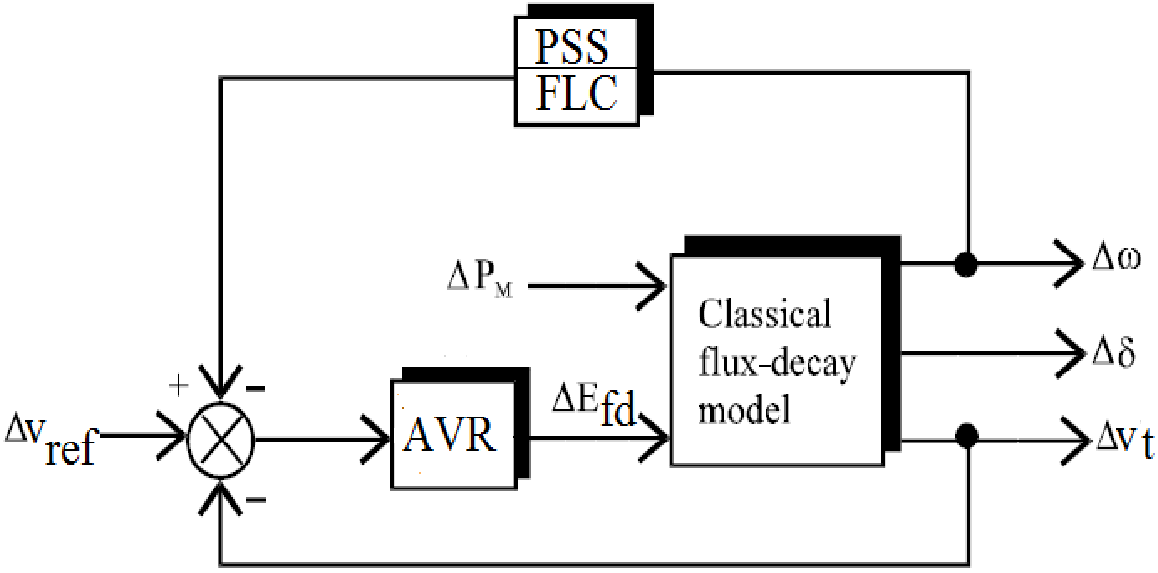

Figure 4.1 block diagram of system model

4.3 Power System Stabilizer (PSS)

The main function of a power system stabilizer (PSS) is to introduce a component of electrical torque in the synchronous machine rotor that is proportional to the deviation of the actual speed from synchronous speed. When the rotor oscillates, this torque acts as a damping torque counter to the low frequency power system oscillations [8].

The block diagram of power system stabilizer is shown in Figure 3.1

Table 4.1 parameters of power system stabilizer

Parameters	Numerical Values
T_1	0.154
T_2	0.033
T_w	1.400
K_{STAB}	20.00

4.4 Power System Stabilizer Based Fuzzy Logic

The power system stabilizer is used to improve the performance of synchronous generator. Therefore, the need for fuzzy logic PSS arises. The fuzzy controller used in power system stabilizer is normally a two-input and a single-output component. It is usually a MIS0 system. The two inputs are change in angular speed and rate of change of angular speed whereas output of fuzzy logic controller is a voltage signal. A modification of feedback voltage to excitation system as a function of accelerating power on a unit is used to enhance the stability of the system [9].

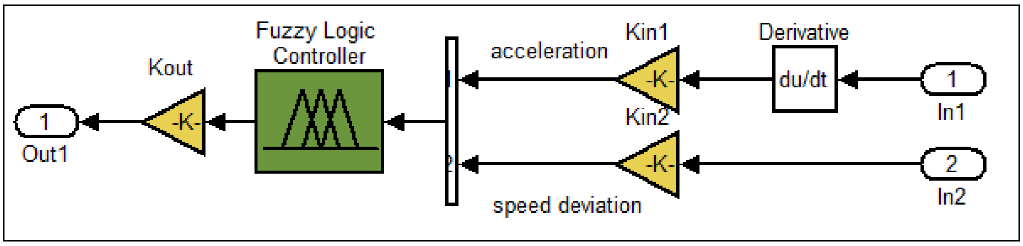

Figure 4.3 Diagram of Fuzzy Logic Based PSS

Table 4.2 Parameters of FLC Based PSS

parameters	Numerical Values
K_{in1}	1.6
K_{in2}	29.56
K_{out}	1.06

4.5 Fuzzy Inference System

Fuzzy logic block is prepared using FIS file in MATLAB program and the basic structure of this file is as shown in Figure 4.4. This is implemented using following FIS (fuzzy Inference System) properties:

And Method: Min
Or Method: Max
Implication: Min
Aggregation: Max
Defuzzification: Centroid

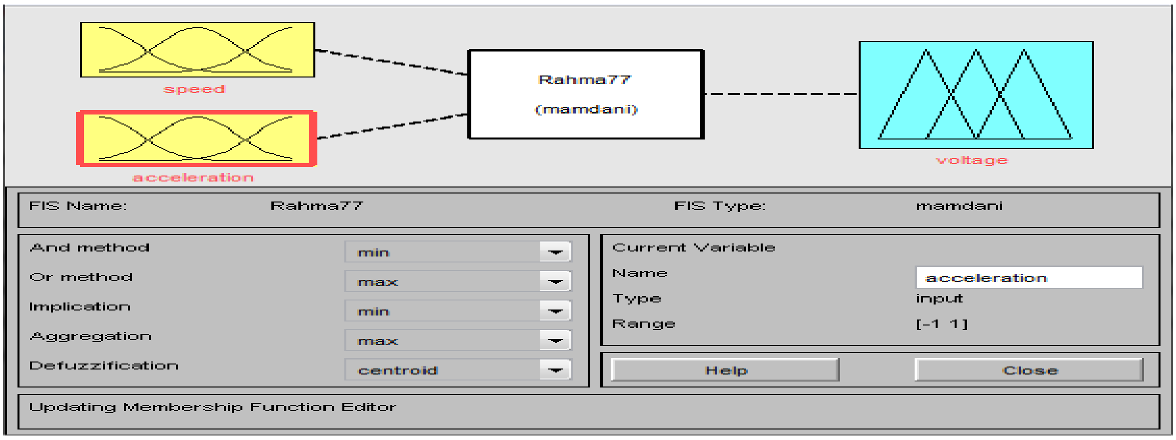

Figure 4.4 Block diagram of Fuzzy Inference System

For the above FIS system Mamdani type of rule-base model is used. This produces output in fuzzified form. Normal system need to produce precise output which uses a Defuzzification process to convert the inferred possibility distribution of an output variable to a representative precise value. In the given fuzzy inference system this work is done using Centroid Defuzzification principle. In this min implication together with the max aggregation operator is used. Given FIS is having seven input member function for both input variables leading to 7*7 that is 49 rules in table [8].

4.6 Excitation System

The standard IEEE type excitation system model has been considered for the study and integrated it with the single machine infinite bus system. The excitation system parameters are taken in system model in table below.

Table 4.4 Excitation system Parameters

Parameters	Numerical Values
K_A	300
T_R	0.015

4.7 K Constants Values

The values of 'K' constants calculated using machine parameters:

Table 4.5 K constants values

Parameters	Numerical Values
K1	1.7299
K2	1.7325
K3	0.1692
K4	2.8543
K5	0.0613
K6	0.3954

4.8 Simulation Model and Results

The performance of single machine infinite bus system has been studied with field circuit and with AVR only and with conventional PSS (lead lag) and with fuzzy logic based PSS. The dynamic models of synchronous machine, excitation system and conventional PSS are described. The system data is given in Table 4.6.

Table 4.6 system parameters

Parameters	Numerical Values
Q	0.3
P	0.9
E_t	1.0
F	50
X_d	1.81
X_q	1.76
X_L	0.00
X_e	0.65
R_a	0.003
T_{do}	8.0
H	3.5
W_0	314
K_D	0.00
T_R	0.015

4.9 System Evaluation with Field Circuit

In this case, the dynamic characteristics of the system are expressed in terms of K constants only that are system is open loop. The deviation in machine speed and angle are shown in Figure 4.5 and Figure 4.6.

From the response shown in Figure 4.6 it shows that it is taking very long time that is more than 25 seconds to settle to steady state. Therefore, the performance of the system with excitation system is analyzed to find the suitability of the excitation system in removing these oscillations.

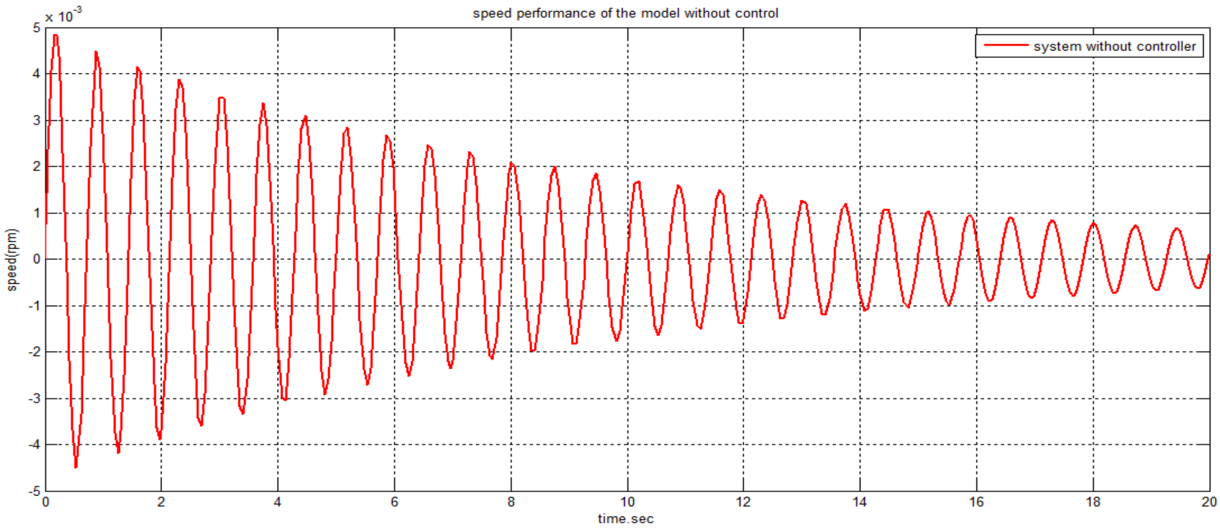

Figure 4.5 Speed responses with field circuit

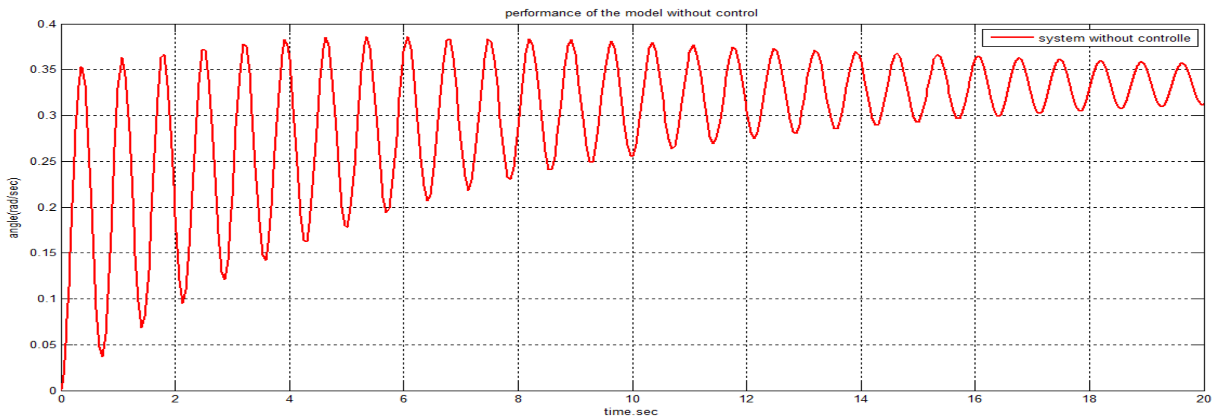

Figure 4.6 angle responses with field circuit

4.10 Performance with Excitation System

The system performance is improved by connecting AVR. The time response of the angular speed and angular position with excitation system has shown in Figure 4.7 and Figure 4.8.

From Figure 4.8 the response characteristic shows that under damped oscillations are resulted. The figure shows that it has positive damping due to the fact that K_5 constant is positive.

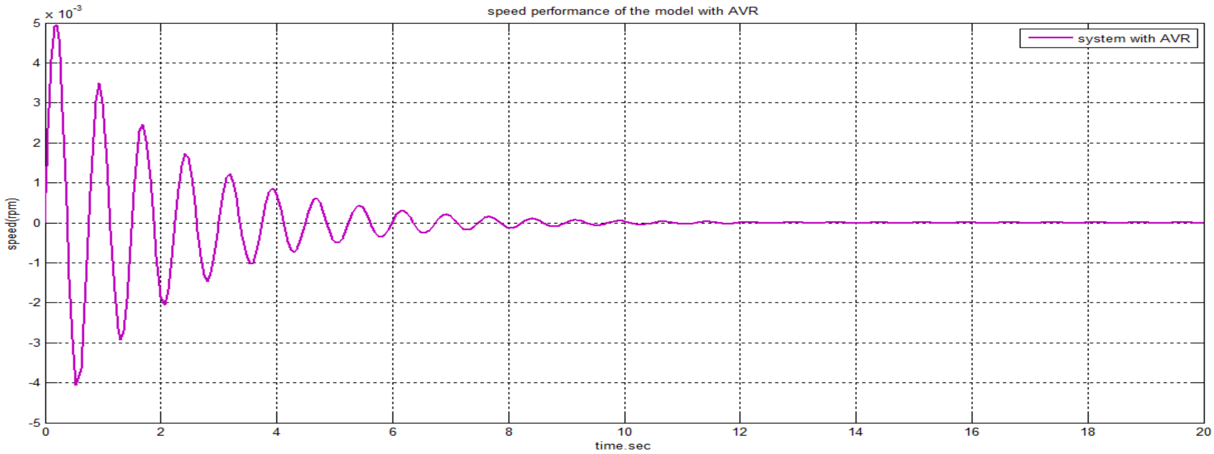

Figure 4.7 Speed responses with AVR

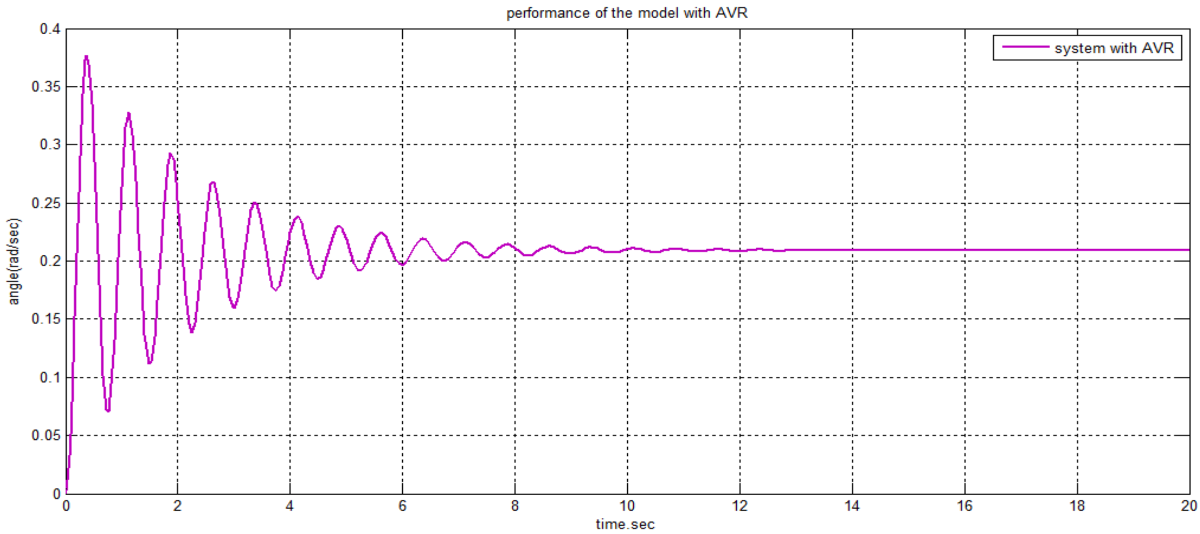

Figure 4.8 angle responses with AVR

4.11 Performance with Conventional Power System Stabilizer

Figure 4.9 and figure 4.10 shows the variation of angular speed and load angle when PSS (lead-lag) is connected in the system. It is clear that from the Figure 4.9 and Figure 4.10 the time response, settling time and overshooting are improved compare to previous conditions. It shows that the system is stable for positive value of *K* constant.

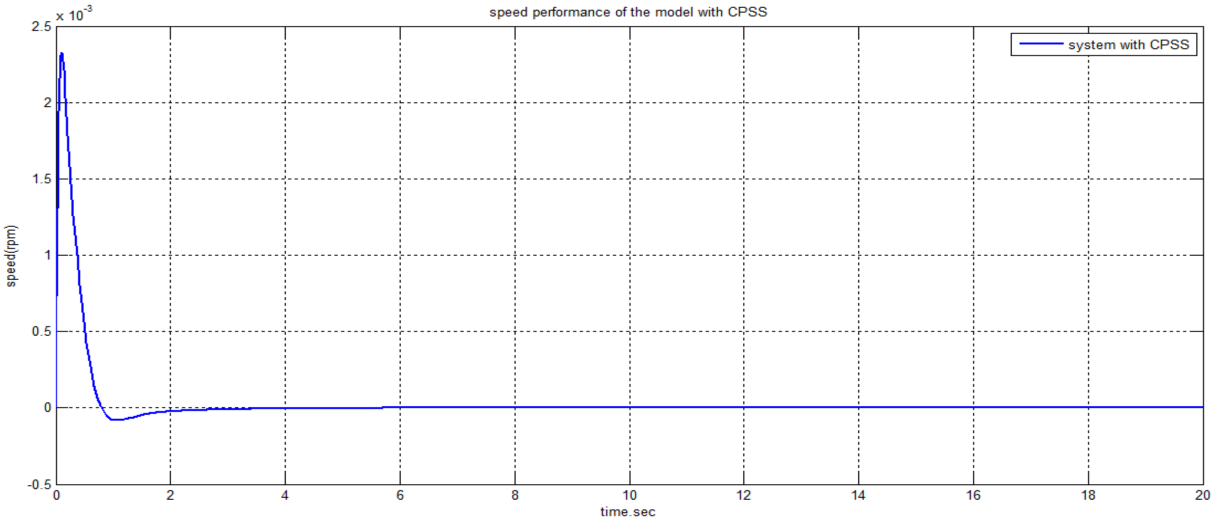

Figure 4.9 Speed responses with power system stabilizer

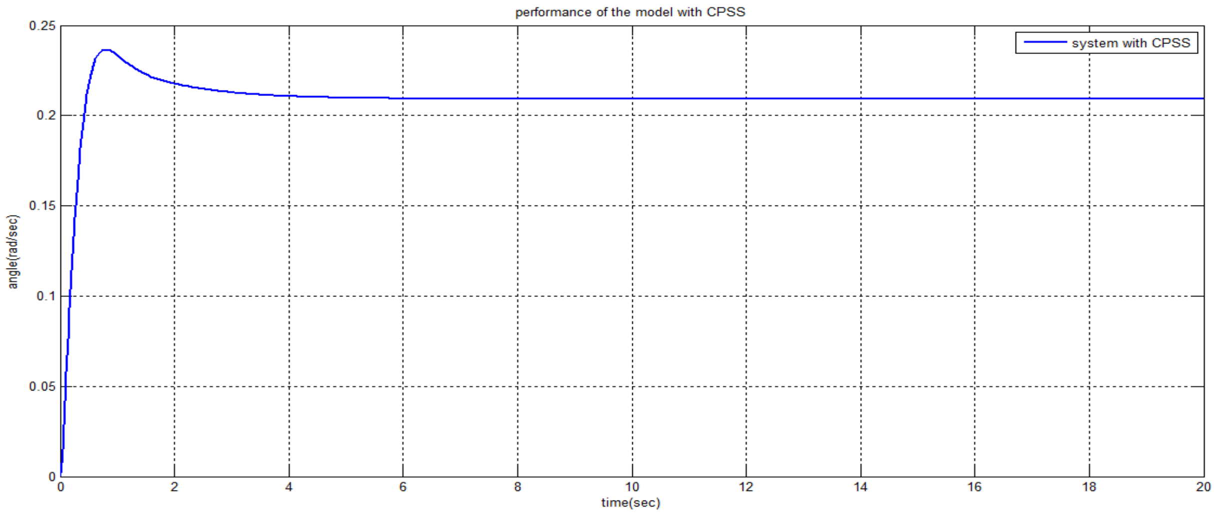

Figure 4.10 angle responses with power system stabilizer

4.12 Performance with FLC Based PSS

The model used in Simulink/Matlab to analyze the effect of fuzzy logic controller in damping small signal oscillations when implemented on single machine infinite bus system is shown in Figure 4.1.

Figure 4.11 and Figure 4.12 show that the load angle and speed a particular value with very few oscillations if thy compared with result of Conventional power system stabilizer.

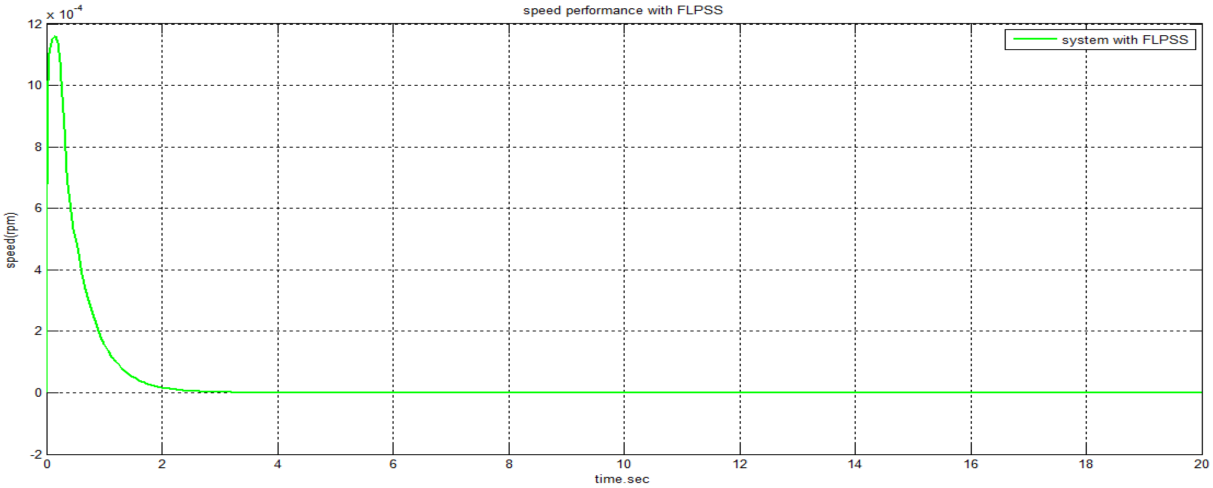

Figure 4.11 Speed response with fuzzy controller based power system stabilizer

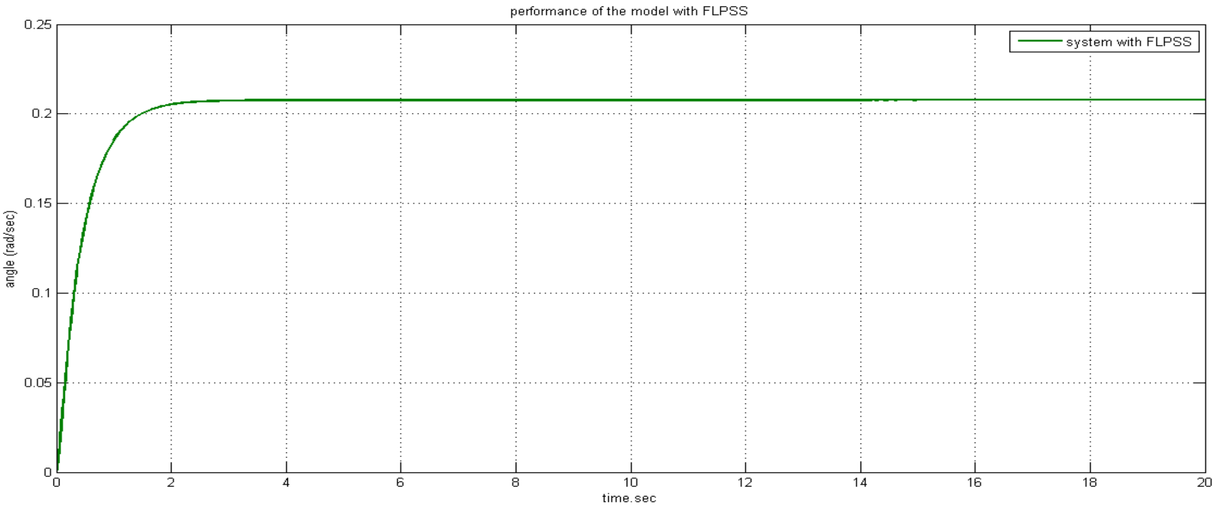

Figure 4.12 angle response with fuzzy controller based power system stabilizer

4.13 Comparing Performance with FLPSS and PSS

Figure 4.13 and Figure 4.14 shows the variation of angular speed and load angle when they compared the Conventional power system stabilizer (CPSS) and controller based power system stabilizer.

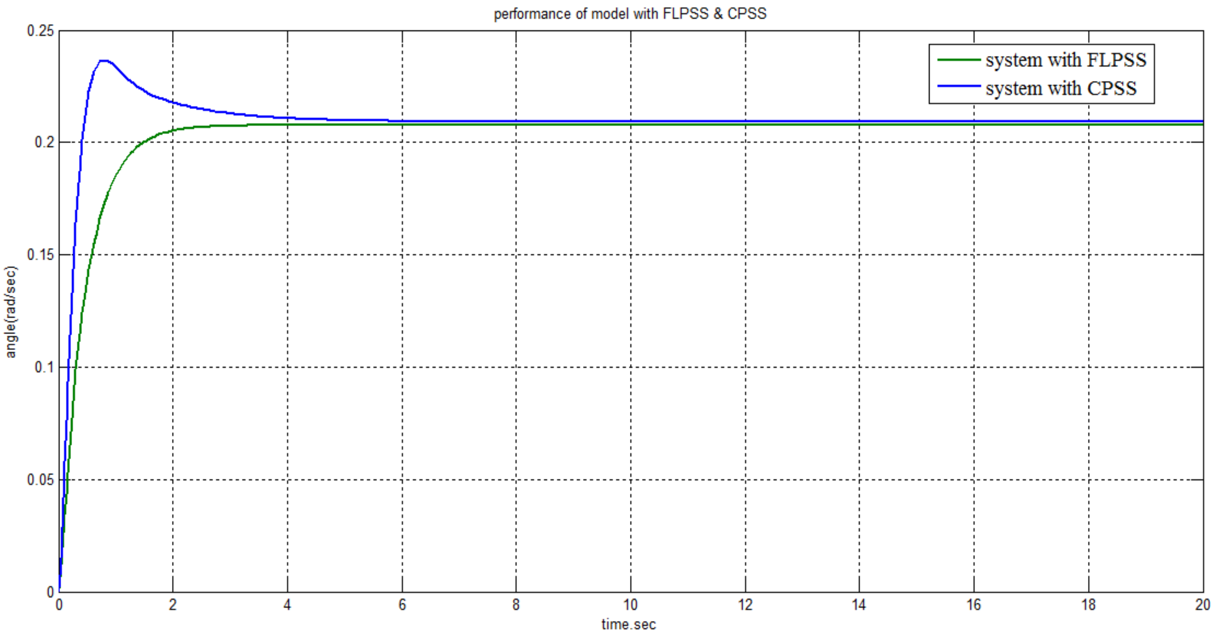

Figure 4.13 Comparison of angular position between CPSS and FLPSS

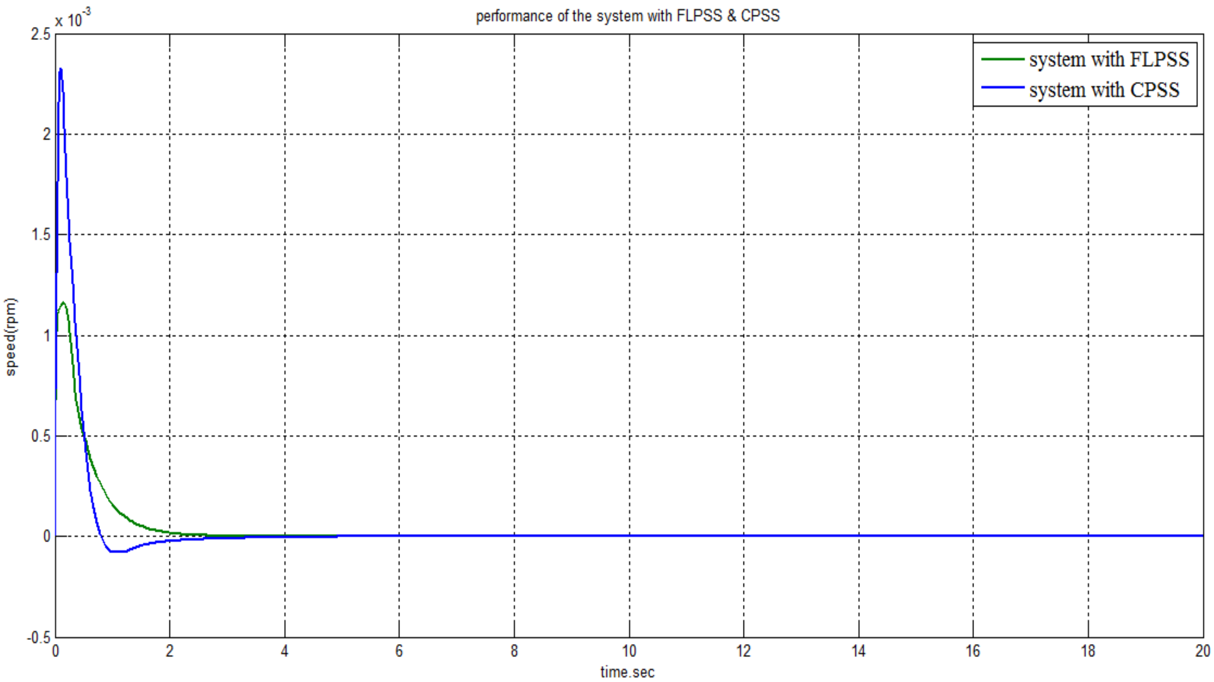

Figure 4.14 Comparison of speed position between CPSS and FLPSS

From the figure 4.14 in term of settling time the angular speed reduces to zero in about 2.5 to 3 seconds with conventional power system stabilizer (CPSS), but with fuzzy controller based power system stabilizer is reduces to zero in about 2 to 2.5seconds.and in term of overshoot the performance of (FLPSS) 1.3rpm is less than (CPSS) 2.6rpm. It has been seen that in the load angle between CPSS and FLPSS in term of overshoot the performance of (FLPSS) 2.2rad/sec is less than (CPSS) 2.8rad/sec.

4.14 Response for Different Operating Conditions

Figure 4.15 and Figure 4.16 show the angular position at different operating conditions the system without controller, using (AVR), (CPSS) and (FLPSS).

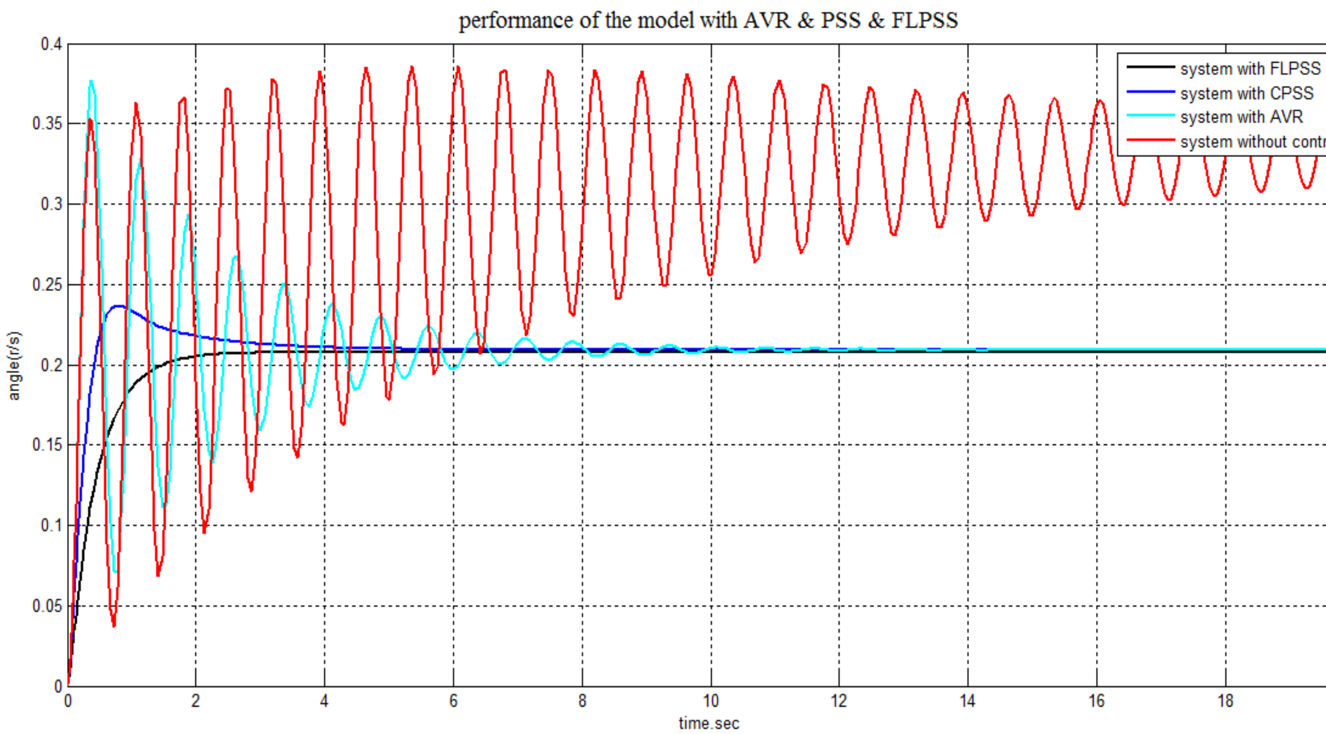

Figure 4.15 system angle responses with AVR & PSS & FLPSS

Table 4.7 comparing between shooting and settling time for angular response

Devices	Settling time	Overshoot
System without controller	More than 20second	0.39 rad/sec
System with AVR	10 second	0.35 rad/sec
System with CPSS	3 second	0.24 rad/sec
System with FLPSS	2 second	0.22 rad/sec

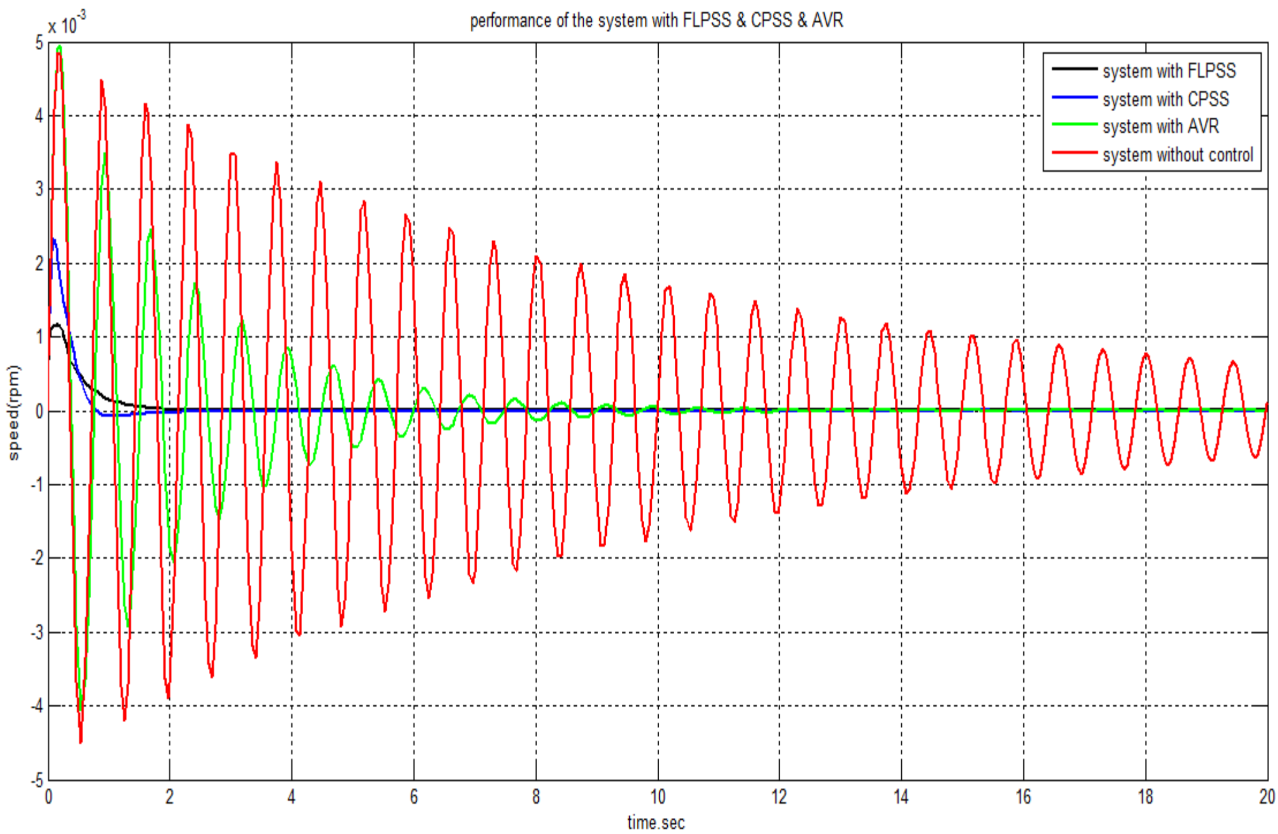

Figure 4.16 system speed response with AVR & PSS & FLPSS

Table 4.8 comparing between shooting and settling time for speed response

Devices	Settling time	Overshoot
System without controller	More than 20seconds	4.9 rad/sec
System with AVR	10 seconds	4.8 rad/sec
System with CPSS	3 seconds	2.3 rad/sec
System with FLPSS	2 seconds	1.2 rad/sec

Figure 4.15 and Figure 4.16 show the response for different operating conditions is test the system without controller and using (AVR), (CPSS) and (FLPSS) the results show that the response is coming out to the stable state with very few oscillations thus enhancing the stability of a system. Table 4.7 and Table 4.8 are showing the comparison of the system condition in term of overshot and settling time.

Chapter Five

Conclusion and Recommendation

1.5 Conclusion

In this dissertation work initially the effectiveness of power system stabilizer in damping power system stabilizer is reviewed. Then the fuzzy logic based power system stabilizer is introduced by taking speed deviation and acceleration of synchronous generator as the input signals to the fuzzy controller and voltage as the output signal. FLPSS shows better control performance than power system stabilizer in terms of settling time and damping effect. Therefore, it can be concluded that the performance of FLPSS is better than conventional PSS. The choice of membership functions has an important bearing on the damping of oscillations. However, the performance of FLPSS with triangular membership functions is superior compared to other membership functions and using the triangular membership function.

2.5 Recommendation

Having gone through the study of fuzzy logic based PSS (FLPSS) for single machine infinite bus system, the scope of the work is

1. The fuzzy logic based PSS (FLPSS) can be extended to multi machine interconnected system having non-linear industrial loads which may introduce phase shift.

2. The fuzzy logic based PSS with frequency as input parameter can be investigated because the frequency is highly sensitive in weak system, which may offset the controller action on the electrical torque of the machine.

3. Testing using more complex network models can be carried out.

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