CHAPTER 1

INTRODUCTION

1.1POWER SYSTEM STABILITY

Power system stability is the ability of the system to regain its steady state operation after removal of the disturbance. The disturbances may be of different types depending on nature of load and the duration for which it is applied on the system. Whenever there is unbalance in load there is change in operating point of the system. The system may return to its previous point or may attain some other stable operating point. If the system attains its stable operating point then one can say that the system is stable and if it does not attain the stable operating point then it is said to be unstable system. Power system stability deals with the capability of system to the stable operating point.

Power system is no more in operation as an isolated system rather it operated as a dynamic system, it is an interconnected multiple system, sometimes consisting up to thousands of electric elements and covers massive geographical areas. Interconnected power systems have number of advantages-

- Deliver huge amount of power and are more reliable system.
- This system can reduces the multiple machine requirement, which are required for smooth operation at maximum value of load and it can be also at spinning reserve to take care of abrupt fluctuation in the load.
- This is an economical source of power.

On the other hand there are disadvantages of using interconnected power systems. The interconnection between neighbouring power systems are comparatively feeble as compared to connections which are present within the system and it easily lead to a lower frequency inter oscillation. There are several early cases of oscillation instability occurring at a lower frequencies when interconnections are made. Power system stability can be classified into three categories

1. Steady-state stability:

Steady state stability of the system deals with small and continuous disturbances in the system applied for a long time. Whenever such a type of disturbance occurs in a power system network the synchronism in different alternators gets disturbed and the alternator operating point changes. The torque angle changes and there is some vibrations in the system. Theses vibrations die out from the system depending on the reactance (transient or subtransient).

If *n*- machine constitutes the power system then the active power supplied by the i_{th} generator is given by eq. (1.1).

$$P_i = \frac{U_{pi}^2}{Z\,ii} \sin \alpha_{ii} + U_{pi} \sum_{\substack{j=i \\ i \neq i}}^{n} \frac{U_{pi}}{Z_{ij}} \sin\left(\delta_i - \delta_j - \alpha_{ij}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 1.1$$

where

U_{pi} - Internal voltage magnitude of the generator (V_{LL})

$Z_{ii} \left(\frac{\pi}{2} - \alpha_{ii}\right)$ - The driving point impedance

$Z_{ij} \left(\frac{\pi}{2} - \alpha_{ij}\right)$ - The transfer impedance amid machines *i* and *j*;

δ_i - The phase angle lead (load angle) of the i_{th} generator with respect to the reference phasor

P_i - The electrical three phase power of the generator.

In worst cases, the oscillation amplitudes reach a level in which protective relays trip the line as well as generation, which may result in either partial or complete system collapse.

2. Transient stability :

Transient state stability deals with large disturbance occurring for a very small duration of time. The analysis of the transient stability is done with the help of swing equation. Swing equation is a non linear differential equation used to find out the operating point of the system after removal of the disturbance. It may die out after two or three oscillations of the disturbance. This depends on sub transient reactance of the alternator.

3. Dynamic Stability :

Dynamic stability deals with small and continuous disturbances for a long duration of time. This is also known as small signal stability. There will be use of external device for stable operating point after the disturbance is removed.

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$$T_{wi}\frac{d^2\delta_i}{dt^2} = P_{Mi} - D_i\frac{d_{\delta i}}{dt} - P_{Ei} \quad \ldots\ldots\ldots\ldots\ldots..1.2$$

Where,

T_{wi} is the impulse moment of the rotor of the generating unit,
D_i is the damping coefficient (representing the mechanical as well as the electrical damping effect),
δ_i is the phase angle (load angle),
P_{Mi} is the turbine power applied to rotor and
P_{Ei} is electrical power output from t stator.

1.1.1 Types of Oscillations

Electro-mechanical oscillations of generators are one of the major disturbances occurring in power system. These oscillations are also known as power swings and the oscillation generated is required to be damped effectively in order to keep the system stable. Electro-mechanical oscillations can be divided into four main classes-

i. Local oscillations: - It is generated amongst unit, remaining generating station, among the later unit and remaining power system. Their frequency typically ranges from 0.2 Hz to 2.5 Hz.

ii. Interplant oscillations: - Oscillation ranging from 1HZ to 2HZ generated between two electrically close generating power plants is known as Interplant oscillations.

iii. Inter-area oscillations: - Oscillation ranging from 0.2 HZ to 0.8 HZ generated between two major groups of generating power plants is known as Inter-area oscillations and also low frequency oscillations.

iv. Global oscillations: - A characteristic of Global oscillations is a common in phase oscillations among all generators when present in an isolated system. The frequencies of such global oscillations are usually below range of 0.2 Hz.

1.1.2 Low Frequency Oscillations

Low frequency oscillations (LFOs) are the rotor angle oscillations of generator having frequency in the range of 0.1 Hz to 3.0 Hz. They are defined by how LFO are generated or where they are positioned in the power system. Use of high gain exciters are the cause of LFOs in below par turned generation excitation system, HVDC converters which gives negative damping in LFOs are related to a a small-signal stability problem. supplementary stabilizing signals are used to minimize the effect of these oscillations and the networks which is utilized to generate these signals are known as ”PSS” networks. Low frequency oscillations involves local plant modes, control modes, turbine-generator system‘s torsional modes caused due to interaction among the mechanical and electrical oscillation, and inter-area modes, caused by either heavy power transfer across weak tie lines or high gain exciters.

1.2 LITERATURE SURVEY

1.2.1 POWER SYSTEM STABILIZER (PSS)

A. Dysko, W.E. Leithead and J. O’Reilly [15] have described coordinated design procedure in step-by-step for PSS with AVR in coupled system. The frequency domain analysis is done on the proposed design. Chow and Sanchez-Gasca [9] proposes a PSS using pole placement technique and this work is carried by Yu and Li [31] for a nine bus system. G Guralla, R Padhi and I Sen [16] have reported the technique of designing constant parameter decentralized Power System Stability used in multi machine power systems which are interconnected. In which Heffron - Philips model uses the PSS structure with compensator and its parameters, tuned for every machine with the multi-machine condition. A. Chatterjee, S.P. Ghosal, and V. Mukherjee have described a comparative transient performance of single-input conventional PSS and dual-input PSS, namely PSS4B. Systems' Eigen values were calculated to calculate stability of the system. About small signal stability, fast acting excitation systems, line loading, and high gain, high impedance of transmission lines explanations are provided in the study [5]. An experience in assigning PSS projects [10] has discussed in an under graduate control design with three different methods (root-locus, frequency-domain, state-space) and interact them to power system engineering. A generalized neuron (GN) requires much smaller training data and shorter training time has developed and by taking benefit of these characteristics of the GN, by which a new PSS is proposed [7]. Wah-Chun Chan, Yuan-Yih Hsu [6] have designed an structure of optimal stabilizer along with increased active stability. Synchronous machine of systemis does so by an increase in its damping torque. De Mello [11] has elucidated the occurrence of stability of synchronous machines under the influence of small disturbance by studying a single machine system coupled with infinite bus with the help of reactance (external). The design of PSS for single machine connected to an infinite bus has been described [15] using fast output sampling feedback. A step-up transformer is utilized for setting up a modified Heffron-Philips (ModHP) model. This model uses the signals which are available in the generating station [16]. An augmented PSS [23] is described which extends the performance capabilities into the weak tie-line case. For guiding the selection process many hands-on methods are developed utilising Eigen value [12] analysis methods.

1.2.2 PID (Proportional-Integral-Derivative) Controller

Radman and Smaili [26] had proposed the PID based PSS and Wu and Hsu [8] have proposed the self tuning PID PSS for a multi machine power system. M. Dobrescu, I. Kamwa [13] in their paper has described a PID controller based FLPSS which has the gains that are adjustable in order to keep a simple structure. The proposed scheme is tested and compared with two standard stabilizers; the IEEE PSS4B and IEEE PSS2B form the IEEE STD 421.5. A. Jalilvand, R. Aghmasheh and E. Khalkhali in their paper [18] had explained the tuning of Proportional Integral Derivative PSS using Artificial intelligence (AI) technique.

1.2.3 Genetic Algorithm

A.S. Al-Hinai and S.M. Al-Hinai [2] have used Genetic Algorithm for a proper designing of a PSS. A Babaei, S.E. Razavi, S.A. Kamali, A. Gholami [4] have used a modified Genetic Algorithm for suitable design of stabilizer.

1.2.4 Fuzzy Logic Controller

Lin [27] proposed a fuzzy logic Power System that reduced the tuning process and membership functions of fuzzy sets. The proposed PSS has two stages, the first one has a proportional derivative type PSS, in the second stage it is transformed into FLPSS. M.L. Kothari, T. Kumar [20] have reported a new approach for designing a fuzzy logic PSS such that it improves both transient and dynamic stabilities. Here they have considered FLPSS based on 3, 5 and 7 MFs of Gaussian shape. S.K. Yee and J.V. Milanovic [30] have proposed a decentralized fuzzy logic controller using a performance index based systematic analytical method.

F. Rashidi [28] has described a sliding mode FLC where the inference method is used to calculate the upper limit of uncertainties. Kamalasadan, S and Swann, G [19] have reported fuzzy model reference adaptive controller which uses a fuzzy reference model generator (FRMG) with the model reference adaptive controller (MRAC) in parallel with it. M. Ramirez, O.P. Malik [27] have described a simple FLC which has very less fuzzy rules. R. Gupya, D.K. Sambariya, R. Gunjan [16] has reported a fuzzy logic PSS for increasing stability of a multi machine power system. For enhancing the stability of two-area four machine system , a study has been presented by N.Nallathambi on study of fuzzy logic PSS[24]. Park and Lee [25] proposed a self-organizing PSS where the rules are generated automatically and rule base updated online by self-organizing procedure. Lu J. [22] proposed a fuzzy logic based adaptive PSS. K.L. Al-Olimat [3] has presented a STR with multi identification models and least variance controller that uses fuzzy logic switching. Taliyat et al. [29] proposed an augmented fuzzy PSS. Hussein et al. [17] proposed self-tuning PSS in which two tuning parameters are introduced to tune fuzzy logic PSS. Abdelazim and Malik [1] proposed a self-learning fuzzy logic PSS.

1.3 PROBLEM STATEMENT

Damper windings placed on the rotor of generator and turbine along with AVR facilitates to improve the steady-state response/stability of power systems. But because of huge, interrelated power systems, second big goal was to effectively transfer huge amounts of power with the help of long transmission lines across vast distances. Use of a complementary controller in control loop, like conventional PSS to the AVRs on the generators, offer a way to decrease the negative impact of the LFO. The traditional PSSs works for the system configuration and steady-state stability for which these were modelled. Once the circumstances modifies it degrades the working of power system.

The conventional PSS such as lead-lag, proportional integral (PI) PSS, proportional integral derivative (PID) PSS operates at a certain point. So the disadvantage of this type of stabilizer is that they cannot operate under different disturbances.

1.4 METHODOLOGY FOR COUNTERING THE PROBLEM

To counter the demerits of conventional PSS, several methods have been reported in past. In the present work, PSS's effect on the system damping is used and then matched with a fuzzy logic based PSS when it is applied to a one machine infinite bus power system. State space representation is used here for the conventional design.

1.5 OBJECTIVES OF THE WORK

The objectives of the project are

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

1.6 CONTRIBUTIONS OF THE THESIS

Chapter 1: Presents the introduction to power system stability, low frequency oscillations, literature survey, and objective of the work and chapter wise contribution of the thesis.

Chapter 2: Presents the modelling of power system and formation of the state space matrix of the single machine infinite bus (SMIB) system.

Chapter 3: Presents a frequency response method for the design of a conventional PSS in the frequency domain.

Chapter 4: Presents briefly the fuzzy logic control theory, need for implementing fuzzy controller. It also describes fuzzy logic based PSS.

Chapter 5: Presents results and discussions for with excitation system, without excitation system, with conventional PSS, with fuzzy logic based PSS and a comparison between conventional PSS and fuzzy logic based PSS.

Chapter 6: Presents conclusion and future work scope.

CHAPTER 2
MODELLING OF POWER SYSTEM

2.1 INTRODUCTION

For stability assessment of power system adequate mathematical models describing the system are needed. The models must be computationally efficient and able to represent the essential dynamics occur in power system. The mathematical model for synchronous machines using small signal analysis, their excitation system and their lag-lead PSS are briefly reviewed.

2.2 SINGLE MACHINE INFINITE BUS (SMIB) MODEL

Figure 2.1 shows the block diagram for the performance of a synchronous machine which is connected in a large system through transmission lines. The synchronous machine is play very important roll in power system operation. The synchronous machine can be connected in an infinite bus through transmission network and represented in Thevenin's equivalent circuit.

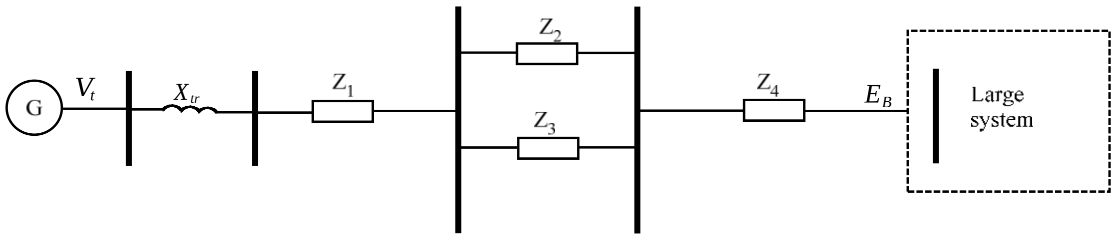

Figure 2.1: General Configuration of SMIB

At first the synchronous machine will be represented by the classical model. Then, the model details will be increased to account for the effects of the dynamics of the field circuit and the excitation system. The block diagram representation and its torque angle characteristic of the system are used to analyse the system-stability characteristics.

For the above said purpose, the system of Figure 2.1 is reduced to the form shown in Figure 2.2.

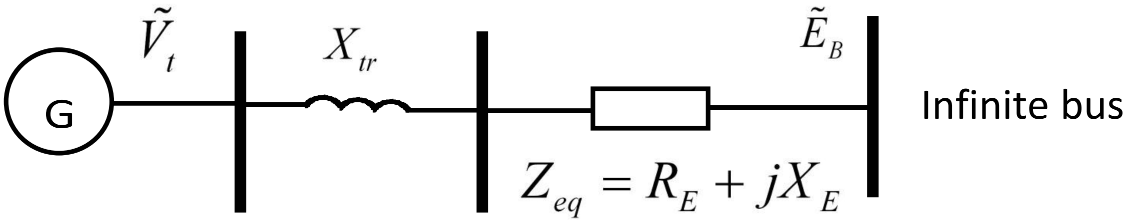

Figure 2.2: Equivalent Circuit of SMIB

2.2.1 Classical Model Representation of the Generator

The model representation of the generator [30] and all the resistances neglected, the system representation in Figure 2.3.

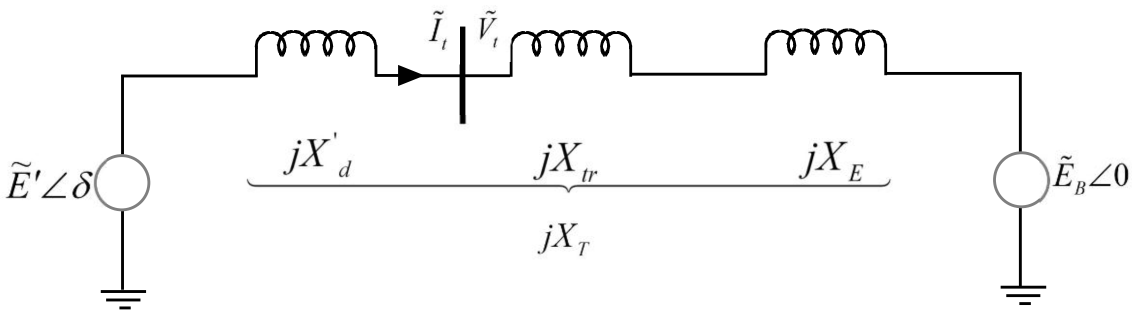

Figure 2.3: Classical model of the synchronous generator

In Figure 2.3, $E^{\sim 0}$ is the voltage behind $X_d{}'$, and $X_d{}'$ is the reactance of direct axis transient reactance of the generator. The magnitude of $E^{\sim 0}$ is assumed to be constant at a value before disturbance. Let $E^{\sim 0}$ leads the infinite bus voltage $E^{\sim}{}_B$ by an angle δ.

The complex power behind $X_d{}'$ is given by

$$S = P + jQ' = \widetilde{E}'\widetilde{I}_t^* = \frac{E'E_B}{X_T}\sin\delta + j\frac{E'(E' - E_B\cos\delta)}{X_T} \tag{2.1}$$

The equations for motion in per unit is given by:

$$P\Delta w_r = \frac{1}{2H}(\Delta T_m - K_s\Delta\delta - K_D\Delta w_r) \tag{2.2}$$

$$P\Delta\delta = w_0\Delta w_r \tag{2.3}$$

Writing equations (2.2) and (2.3) in the vector-matrix form, we obtain

$$\frac{d}{dt}\begin{bmatrix}\Delta w_r\\ \Delta\delta\end{bmatrix} = \begin{bmatrix}-\frac{K_D}{2H} & -\frac{K_S}{2H}\\ w_0 & 0\end{bmatrix}\begin{bmatrix}\Delta w_r\\ \Delta\delta\end{bmatrix} + \begin{bmatrix}\frac{1}{2H}\\ 0\end{bmatrix}\Delta T_m \tag{2.4}$$

Where

$\Delta\omega_r$ is the per unit angular speed deviation of the rotor

H is the per unit inertia constant

T_m is the applied mechanical torque

K_D is the damping torque coefficient

δ is the rotor angle in electrical radians

ω_0 is the rotor speed in rad/sec

K_s is the synchronizing torque coefficient

The synchronizing torque coefficient K_s is given by

$$K_s = \frac{E' E_B}{X_T}\cos\delta \tag{2.5}$$

This is the state-space representation of the system in the form $\dot{x} = Ax + Bu$. The elements of the state matrix A are seen to be dependent on the system parameters H, K_D, X_T and the initial operating condition represented by the values of $E^{\sim 0}$ and δ_0. Vector b is also dependent on H.

Therefore, the undamped natural frequency is

$$w_n = \sqrt{K_s \frac{w_0}{2H}} \tag{2.6}$$

$$\zeta = \frac{1}{2}\frac{K_D}{2H\omega_n} = \frac{1}{2}\frac{K_D}{\sqrt{K_s 2H\omega_0}} \tag{2.7}$$

As the synchronizing torque coefficient K_s increases, the natural frequency increases and the damping ratio decreases. An increase in damping torque coefficient K_D increases the damping ratio, whereas an increase in inertia constant decreases both ω_n and ζ.

The phasor diagram of the relative positions of machine quantities is shown in Figure 2.4. As the rotor oscillates during a disturbance, δ changes.

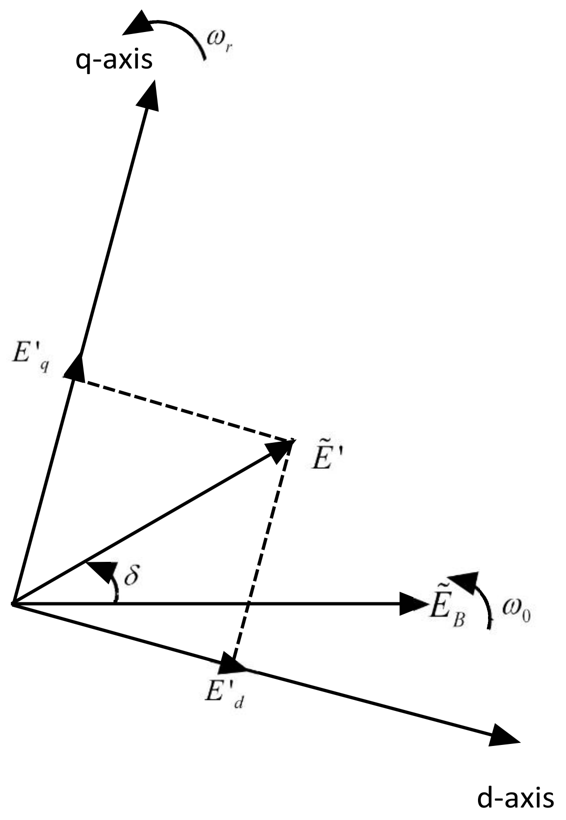

Figure 2.4: Phasor diagram of machine quantities

2.3 EFFECTS OF SYNCHRONOUS MACHINE FIELD CIRCUIT DYNAMICS

Now the system is considered for performance analysis and also the effect of variations in field flux. Then the state-space model for the system is developed, firstly the synchronous machine equations are reduced to an appropriate form and then these equations are combined with the network equations.

As in the case of the classical generator model, the linearized equations of motion are

$$\frac{d}{dt}\Delta\omega_r = \frac{1}{2H}(\Delta T_m - \Delta T_e - K_D\Delta w_r) \tag{2.8}$$

$$\frac{d}{dt}\Delta\delta = \omega_0\Delta\omega_r \tag{2.9}$$

$$\delta = \delta_t + \delta_i \tag{2.10}$$

where ΔT_e is the electrical (air-gap) torque. In this case, the δ is the rotor angle in electrical radians. It is the angle by which the q-axis leads the reference $\tilde{E}_B$. The phasor diagram shown in Figure 2.5 shows the relative position of synchronous machine variables. The rotor angle is given by

$$\delta = \delta_t + \delta_i \tag{2.11}$$

In Figure 2.5 δ_t is the angle by which the terminal voltage $\tilde{V}_t$ lead the reference voltage $\tilde{E}_B$ and its steady state value of δ_i is given by:

$$\delta_i = a\tan\left(\frac{X_q\, I_t\, \cos\varphi - R_a\, I_t \sin\varphi}{V_t + R_a\, I_t \cos\varphi + X_q\, I_t \sin\varphi}\right) \tag{2.12}$$

Where

V_t and I_t are terminal voltage and current
ϕ is the power factor angle
R_a is the armature resistance per phase
X_q is the quadrature-axis synchronous reactance

The effect of field flux variations can be represented as

$$\frac{d}{dt}\Delta\Psi_{fd} = \frac{\omega_0 R_{fd}}{L_{adu}}\Delta E_{fd} - \omega_0 R_{fd}\Delta i_{fd} \tag{2.13}$$

where

$\Delta\psi_{fd}$ is the rotor circuit (field) flux linkage
R_{fd} is the rotor circuit resistance
L_{adu} is the unsaturated direct-axis manual inductance between stator and rotor windings
E_{fd} is the exciter output voltage
i_{fd} is the field circuit current

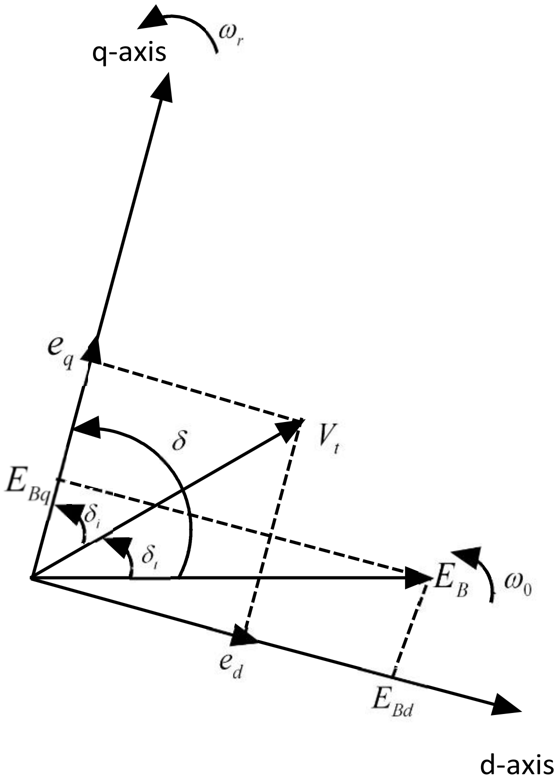

Figure 2.5: Phasor diagram of relative position of synchronous machine variables

To represent the system equations in the of form state-space ΔT_e and Δi_{fd} should in form of the state variables as determined by the machine flux linkage equations and network equations. So we can write that

$$\Delta i_{fd} = \frac{1}{L_{fd}}\left(1 + m_2 L'_{ads} - \frac{L'_{ads}}{L_{fd}}\right)\Delta\Psi_{fd} + \frac{1}{L_{fd}} m_1 L'_{ads}\Delta\delta \qquad (2.14)$$

where

$$L'_{ads} = \frac{L_{ads}\, L_{fd}}{L_{ads} + L_{fd}} \qquad (2.15)$$

$$m_1 = \frac{E_B\,(X_{Tq}\sin\delta - R_T\cos\delta)}{D} \qquad (2.16)$$

$$m_2 = \frac{X_{Tq}}{D}\left(\frac{L_{ads}}{L_{ads} + L_{fd}}\right) \qquad (2.17)$$

$$R_T = R_a + R_E \qquad (2.18)$$

$$X_{Tq} = X_{tr} + X_E + \left(L_{aqs} + L_l\right) \tag{2.19}$$

$$X_{Td} = X_{tr} + X_E + (L'_{ads} + L_l) \tag{2.20}$$

$$D = R_T^2 + X_{Tq}X_{Td} \tag{2.21}$$

where

X_{tr} is the reactance of the transformer
R_E is the Thevenin resistance of the network
X_E is the Thevenin reactance of the network
R_a is the armature resistance
L_l is the leakage inductance of the stator
L_{ads} is the saturated mutual inductance between stator and rotor windings on d-axis
L_{aqs} is the saturated mutual inductance between stator and rotor windings on q-axis

Also we can derive that

$$\Delta T_e = K_1 \Delta\delta + K_2 \Delta\Psi_{fd} \tag{2.22}$$

$$K_1 = n_1\left(\Psi_{ad0} + L_{aqs} i_{d0}\right) - m_1\left(\Psi_{aq0} + L'_{ads} i_{d0}\right) \tag{2.23}$$

$$K_2 = n_2\left(\Psi_{ad0} + L_{aqs} i_{d0}\right) - m_2\left(\Psi_{aq0} + L'_{aq0} i_{d0}\right) + \frac{L'_{ads}}{L_{fd}} i_{q0} \tag{2.24}$$

Here

$$n_1 = \frac{E_B\,(R_T \sin\delta_0 - X_{Td}\cos\delta_0)}{D} \tag{2.25}$$

$$n_2 = \frac{R_T}{D}\left(\frac{L_{ads}}{L_{ads} + L_{fd}}\right) \tag{2.26}$$

$$i_{d0} = \frac{X_{Tq}\left[\Psi_{fd0}\left(\frac{L_{ads}}{L_{ads} + L_{fd}}\right) - E_B\cos\delta_0\right] - R_T E_B \sin\delta_0}{D} \tag{2.27}$$

$$i_{q0} = \frac{R_T\left[\Psi_{fd0}\left(\frac{L_{ads}}{L_{ads}+L_{fd}}\right)-E_B\cos\delta_0\right]-X_{Tq}E_B\cos\delta_0}{D} \tag{2.28}$$

$$\Psi_{ad0} = L'_{ads}\left(\frac{\Psi_{fd0}}{L_{fd}} - i_{d0}\right) \tag{2.29}$$

$$\Psi_{aq0} = -L_{aqs}i_{q0} \tag{2.30}$$

By substituting the expressions for Δi_{fd} and ΔT_e given by equations (2.13) and (2.21) into equations (2.8) and (2.12), the state-space representation of the system is obtained as follows:

$$\frac{d}{dt}\begin{bmatrix}\Delta\omega_r\\ \Delta\delta\\ \Delta\psi_{fd}\end{bmatrix} = \begin{bmatrix}a_{11} & a_{12} & a_{13}\\ a_{21} & 0 & 0\\ 0 & a_{32} & a_{33}\end{bmatrix}\begin{bmatrix}\Delta\omega_r\\ \Delta\delta\\ \Delta\psi_{fd}\end{bmatrix} + \begin{bmatrix}b_{11} & 0\\ 0 & 0\\ 0 & b_{32}\end{bmatrix}\begin{bmatrix}\Delta T_m\\ \Delta E_{fd}\end{bmatrix} \tag{2.31}$$

where

$$a_{11} = -\frac{K_D}{2H} \tag{2.32}$$

$$a_{12} = -\frac{K_1}{2H} \tag{2.33}$$

$$a_{13} = -\frac{K_2}{2H}$$

(2.34)

$$a_{21} = \omega_0 = 2\pi f_0 \tag{2.35}$$

$$a_{32} = -\frac{\omega_0 R_{fd}}{L_{fd}} m_1 L'_{ads} \tag{2.36}$$

$$a_{33} = -\frac{\omega_0 R_{fd}}{L_{fd}}\left(m_2 L'_{ads} + 1 - \frac{L'_{ads}}{L_{fd}}\right) \tag{2.37}$$

$$b_{11} = \frac{1}{2H}$$

(2.38)

$$b_{32} = -\frac{\omega_0 R_{fd}}{L_{adu}} \tag{2.39}$$

ΔT_m and ΔE_{fd} depends on prime mover and the excitation controls. Having fixed mechanical input torque ΔT_m= 0 and with constant exciter output voltage ΔE_{fd}= 0.

2.4 REPRESENTATION OF SATURATION IN STABILITY STUDIES

For stability studies the following assumptions are made in the representation of magnetic saturation.

- The leakage inductances do not saturates and only elements that saturate are the mutual inductances.

- The leakage fluxes are not part of iron saturation and the saturation level is determined by the flux linkage of air gap.

- The relationship between the saturation level of resultant air-gap flux and the saturation level of mmf under loaded conditions is the same as that in under no-load conditions.

- The d-axis and q-axis do not have any magnetic coupling.

2.5 EFFECTS OF EXCITATION SYSTEM

Since, the field circuit time constant is very high, quick controlling of field current requires application of forcing field. This leads the exciter to have a large voltage that helps it to operate rapidly with voltage which are 3- 4 times the standard. The rate of voltage alteration must be quick. The requirement of great reliability, unit exciter scheme is predominant where every generating system has its separate exciter. The excitation system's main objective is to control the field current of the synchronous machine. The field current is controlled in such a way so that the terminal voltage of the machine gets regulated. Keeping the power system in point of view, the excitation system which is used must aid to the control of voltage and improvement of steadiness of system. It should be competent enough to respond to any disturbance quickly, so that the transitory stability of the system could be improved and maintained. In the present thesis, excitation control has been considered for analysis. Basically, simple excitation systems consisting a single exciter only have been considered. The excitation system is also capable of performing in maintain a constant voltage of alternator. Also, When the load conditions are varied it also functions as voltage regulator.

The diagram of control system of a large synchronous generator is shown in Figure 2.6. Various subsystems in the shown in the figure are described as follow:

- Exciter: It constitutes the power angle of the excitation system by providing dc to the field winding of synchronous machine.

- Regulator: it form proper for control of the exciter by processing and amplifying input control signal to a level.

- Terminal voltage of generator is sensed by a transducer and load compensator. Rectifier is utilised for filtering.

- PSS: To damp power system oscillation it delivers an extra input signal to regulator. Input signals are regularly used for speed deviation of rotor, frequency deviation and power.

- Limiter and protective circuits: They take in account an extensive array of control and defensive function that ensures the exciter and generator do not exceed their capability limit.

Various types of excitation systems of synchronous generator are given below.

- Excitation system (DC) used as excitation system with the help of commutator.

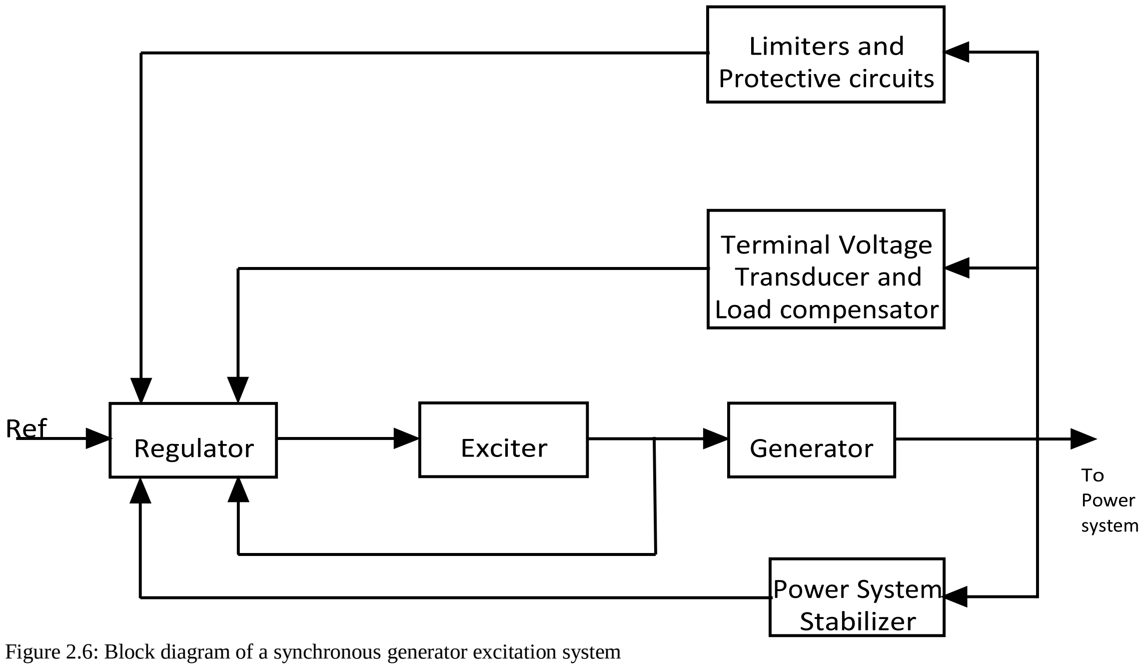

Figure 2.6: Block diagram of a synchronous generator excitation system

- Excitation system (AC): The requirement of direct current for the field of generator is fulfilled by an alternator with and/or stationary or rotating rectifiers.

- Excitation system (ST): Transformers and rectifiers are used to supply excitation power.

The main two kinds of exciters also called as rotating exciter, mounted on the same shaft like generator and which are driven by the prime mover. Voltage regulator of DC excitation system was established on rotating amplifier or magnetic amplifiers. The AC excitation system and static excitation system use electronic regulators which are fast acting resulting in phase control of the controlled rectifier with the help of thyristor. Static excitation system provides a response and it is almost negligible. However, ceiling voltage which can be restricted only by the generator rotor design considerations. In the first swing the machine output is increased with reference to slow exciter. The ST system uses transformers and converts voltage at suitable level and rectifier makes available the necessary dc for generator field. The simplified model of a thyristor (static)

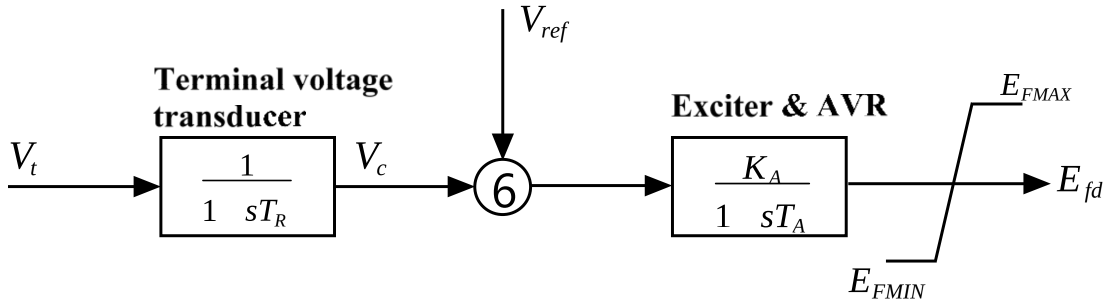

Figure 2.7: Thyristor excitation system with AVR

excitation system as given above in Figure 2.7. A high exciter gain, having no transient gain reduction or derivative feedback is applied. Attribute T_R represent the terminal voltage transducer time constant. The nonlinearity associated with this model is only caused by the ceiling on the exciter output voltage represented by E_{FMAX} and E_{FMIN}. Due to less disturbances the limit is ignored so that E_{fd} is always within the limits and in Laplace domain can be given as

$$E_{fd} = \frac{K_A}{1+ST_A}\left(V_{ref} - V_c\right) \tag{2.40}$$

Assuming that V_{ref} is constant during a short period after application of disturbance and by linearising equation (2.40), deviation of E_{fd} with respect to the steady state value is obtained as

$$\Delta E_{fd} = \frac{K_A}{1+ST_A}(-V_c) \tag{2.41}$$

In the time domain the equation (2.41) can be written as

$$\frac{d}{dt}\Delta E_{fd} = -\frac{K_A}{T_A}\Delta V_c - \frac{1}{T_A}\Delta E_{fd} \tag{2.42}$$

From Figure 2.7 we can write that

$$\Delta V_c = \frac{K_A}{1+ST_A}\Delta V_t$$ (2.43) In the time domain equation (2.43) can be written as

$$\frac{d}{dt}\Delta V_c = \frac{1}{T_R}(\Delta V_t - \Delta V_c) \tag{2.44}$$

In order to obtain the state-space representation of the system, the state vector should be redefined. Equations (2.42) and (2.44) introduce two new state variables, namely ΔV_c and ΔE_{fd}. However ΔV_t is not a state variable and should be expressed in terms of other state variables. So we can write that

$$\Delta V_t = K_5\Delta\delta + K_6\Delta\Psi_{fd} \tag{2.45}$$

$$\mathrm{K_6} = \frac{\mathrm{e_{d0}}}{\mathrm{V_{t0}}}\left[-\mathrm{R_a m_2} + \mathrm{L_1 n_2} + \mathrm{L_{aqs} n_2}\right] + \frac{\mathrm{e_{q0}}}{\mathrm{V_{t0}}}\left[-\mathrm{R_a n_2} - \mathrm{L_1 m_2} - L'_{ads}\left(\frac{1}{L_{fd}} - m_2\right)\right] \tag{2.47}$$

where

$$\mathrm{K_5} = \frac{\mathrm{e_{d0}}}{\mathrm{V_{t0}}}\left[-\mathrm{R_a m_1} + \mathrm{L_1 n_1} + \mathrm{L_{aqs} n_1}\right] + \frac{\mathrm{e_{q0}}}{\mathrm{V_{t0}}}\left[-\mathrm{R_a n_1} - \mathrm{L_1 m_1} - \mathrm{L_{ads} m_1}\right] \tag{2.46}$$

where e_{d0} and e_{q0} can be calculated as

$$e_{d0} = R_E i_{d0} - X_E i_{q0} + E_B \sin\delta_0 \tag{2.48}$$

$$e_{q0} = R_E i_{q0} + X_E i_{d0} + E_B \cos\delta_0$$
(2.49)

i_{d0} and i_{q0} can be obtained from equations (2.27) and (2.28). From the previous expressions the state-space representation of the system is given by

$$\frac{d}{dt}\begin{bmatrix}\Delta\omega_r\\ \Delta_\delta\\ \Delta\Psi_{fd}\\ \Delta V_c\\ \Delta E_{fd}\end{bmatrix} = \begin{bmatrix}a_{11} & a_{12} & a_{13} & 0 & 0\\ a_{21} & 0 & 0 & 0 & 0\\ 0 & a_{32} & a_{33} & 0 & a_{35}\\ 0 & a_{42} & a_{43} & a_{44} & 0\\ 0 & 0 & 0 & a_{54} & a_{55}\end{bmatrix}\begin{bmatrix}\Delta\omega_r\\ \Delta_\delta\\ \Delta\Psi_{fd}\\ \Delta V_c\\ \Delta E_{fd}\end{bmatrix} + \begin{bmatrix}b_1\\ 0\\ 0\\ 0\\ 0\end{bmatrix}\Delta T_m \quad (2.50)$$

where

$$a_{35} = b_{32} = \frac{\omega_0 R_{fd}}{L_{adu}} \quad (2.51)$$

$$a_{42} = \frac{K_5}{T_R} \quad (2.52)$$

$$a_{43} = \frac{K_6}{T_R} \quad (2.53)$$

$$a_{44} = -\frac{1}{T_R} \quad (2.54)$$

$$a_{54} = -\frac{K_A}{T_A} \quad (2.55)$$

$$a_{55} = -\frac{1}{T_A} \quad (2.56)$$

$$b_1 = b_{11} = \frac{1}{2H} \quad (2.57)$$

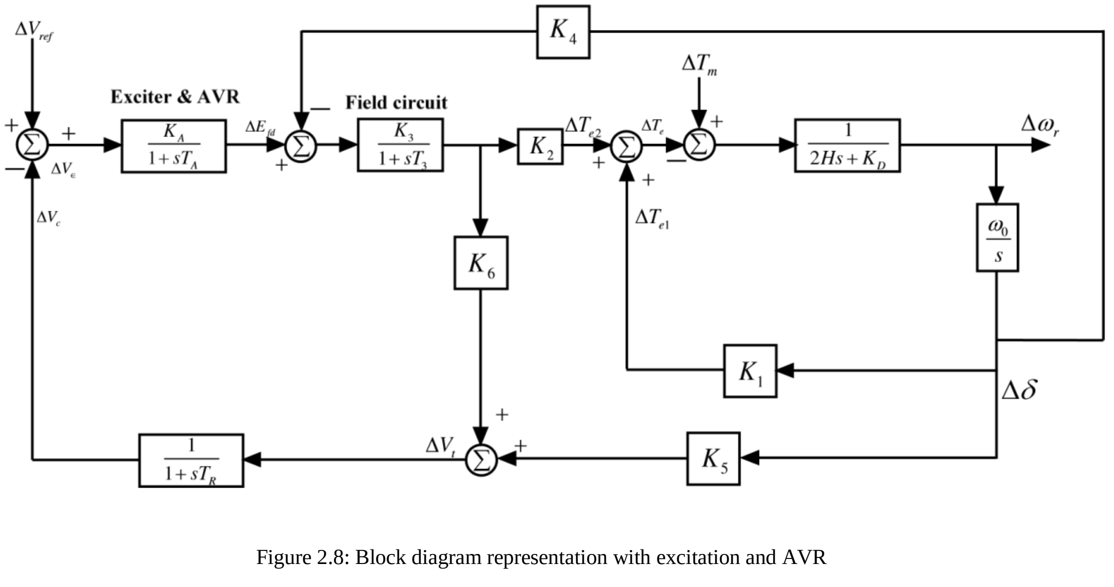

Figure 2.8: Block diagram representation with excitation and AVR

Laplace transformation of equation (2.8) gives

$$\Delta\omega_r = \frac{1}{2Hs + K_D}(\Delta T_m - \Delta T_e) \tag{2.58}$$

The variation of ψ_{fd} is determined by the field circuit dynamic equation, which is given by equation (2.50) as

$$\frac{d}{dt}\Delta\Psi_{fd} = a_{32}\Delta\delta + a_{33}\Delta\Psi_{fd} + a_{35}\Delta E_{fd} \tag{2.59}$$

Laplace transform of equation (2.59) gives

$$\Delta\Psi_{fd} = \frac{K_3}{1+ST_3}\left(\Delta E_{fd} - K_4\Delta\delta\right) \tag{2.60}$$

Where

$$K_3 = -\frac{a_{35}}{a_{33}} \tag{2.61}$$

$$K_4 = -\frac{a_{32}}{a_{35}} \tag{2.62}$$

$$T_3 = -\frac{1}{a_{33}} \tag{2.63}$$

Using equations (2.58), (2.60), (2.45), (2.22) and Fig. 2.7 the block of system with excitation system can be derived and it is shown in Figure 2.8. So far the equations derived the constants K_2, K_3 and K_4 are generally positive. Till the value of 'K_4' is remains positive, due to armature reaction effect of field flux variation would cause a positive damping torque component. Also 'K_4' can also be negative. When a hydraulic generator operates under less load without damper windings it is negative and also it is connected using high resistance to reactance ratio line.

It will also be negative when a huge local load is connected to machine, getting supply partially with generator and partially by remotely present large power system. In such settings, the torque produced due to induced current in the field caused because of armature reaction which has components that are in phase opposition with $\Delta\omega$ and it produces deleterious damping.

The K_6 coefficient is always positive, whereas K_5 can assume both the values of positive or negative, its value depends on the operating condition and impedance of network $R_E + jX_E$. The K_5 value has a substantial impact over the effect of AVR for damping capacity of the oscillations of system. With K_5 positive, the AVR's effect is to introduce a negative synchronizing torque and a positive damping torque component. The constant K_5 have positive sign for the less values of external system reactance and less outputs of generator.

The reduction in K_s due to AVR action in such cases is usually of no particular concern, because K_1 is so high that the net K_s is significantly greater than zero.

With K_5 negative, the AVR action introduces a positive synchronizing torque component and a negative damping torque component. This result is more pronounced as the exciter response increases.

For high reactance of external system and high output of generator.

K_5 is negative. In practice, the situation where K_5 is negative are commonly encountered. For such cases, the high response exciter is profitable in increasing synchronizing torque. In doing so, however it introduces the negative damping. We thus have conflicting requirement with regard to exciter response. One possible resource is to strike a compromise and set the exciter response so that it results in sufficient synchronizing and damping torque components for the expected range of the system operating conditions. This may not always be possible. It may be necessary to use a high response exciter to provide the required synchronizing toque and system stability performance. With a very high external system reactance, even with low exciter response the net damping torque coefficient may be negative.

With small perturbations in electrical power systems, the variation of electrical torque of a synchronous machine, can be solved into 2 different parts.

$$\Delta T_e = K_s\Delta\delta + K_D\Delta\omega$$

Where

$K_s\Delta\delta$, the part of change in torque is in phase with the rotor angle disconcertion $\Delta\delta$ or called as synchronizing torque.

$K_D\Delta\omega$, the part of torque change, in phase with deviation in velocity $\Delta\omega$ are called as damping torque portion.

System stability depends on the existence of both components of torque.

- Lack of sufficient synchronizing torque results in instability through a periodic drift in rotor angle.

- Lack of sufficient damping torque results in oscillatory instability.

When a generator is connected outward to a large power system, without automatic voltage regulator, the instability is since there is no sufficient synchronizing torque. As a result instability through a non-oscillatory mode occurs. For +ve value of K_s, the synchronizing torque component oppose change in rotor angle from equilibrium point. In a similar way for +ve values of K_D the damping torque component opposes changes in the rotor speed from the steady-state operating point.

There is instability because of absence of sufficient damping torque where generator is connected radially to a bigger power system, in the existence of automatic voltage regulator. This leads to instability through an oscillatory mode. The various factors effect the damping coefficient of synchronous generator, which includes the power of machine’s interconnection to the grid, the generator design and the setting of the excitation system. The - ve damping torque affects the electromechanical oscillations to increase and finally leads to loss of synchronism. This type of instability is generally known as dynamic, small-signal or oscillatory instability to distiguish it from steady-state stability and transient stability.

There is instability because of lack of sufficient damping torque (i.e. –ve K_D) where generator is connected radially to a bigger power system, in existence of automatic voltage regulator. This leads to instability through an oscillatory mode. The various factors effect the synchronous generator’s damping coefficient, which includes the strength of machine’s interconnection to the grid, the generator design and the setting of the excitation system. The –

ve damping torque (i.e. -ve K_D) affects the electromechanical oscillations to increase and finally causes loss of synchronism. This instability is generally called as dynamic, small-signal or oscillatory instability to differentiate it from the steady state stability and transient stability.

2.6 POWER SYSTEM STABILIZER (PSS) MODEL

The PSS equation is mainly to increase the damping of generator's rotor oscillations by governing its excitation using secondary stabilizing signal(s). The stabilizer should produce a part of electrical torque which is in phase with the rotor speed variations for providing damping.

Exciter having high gain AVR causes oscillation in power system. This causes instability resulting low frequency oscillation which may grow in magnitude if persists for longer duration. This type of instability can badly affects the system security and limit power transfer. Factors contributing to instability are .

- Generator loading / tie line
- Transmission lines capability to transfer power.
- Poor power factor (i.e leading power factor causes more problem than lagging power factor).
- AVR gain

The solution for oscillatory in stability problem can be over come by providing damping for rotor oscillations in generator using PSS which acts as more economical and flexible solution. This is normally done by providing PSSs which are supplementary controllers in the excitation systems. The objective of designing PSS is to give 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. 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.

The theoretical basis for a PSS may be exemplified with the aid of the block diagram shown in Figure 2.12. This is an extension of the block diagram shown in Figure 2.8 and includes the effects of a PSS. PSS is introduced as a restraining torque; a logical signal to use for governing generator excitation is the speed variation $\Delta\omega_r$.

If the transfer function of exciter and the transfer function of generator between ΔE_{fd} and ΔT_e are gains, a straight feedback of $\Delta\omega_r$ results in a inhibiting torque component. Practically generator and exciter both shown phase characteristics and frequency dependent gain. Therefore PSS transfer function should compensate for phase lag by having using proper phase compensation.

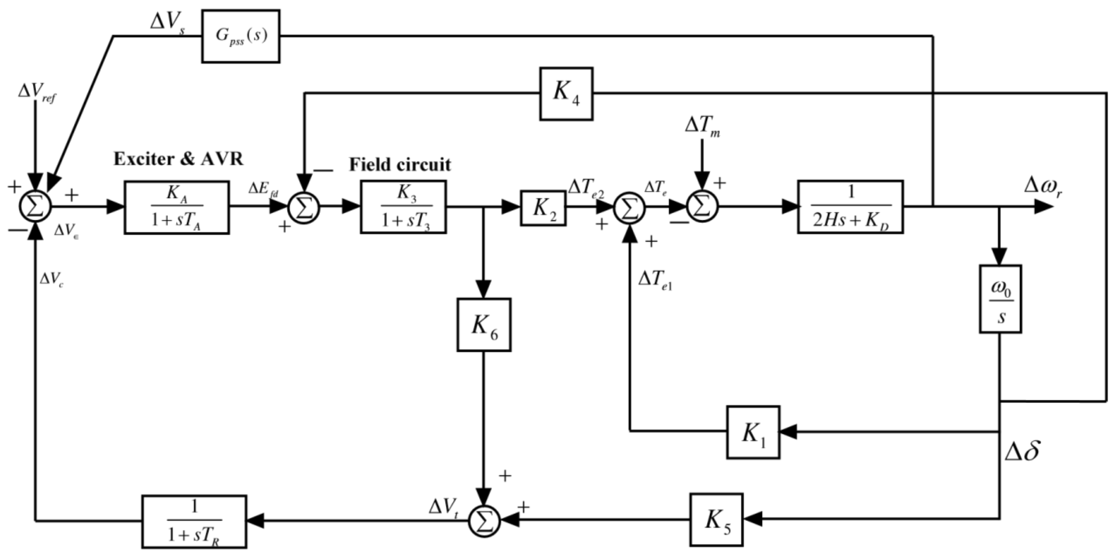

Figure 2.9: Block diagram of thyristor excitation system with AVR and PSS

input and the electrical torque. Theoretical it is consider that the phase angle of the exciter and generator to be compensated is an exact inverse with the phase of $G_{PSS}(s)$. This results in total damping torque for all oscillation frequency.

Figure 2.12 depicts the block diagram of the excitation system, includes AVR with PSS. The representation of PSS in Fig. 2.13 consists of 3 blocks: block for phase compensation, a washout block of signal, a gain block.

Practically two or more blocks of first order are used for expected phase compensation and second order block having complex roots can be also used in some cases. Figure shows a single first-order block diagram which provides desired phase lead compensation for compensating phase lag between exciter and generator's torque.

Generally, 0.1 to 2.0 Hz is a frequency range for which phase lead network must provide desired compensation. With change in system conditions the phase characteristic is compensated, hence a negotiation is made and a representative is acceptable for a other system condition is selected. Generally under compensation is

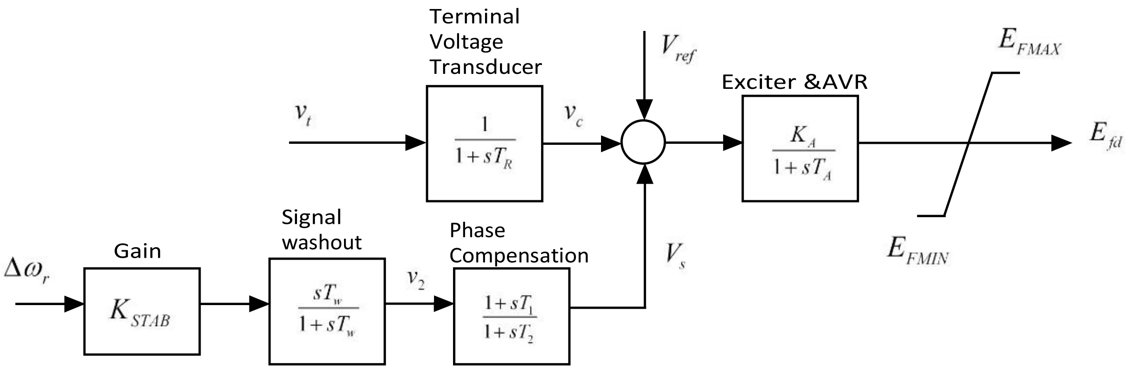

Figure 2.10: Block diagram of thyristor excitation system with AVR and PSS

required so that the PSS, in accumulation to significantly increase the damping torque, results in a slight increase of the synchronizing torque.

Figure shown signal washout block which is high pass filter having high enough time constant to permits signals in ω_r for passing without this any variation in speed would change the terminal voltage which permits. The value of T_w can be in the range of 1 to 20 second and it is not critical. A trade off can be made and it can be selected which is acceptable for different system condition.

The gain of stabilizer can be determined the magnitude of damping by using the PSS. Ideally, the gain should be set at a maximum damping to corresponding value; however it is obtained by other respects. From Figure 2.13, using perturbed values, we have

$$\Delta v_2 = \frac{pT_w}{1+pT_w}(K_{STAB}\Delta\omega_r) \tag{2.64}$$

Hence

$$p\Delta v_2 = K_{STAB}\mathrm{p}\Delta\omega_r - \frac{1}{T_w}\Delta v_2 \tag{2.65}$$

Substituting for $p\Delta\omega_r$ by equation (2.31), we obtain the expression for $p\Delta v_2$ in terms of the state variables.

$$p\Delta v_2 = K_{STAB}\left[a_{11}\Delta\omega_r + a_{12}\Delta\delta + a_{13}\Delta\Psi_{fd} + \frac{1}{2H}\Delta T_m\right] - \frac{1}{T_w}\Delta v_2$$

$$= a_{51}\Delta\omega_r + a_{52}\Delta\delta + a_{53}\Delta\Psi_{fd} + a_{55}\Delta v_2 + \frac{K_{STAB}}{2H}\Delta T_m \quad (2.66)$$

where

$$a_{51} = K_{STAB} a_{11} \quad (2.67)$$

$$a_{52} = K_{STAB} a_{12} \quad (2.68)$$

$$a_{53} = K_{STAB} a_{13} \quad (2.69)$$

$$a_{55} = -\frac{1}{T_w} \quad (2.70)$$

Since $p\Delta v_2$ is not a function of Δv_c and Δv_3, $a_{54} = a_{56} = 0$

$$\Delta v_s = \Delta v_2\left(\frac{1+pT_1}{1+pT_2}\right) \quad (2.71)$$

Hence

$$p\Delta v_s = \frac{T_1}{T_2}p\Delta v_2 + \frac{1}{T_2}\Delta v_2 - \frac{1}{T_2}\Delta v_S \quad (2.72)$$

Substitution for $p\Delta v_2$, given by equation (2.66), yields

$$p\Delta v_s = a_{61}\Delta\omega_r + a_{62}\Delta\delta + a_{63}\Delta\Psi_{fd} + a_{64}\Delta v_C + a_{65}\Delta v_2 + a_{66}\Delta v_s + \frac{T_1}{T_2}\frac{K_{STAB}}{2H}\Delta T_m$$

(2.73)

where

$$a_{61} = \frac{T_1}{T_2}a_{51} \quad (2.74)$$

$$a_{62} = \frac{T_1}{T_2}a_{52} \quad (2.75)$$

$$a_{63} = \frac{T_1}{T_3} a_{53} \tag{2.76}$$

$$a_{65} = \frac{T_1}{T_2} a_{55} + \frac{1}{T_2} \tag{2.77}$$

$$a_{66} = - \frac{1}{T_2} \tag{2.78}$$

From Figure 2.12 we have

$$\Delta E_{fd} = K_A \left(\Delta V_s - \Delta V_c \right) \tag{2.79}$$

The field circuit equation, with PSS included becomes

$$p\Delta\Psi_{fd} = a_{32}\Delta\delta + a_{33}\Delta\Psi_{fd} + a_{34}\Delta v_C + a_{35}\Delta v_s \tag{2.80}$$

Where

$$\mathrm{a}_{36} = \frac{\omega_0 \mathrm{R_{fd}}}{\mathrm{L_{adu}}} \mathrm{K_A} \tag{2.81}$$

The complete state-space model, including the PSS, has the following form (with$\Delta T_m = 0$)

$$\begin{bmatrix} \Delta\omega_r \\ \Delta_\delta \\ \Delta\Psi_{fd} \\ \Delta V_c \\ \Delta V_2 \\ \Delta V_s \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 & 0 & 0 \\ a_{21} & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{32} & a_{34} & a_{35} & 0 & a_{36} \\ 0 & a_{42} & a_{43} & a_{44} & 0 & 0 \\ a_{51} & a_{52} & a_{53} & 0 & a_{55} & 0 \\ a_{61} & a_{62} & a_{63} & 0 & a_{65} & a_{66} \end{bmatrix} \begin{bmatrix} \Delta\omega_r \\ \Delta_\delta \\ \Delta\Psi_{fd} \\ \Delta V_c \\ \Delta V_2 \\ \Delta V_s \end{bmatrix} \tag{2.82}$$

The parameters of PSS must be kept for the control system to yield following.

- Without compromising a stability of additional modes, it should highest the checking of the native plant mode as well as inter-area mode fluctuations.

- Improve system transient steadiness.

- Should not negatively disturb system’s working through major system downtime which usually causes big frequency expeditions.

- It should diminish the magnitudes of excitation system glitch because of module failure.

CHAPTER 3

CONVENTIONAL POWER SYSTEM STABILIZERS

3.1 INTRODUCTION

In this section, an accepted PSS is composed on the premise of the piece outline representation of the framework presented in chapter 2. Here the outline method is performed in the frequency domain. Traditional power system stabilizers are essentially planned on the premise of a straight model for the power system. The power system is initially linearised around a particular working purpose of the system. At that point, accepting that unsettling influences are little such that the straight model stays legitimate, the CPSS is planned. Consequently, a CPSS is most helpful for saving element steadiness of the power system.

3.2 CONVENTIONAL POWER SYSTEM STABILIZER DESIGN

The fundamental job of a PSS is to augment damping to the generator rotor oscillatory motions by governing its excitation utilizing secondary stabilizing signal.. To provide damping, the stabilizer should create a portion of electrical torque in phase with the rotor speed deviation.

For straightforwardness an ordinary PSS is displayed by two identical stage, lead or lag system which is characterized to by an increase KSTAB and time constants T1, T2. Present system is associated with washout circuit of a period consistent Tw as shown in Figure 3.1.

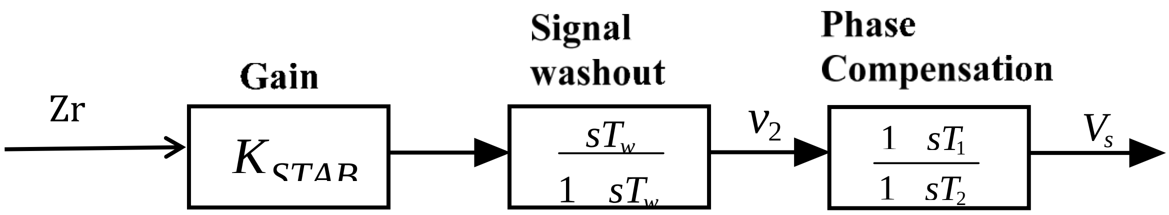

Figure 3.1: Block diagram of PSS

Figure 3.1, compensation phase block, gives the suitable phase lead features to make up for the lag in phase amongst the input of exciter and the electrical torque of generator. 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.

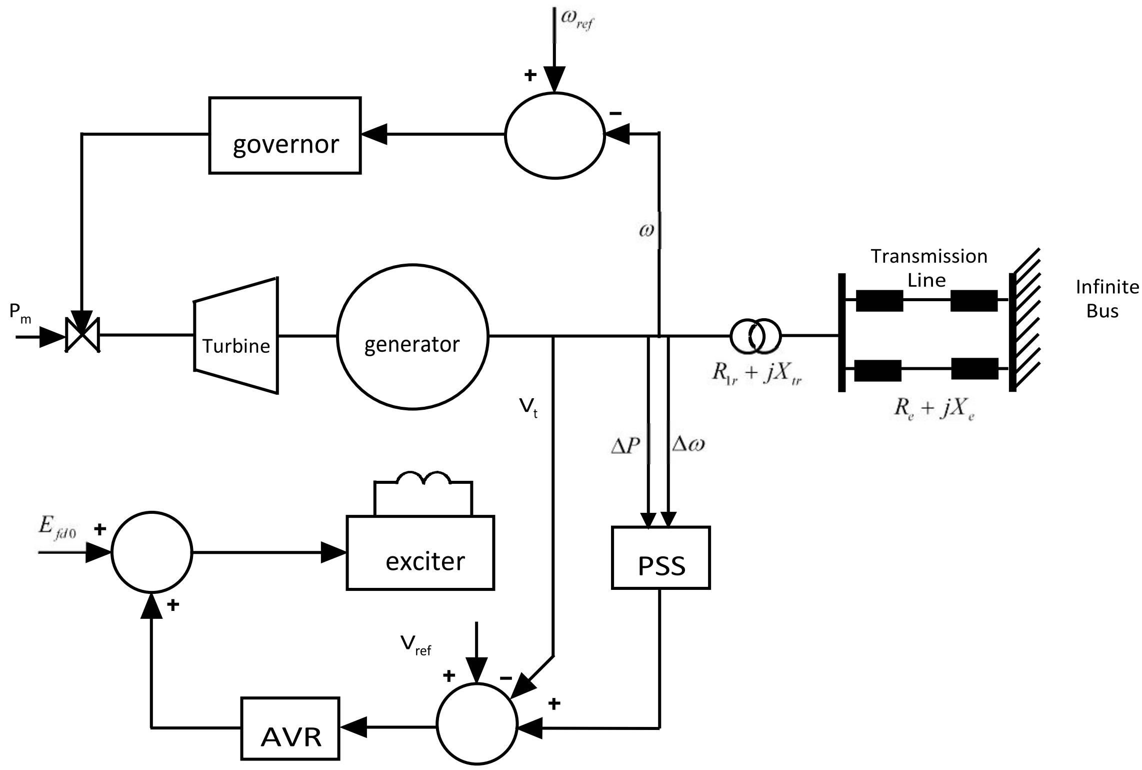

Figure 3.2: Power System Configuration

The block of signal washout square (high pass filter), with time consistent Tw sufficiently high to permit signals connected with motions in ωr to pass unchanged, which remove d.c. signals. Else terminal voltage is adjusted by steady changes in speed. It permits PSS to react just to changes in speed.

The stabilizer increase KSTAB decides the measure of damping presented by PSS. Ideally , the increase ought to be set at a value relating to most extreme damping; however, it is constrained by other thought

The block diagram of a single machine infinite bus (SMIB) system, which illustrates the position of a PSS, is given in Fig. 3.2.

The system comprises of a generating unit associated with an infinite bus through a transformer and a couple of transmission lines. The generator's terminal voltage is controlled by excitation system and automatic voltage controller (AVR).. The shaft frequency and control of mechanical power is done by a governor.

Adding a PSS to the block diagram indicated in Figure 2.8, the block diagram of the power system with PSS is acquired as shown in Figure 3.3. Since the reason for a PSS is to present a damping torque component, a logical signal.

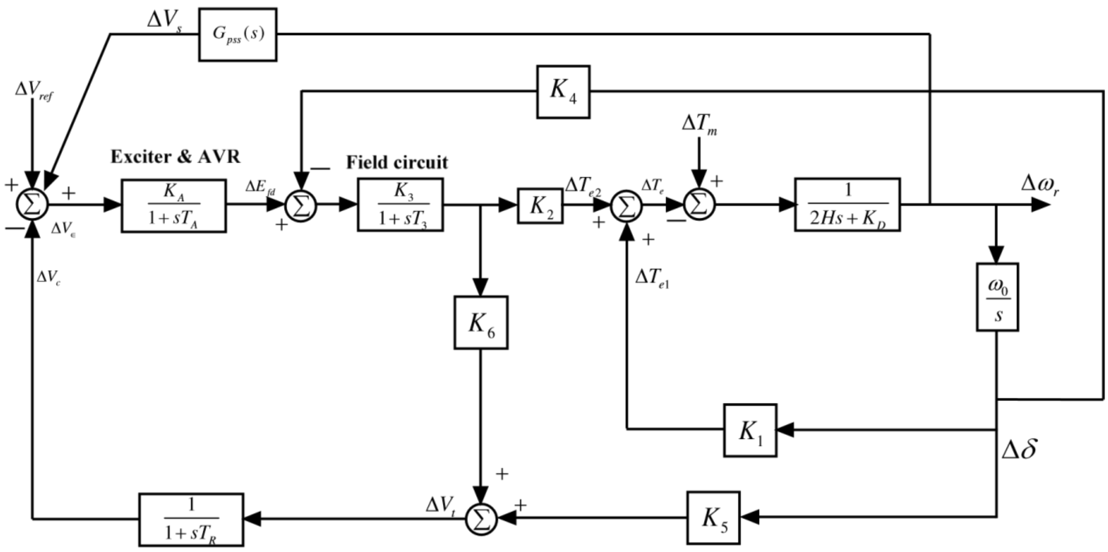

Figure 3.3: Block diagram of a linear model of a synchronous machine with a PSS purpose of a PSS

to use as the input of PSS is Δωr. For the transfer function of exciter and the generator exchange function in the Δefd and Δte increases, an immediate feedback of Δωr would bring about a damping torque part. However, both exchange function in the Δefd and Δte show exhibit frequency increase and phase characteristics. Consequently, the CPSS exchange function should have a suitable phase recompense circuit to make up for the phase delay in the exciter input and torque (Te).

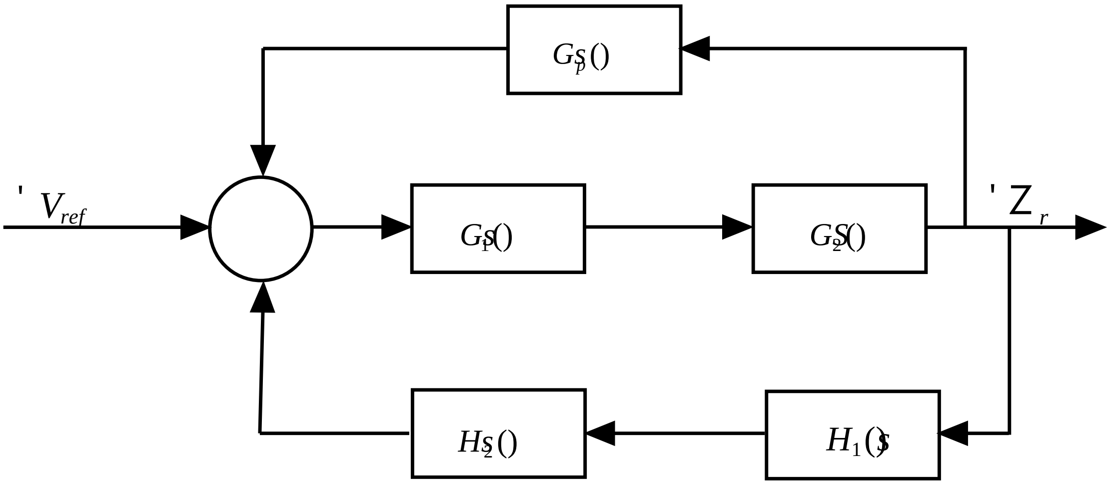

Figure 3.4: Simplified block diagram to design a CPSS

The block diagram of Figure 3.3 can be reduced to the block diagram shown in Figure 3.4, where

$$G_1(s) = \frac{K_A K_3}{T_A T_3 s^2 + (T_A T_3)s + 1} \tag{3.1}$$

$$G_2(s) = \frac{K_2 K_3 s^2 + K_2 s}{2HT_3 s^2 + (2H + K_d T_3)s^2 + (K_1 T_3 \omega_0 + K_d)s + \omega_0 (K_1 - K_2 K_3 K_4)} \tag{3.2}$$

$$H_1(s) = \frac{-2K_6 H s^2 - K_6 K_d s + \omega_0 (K_2 K_5 - K_1 K_6)}{K_2 s} \tag{3.3}$$

$$H_2(s) = \frac{1}{1 + sT_R} \tag{3.4}$$

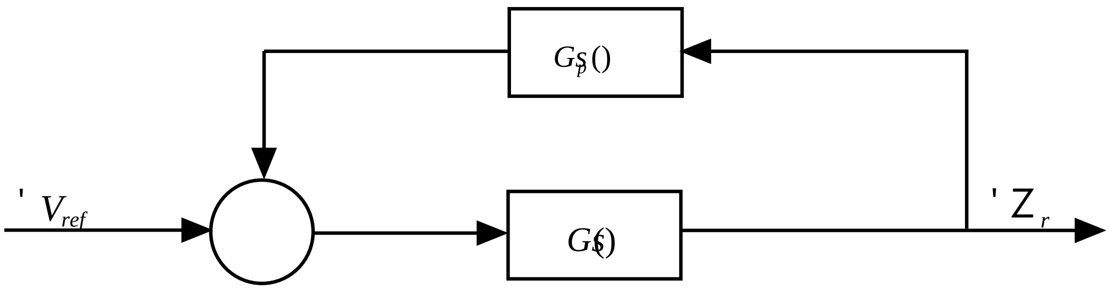

Figure 3.5: Compact block diagram to design a CPSS

The block diagram in Figure 3.4 can be simplified to the block diagram shown in Figure 3.5.

$$G(s) = \frac{G_1(s)G_2(s)}{1 + G_1(s)G_2(s)H_1(s)H_2(s)} \tag{3.5}$$

which is expanded to

$$G(s) = \frac{-K_A K_3(K_3 s + 1)}{a_6 s^6 + a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0} \tag{3.6}$$

where

$$a_6 = 2T_A T_R T_3^2 H \tag{3.7}$$

$$a_5 = T_3[2K_A T_3 H + K_A T_R(2H + K_d T_3) + 2T_R H(T_A + T_3)] \tag{3.8}$$

$$a_4 = (2H+K_d T_3)[K_A T_3+T_R(T_A+T_3)]+2T_3 H(T_A+T_3+T_R)+T_A T_3 T_R(K_1 T_3 \omega_0+K_d) \tag{3.9}$$

$$a_3 = (K_1 T_3 \omega_0 + K_d)[T_A T_3 + T_R(T_A + T_3)] + (2H + K_d T_3)(T_A + T_3 + T_R)+ 2H(T3 + KAK32K6) + TAT3TR\omega0(K1 - K2K3K4) \tag{3.10}$$

$$a_2 = (T_A + T_3 + T_R)(K_1 T_3 \omega_0 + K_d)+ \omega_0(K_1 - K_2 K_3 K_4)[T_A T_3 + T_R(T_A + T_3)] + K_6(2H + K_A K_d K_3^2) + 2H + K_d T_3 \tag{3.11}$$

$$a1 = \omega0(K1-K2K3K4)(TA+T3+TR)+KAK32\omega0(K1K6-K5)+Kd(K6+1)+K1T3\omega0 \tag{3.12}$$

$a_0 = \omega_0[K_1(K_6 + 1) - K_2(K_5 + K_3K_4)]$ (3.13)

The CPSS is designed for the normal operating point, i.e., P_0 = 0.8 pu, with a lagging power factor of 0.8 and E_B = 1.0 pu, where P_0 is the generated active power and E_B is the infinite bus voltage. Here the frequency response method is used to design the CPSS. Bode plot of the plant without PSS (G(s)) for this operating condition is shown in Figure 3.6.

As shown in the Figure 3.6, a response occurs at ω_r= 10 rad/sec. That's why if there is a step change in V_{ref}, the rotor speed will oscillate around the synchronous speed. So a PSS is required to damp the oscillations.

The CPSS is constructed of two lead stages cascaded with a wash-out term, with the following transfer function:

$$G_p(s) = K_{STAB}\frac{sT_w}{1+sT_w}\left(\frac{1+sT_1}{1+sT_2}\right) \tag{3.14}$$

Frequency response of G(jw)

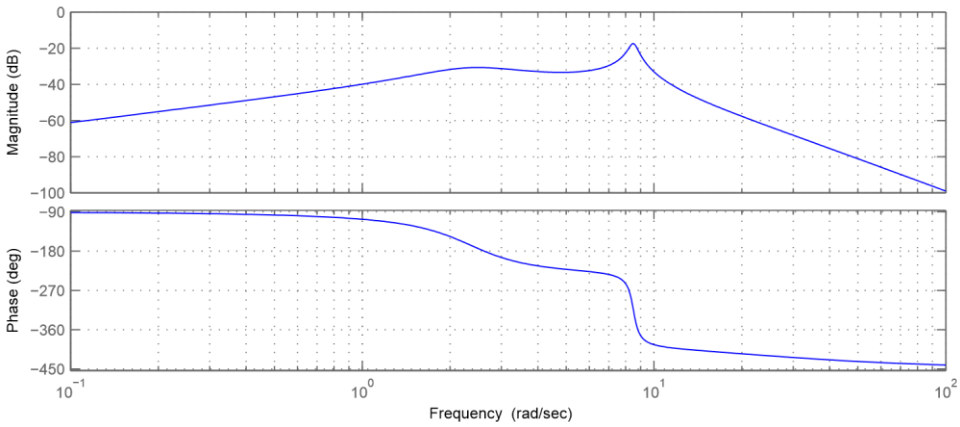

Figure 3.6: Frequency response of the plant without PSS

The first term in equation (3.14) is a high pass filter that is used to "wash out" the compensation effect for very low-frequency signals. It attenuates signals with angular frequency less than $1/T_\omega$ rad/sec. The use of this term eliminates permanent offset in the terminal voltage due to sustained error in the power system frequency, such as might occur in overloading or islanding cases. The second term is a lead compensation pair that is used to compensate for the phase lag through the system.

The CPSS is a compensator in the feedback path of the system. For the case of cascade (series) compensation the effect of the controller on the closed-loop transfer function is directly determined. However, the effect of the feedback compensator on the closed-loop transfer function of the system is not easily determined. Therefore, techniques for developing feedback compensators are different and usually more involved than those for developing cascade compensators.

The overall transfer function of the system with the PSS is:

$$G_1(j\omega) = \frac{G(j\omega)}{1 - G(j\omega)G_p(j\omega)} \tag{3.15}$$

The overall transfer function can be approximated by

$$G_1(j\omega) \approx G(j\omega) \;\; for \left(\left|G(j\omega)G_p(j\omega)\right| \ll 1\right) \tag{3.16}$$

and

$$G_1(j\omega) \approx \frac{1}{G_p(j\omega)} \;\; for \left(\left|G(j\omega)G_p(j\omega)\right| \gg 1\right) \tag{3.17}$$

The condition when $|G(j\omega)G_p(j\omega)| \approx 1$ is still undefined, in which case neither equation (3.16) nor equation (3.17) is applicable. In the design procedure, this condition is neglected. The aforementioned approximations allow investigation of the qualitative results to be obtained. After the design of $G_p(s)$ is completed, the closed-loop frequency response of the whole system will be obtained and the designer will make sure that the stabilizer performance is satisfactory in the frequency design of interest.

Thus, $G_p(s)$ should be designed such that:

- $\left|G(j\omega)G_p(j\omega) \gg 1\right|$ in the vicinity of the resonance region of the system. This means that the overall transfer function of the system will be approximately equal to $-\frac{1}{G_p(j\omega)}$ in the resonance region of the system. Therefore, gain and phase responses of $-\frac{1}{G_p(j\omega)}$ should be desirable in that region.

- $\left|\frac{1}{G_p(j\omega)}\right|$ is considerably less than $|G(j\omega)|$ in that region.

- Phase of $G(j\omega)G_p(j\omega)$ is approximately equal to -180 degrees in that region. This means that the output of $G_p(s)$ will have an opposite phase with respect to the input to $G(s)$ causing a negative feedback (notice positive signs of the comparator inputs in Figure 3.4). For this to happen, $G_p(s)$ must be a lead compensator.

Taking the above situations into consideration, the CPSS is designed. The designed values are K_{STAB}= 20, T_w=1.4 sec, T_1=0.154 sec, T_2=0.033 sec. Figure 3.7 shows the frequency response of the CPSS.

Figure 3.8 shows the log magnitude of $\frac{1}{G_p(j\omega)}$ placed over log magnitude of $G(j\omega)$.

Frequency response of the CPSS

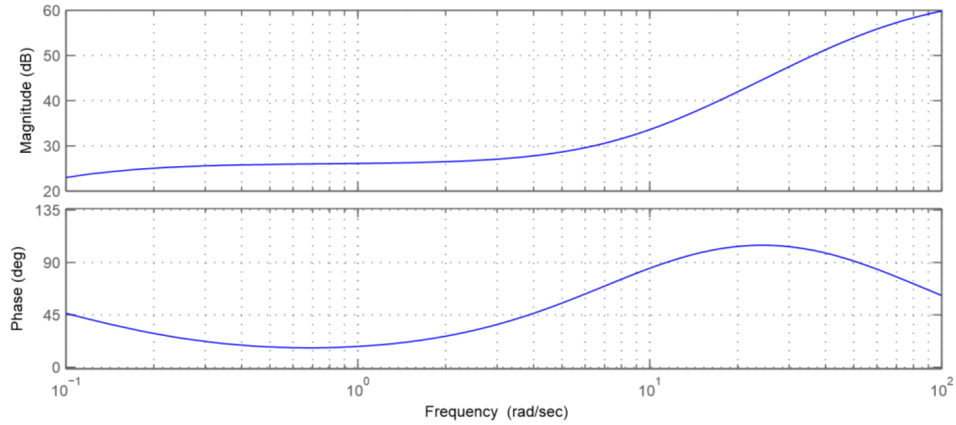

Figure 3.7: Frequency response of the CPSS ($G_p(j\omega)$)

Frequency response of G(jw) and l/Gp(jw)

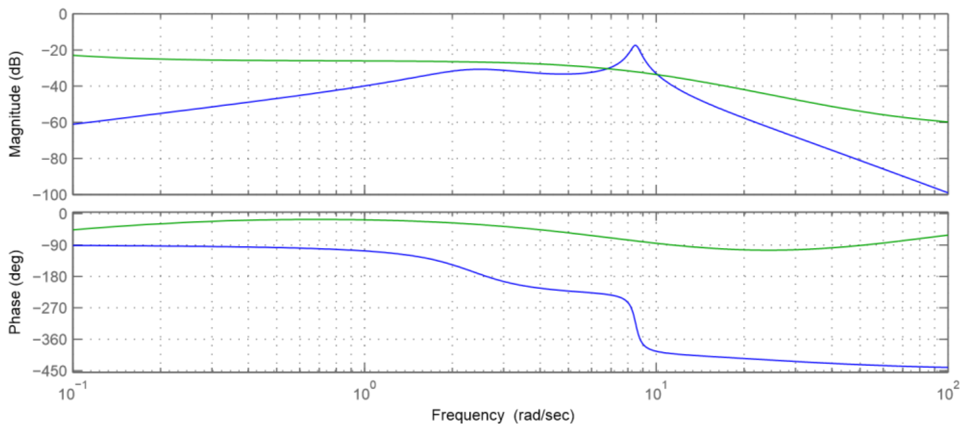

Figure 3.8: Frequency response of log magnitude of $G(j\omega)$ and $^{1}/_{G_p(j\omega)}$

By applying the designed $G_p(s)$ to the system, the closed loop frequency response will be obtained as Figure 3.9.

From Figure 3.9 it shows that the sharp resonance which was observed in Figure 3.6 is made smooth with a smaller magnitude and it occurs at a smaller frequency.

3.3 CONCLUSION

The Conventional PSS damps the low frequency oscillations in the shaft speed of a synchronous machine. Since the design is on the basis of a block diagram of the system derived for a specific op-

Closed loop frequency response

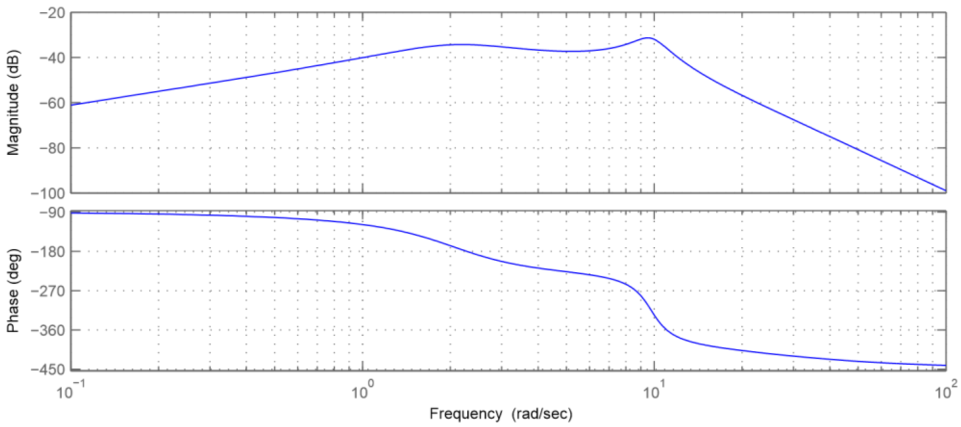

Figure 3.9: Closed loop frequency response of the system with CPSS

erating point, the CPSS has the best response for this operating point. If the operating point of the system changes, the performance of the CPSS will degrade.

CHAPTER 4

DESIGN OF FUZZY LOGIC BASED PSS

4.1 INTRODUCTION

In 1965, L.A. Zadeh observed that traditional computer represented the argument distinguishing fuzzy computers to determine whether to permit do not manipulate data created.

FLCs are very useful when there is not a precise mathematical model of the plant. However, experienced human operators control the qualitative rules of the system. Fuzzy logic, fuzzy logic control based on logic, which traditionally compare human logic systems and natural language is very close in spirit. From this perspective, fuzzy logic controller requires (FLC) dual fuzzy implications related to linguistic control concepts and a set of rules by the compositional rule. In short, the FLC is an algorithm in which linguistic control strategy based on expert knowledge can change an automatic control strategy. FLC method appears to be very useful when analysed by quantitative techniques to traditional processes which are complex.

It derived from the classical Boolean logic fuzzy logic and soft means true linguistic variable values between traditional binary values applied to a continuous range of [0,1]. It is often traditional set theory that can be considered a subset. Fuzzy logic is able to handle the estimated systematic information and therefore cannot control nonlinear systems and complex systems in an inexact model. The importance of fuzzy logic is the fact that human reasoning and in particular are the most common sense reasoning derives from nature almost in running mode. In doing so, fuzzy logic approach designers efficiently very complex closed-loop control allows to handle problems. There are many artificial intelligence techniques that has been employed in modern power systems fuzzy logic, but challenging to solve problems has emerged as powerful tool. As compared to the conventional PSS, the Fuzzy Logic Controller (FLC) has some advantages such as:

- A simpler and faster methodology.
- Elimination of mathematical model.
- Handling nonlinearity of complex system.
- Based on linguistics with IF-THEN rules, the basis of human logic.
- More robust than conventional nonlinear controllers.

4.2 FUZZY SETS

As the name implies, fuzzy sets have a crisp a set without limits. "a set to a set" related to "not related to" the gradual change from the smooth transition by Fuzzy set theory, where, there is a particular object can be anywhere in the range from 0 to 1 degree a given set membership, is based on fuzzy logic. On the other hand, classical set theory is where a particular object, Boolean logic is based on a set of variables given (argument 1) or is not a member, or (logic 0).

4.3 MEMBERSHIP FUNCTIONS

A membership function is a curve between -1 and 1 that defines how the value of a fuzzy variable in a certain area a subscription value μ (or degree) are mapped. The MF 0 and 1 (inclusive) between a subscription for maps each element of x. Of course, the definition of a fuzzy set is a classic (crisp) is a simple extension of the definition which is set to any value between 0 and 1 to be the characteristic function is allowed. 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 have also set up simple sets, crisp, non-fuzzy sets, or simply as a set of classic will set. Generally, to the x-universe of discourse, or simply referred to as Cosmos, and discrete (ordered or non-ordered) may consist of objects, or it can be a continuous space. When is a universe of discourse X continuous space, behavior, we usually have many fuzzy set whose mutual funds in a more or less uniform manner covered partitions. These fuzzy sets, which typically use such adjectives in our daily language, such as "large," "medium," or "little", taking the name appearing in the corresponding language or linguistic labels are called. 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. If X is a normal x is the collection of objects marked with x in a fuzzy set is a set of ordered pairs is defined as.

$$A = \left\{ \frac{x\mu_{A(x)}}{x_{\in}X} \right\} \tag{4.1}$$

where $\mu_A(x)$ is called the membership function of set A. There exist different shapes of membership functions. The shapes could be triangular, trapezoidal, curved or their variations.

4.3.1 Triangular MF

The triangular membership function is specified by three parameters {a,b,c} as follows:

$$f(x;a,b,c) = \begin{cases} 0, & x \leq a \\ \dfrac{x-a}{b-a}, & a \leq x \leq b \\ \dfrac{c-x}{c-b}, & b \leq x \leq c \\ 0, & c \leq x \end{cases} \tag{4.2}$$

The parameters a and c locate the feet of the triangle and the parameter b locate the peak.

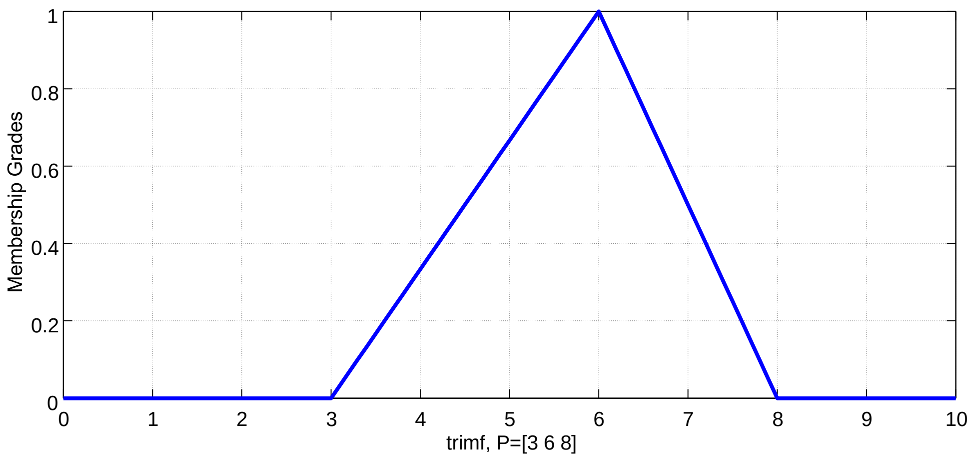

Figure 4.1: Triangular Membership Function

For example the triangular membership function trimf (x; 3, 6, 8) can be illustrated as shown in Figure 4.1.

4.4 FUZZY SYSTEMS

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

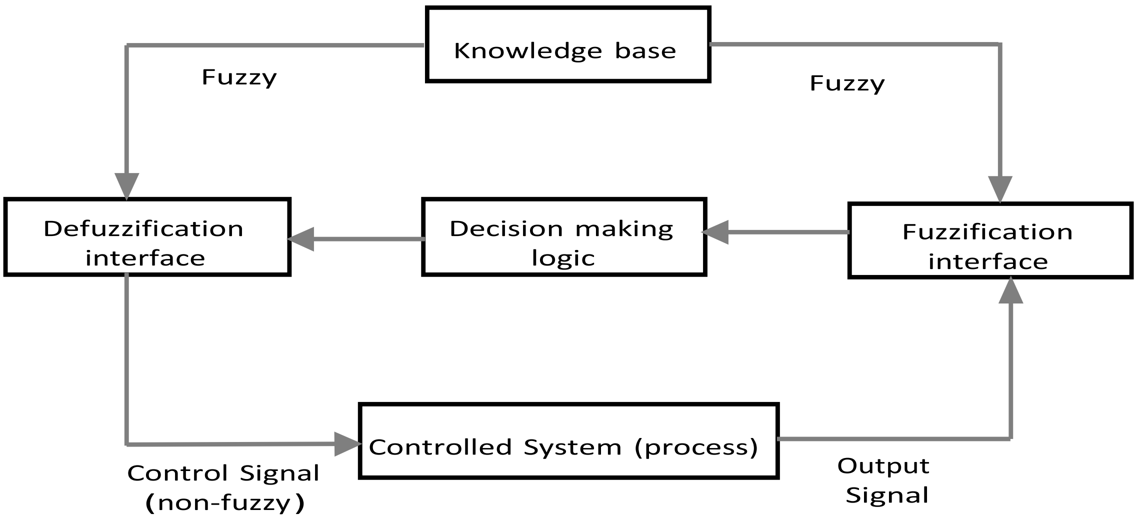

Figure 4.2: Block diagram of Fuzzy logic controller

Fuzzy inference system is basically a given input an output as shown in Figure 4.6 FL set using set consists of a mapping from the building. The mapping process which can be made with the findings or conclusions based offers. A fuzzy inference system infrastructure consists of three conceptual components: a rules basis, which means assortment of fuzzy rules; a database, which perform the function of defining membership functions. Fuzzy logic controller 4 principle components include: decision making logic interface, knowledge base, fuzzification and defuzzification interface.

- Fuzzification: by converting the input data into suitable linguistic values, the values of input variables are measured in fuzzification.

- Knowledge base: it’s a database and linguistic control rule bas. The linguistic control rules and required the database definitions, fuzzy set data manipulation in a FLC are used to define the offers. The rule-based linguistic control rules through a set of control policy are characterized by domain experts.
- Decision making logic: Decision making based on fuzzy concepts stimulating human reasoning is the ability to make decisions.
- Defuzzification: the function of defuzzification is to perform scale mapping. It changes the output variables range in their respective universe of discourse. If the result from a process acts as a control action for a process from the defuzzifier, then the system can be called to have a non-fuzzy logic decision system. Many other methods such as centroid defuzzification method, maximum height, the centroid method.

Inference procedure consists of five steps:

1. Input variables fuzzification
2. Applying fuzzy operators in IF part of the rule.
3. Implication to the consequent THEN part of the rule.
4. Aggregation of the consequents across the rule.
5. Defuzzification

4.5 DESIGN OF FUZZY LOGIC BASED PSS

The basic structure of the fuzzy logic controller is shown in Figure 4.3 . 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 $'K_0'$ to give the appropriate control signal $^0U^0$. The output gain is also taken as a constant for this fuzzy logic controller.

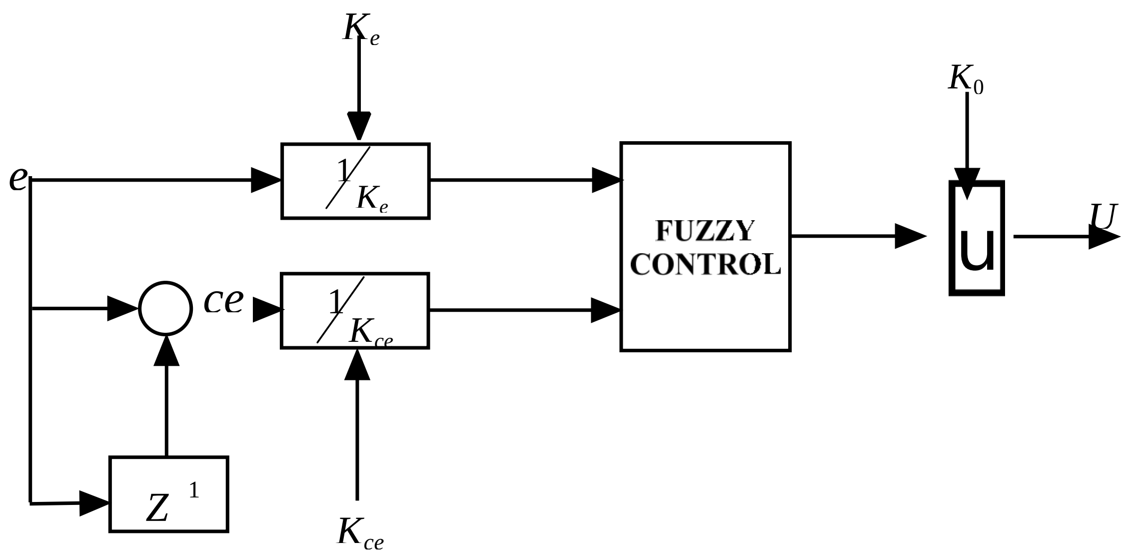

Figure 4.3: Basic Structure of Fuzzy Logic Controller

In power system stability, the fuzzy controller is used generally as a two input and one output component. This is known as MISO system. Angular speed and rate of change of angular speed are change in two input whereas the voltage signal is the output of fuzzy logic contorller.

4.5.1 Input/output Variables

The FLC consist of generator speed deviation and the second is acceleration. The output variable to the FLC is the voltage.

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.

Appropriate variable input and output as select fuzzy controller, it is necessary to decide on the linguistic variables. These variable fuzzy fuzzy controller input numeric values to conversion amount. A description of the linguistic fuzzy subset of variables variable changes according to the number of applications. Here's seven each for the input linguistic variables and output variables they are using to describe. Table 4.1 shows the Membership functions of fuzzy variables.

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

Table 4.1: Membership functions of fuzzy variables

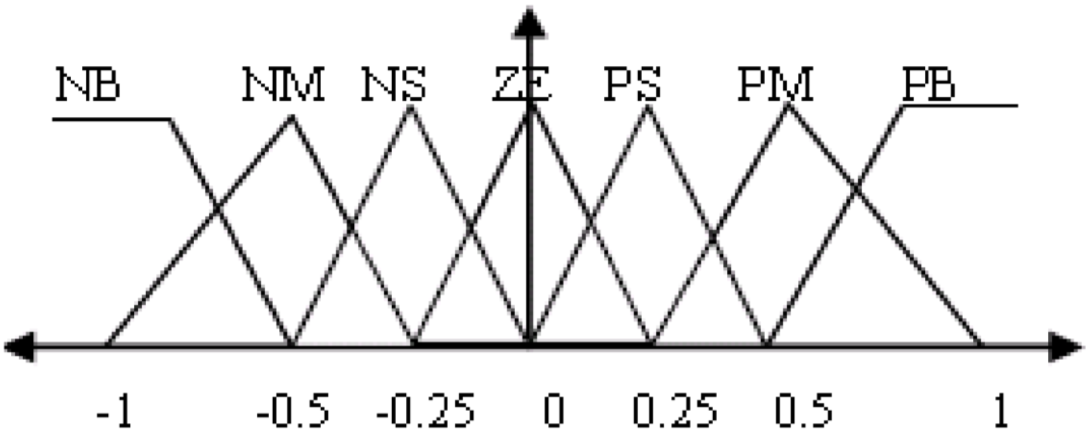

Figure 4.4: Membership function for speed deviation

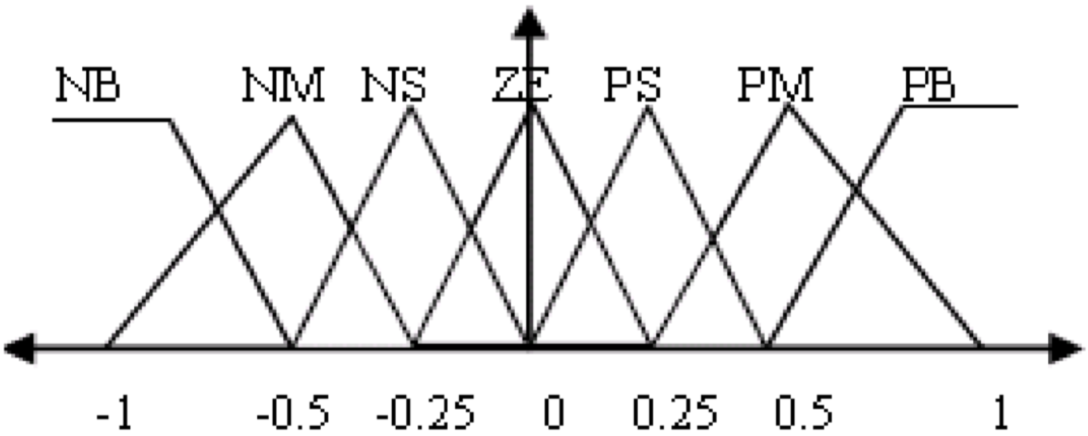

Figure 4.5: Membership function for acceleration

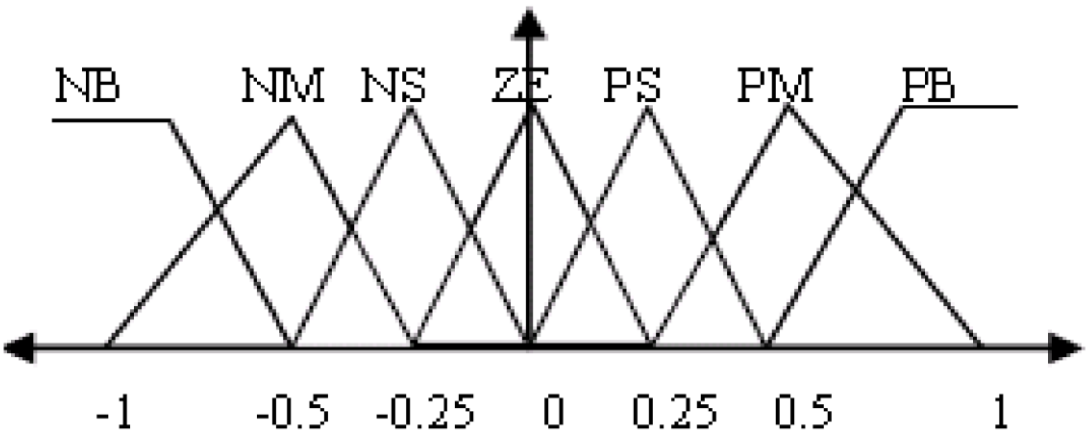

Figure 4.6: Membership function for voltage

acceleration / Speed deviation	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NS	ZE	ZE	PS
NM	NB	NB	NM	NS	ZE	PS	PM
NS	NB	NB	NM	ZE	PS	PM	PB
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NB	NM	NS	ZE	PM	PB	PB
PM	NM	NS	ZE	PS	PM	PB	PB
PB	NS	ZE	ZE	PS	PB	PB	PB

Table 4.2 Decision Table

The normalisation is done by multiplying with gain K_e, K_{ce}, K_0 resp so that their values lie between -1 and +1. The membership function for speed deviation, acceleration and voltage are shown in Figures 4.4 to 4.6..

Includes the knowledge base defined as IF the rules-in terms of the membership functions represented input and output variables governing the relationship between statements rules. 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 4.2.

Each entity shown in Table 4.2 represents a rule. The antecedent of each rule conjuncts speed deviation (Δω) and acceleration (Δa) fuzzy set values.

Monotonic systems, a very appropriate symmetric rules table, although sometimes it's a little bit depending on the specific system of behaviour may need adjusting. If the system dynamics are not known or are highly nonlinear, trial and error process and experience played a key role in defining the rules of play.

An example of the rule is: If Δω is NS and Δa 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.

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 $\Delta\omega$ is PS with a membership degree of 0.6 and Δa is PM with a membership degree of 0.4 then the degree of firing of this rule is 0.4.

Step2: Inference Mechanism

Fuzzy implication and inference mechanism consists of two processes called aggregation. A rule firing is a subset of the degrees of governance, to provide the output fuzzy consequently interacts with. How to set formulation for DOF and consequently fuzzy to determine the interaction terms output is called a fuzzy implication.

Step3: Defuzzification

To achieve crisp value fuzzy sets obtained in the previous step is used to produce as given in Figure 4.6.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 THE CASE STUDY

In this chapter, simulation results using MATLAB / SIMULINK for both types of PSS (conventional and fuzzy based) are shown.

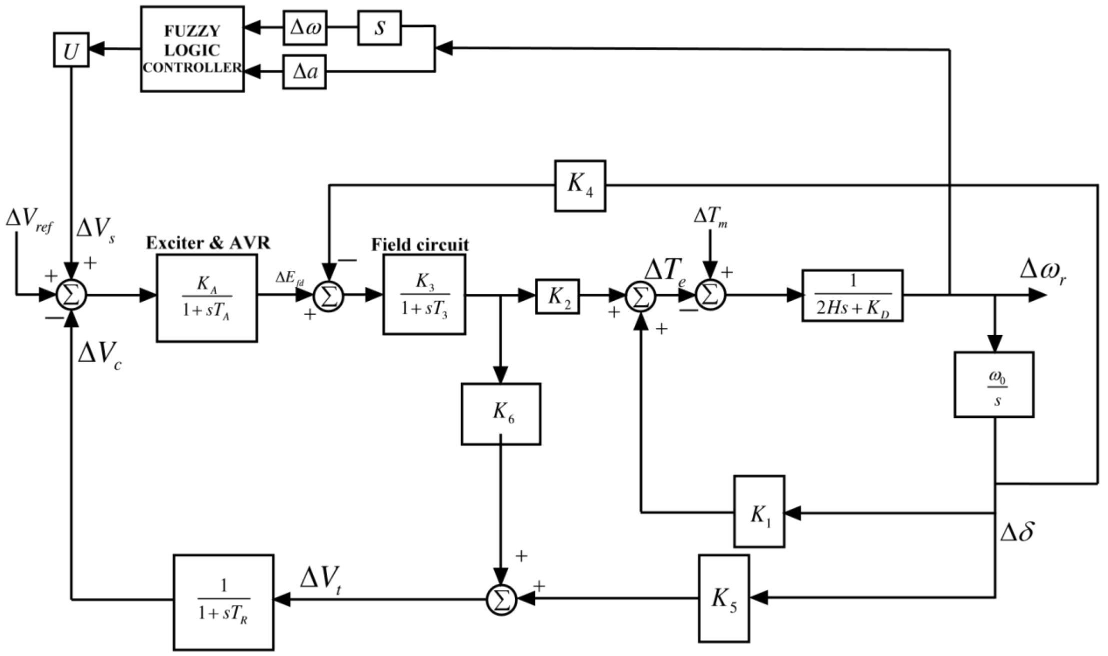

Figure 5.1: Test System for Proposed Fuzzy Logic Based PSS

The performance of the proposed model is tested on Single Machine Infinite Bus System (SMIB) as shown in Figure 5.1. Then the performance of SMIB system was examined with excitation system, without excitation system, with conventional PSS (lead-lag) and with fuzzy logic based PSS by using the K constants. The dynamic models of synchronous machine, excitation system, prime mover, governing system and conventional PSS are described in Chapter 2.

5.2 PERFORMANCE WITHOUT EXCITATION SYSTEM

In chapter 2, Figure 2.12 shows the block diagram representation with AVR and PSS. In this presentation, the dynamic characteristics of the system are expressed in terms of the so-called K - constants. The values of K - constants calculated using above parameters are:

$K_1 = 1.7299$, $K_3 = 0.1692$, $K_5 = -0.0613$,

$K_2 = 1.7325$, $K_4 = 2.8543$, $K_6 = 0.3954$

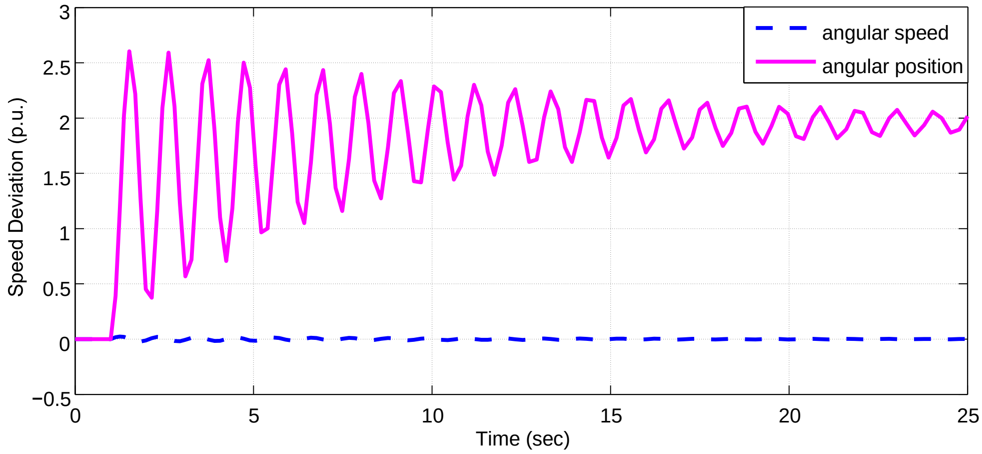

Figure 5.2: response without excitation system

Figure 5.2 shows the variation in angular speed and angular position. From the above response shown in Figure 5.2 it is observed that it takes very large time i.e. more than 25sec to get into stable state. Therefore, the performance of the system with excitation system is analyzed to find the suitability of the excitation system in removing these oscillations.

5.3 PERFORMANCE WITH EXCITATION SYSTEM

The time response of the angular speed and angular position with excitation system has shown in Figure 5.3 and Figure 5.4 for positive and negative value of K_5 constant.

From Figure 5.3 the response characteristic shows that under damped oscillations are resulted. It is seen that it has negative damping due to K_5 constant calculation which is negative; it is true for high values of high generator outputs and also for external system reactance.

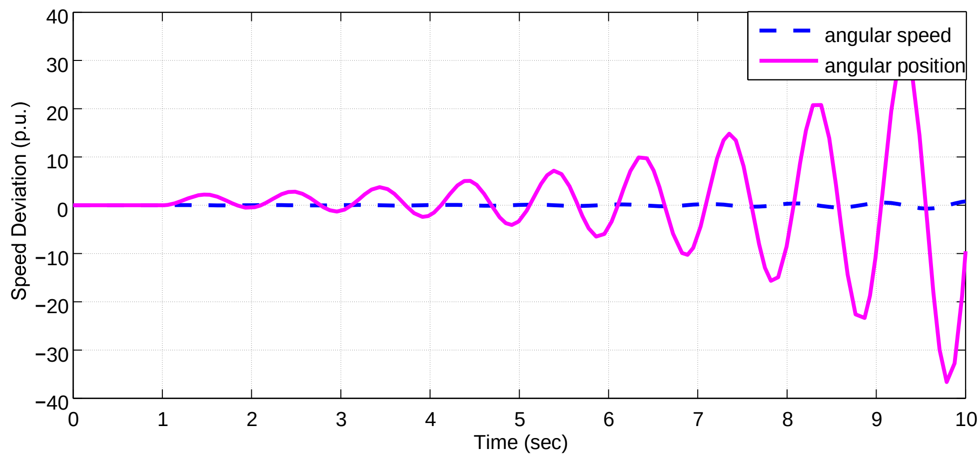

Figure 5.3: Response with excitation system for -ve K_5

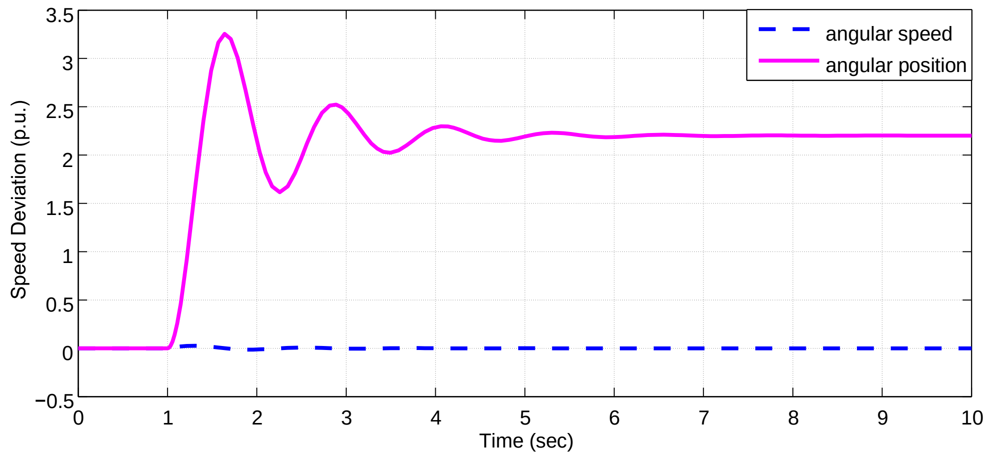

Figure 5.4: Response with excitation system for +ve K_5

The performance when analyzed with positive value of K_5, the system is stable. Positive K_5 is possible for low values of external system reactance and low generator outputs. So for positive the damping is positive and thus the system is stable.

5.4 PERFORMANCE WITH CONVENTIONAL PSS

Figure 5.5 shows the variation of angular speed and angular position when PSS (lead-lag) is applied for negative value of K_5.

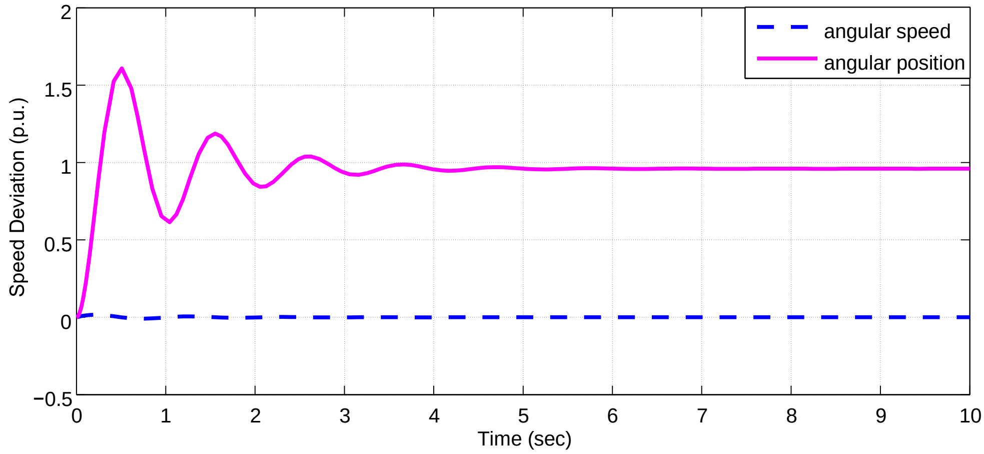

Figure 5.5: Response with CPSS for -ve K_5

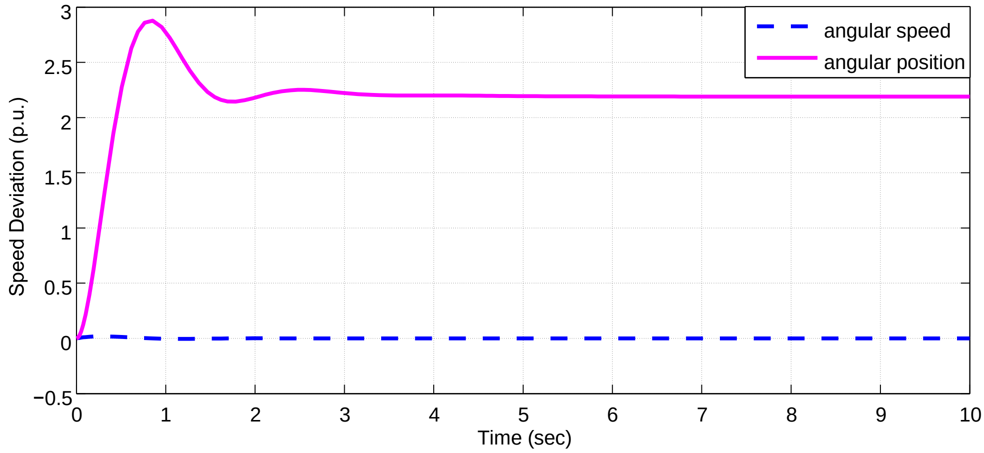

Figure 5.6: Response with CPSS for +ve K_5

From the Figure 5.5 and Figure 5.6 it shows that the system is stable for both positive and negative value of K_5 constant. The transients are more for negative K_5 whereas higher angular position is attained with positive K_5.

5.5 PERFORMANCE WITH FUZZY LOGIC BASED PSS

The model used in SIMULINK/MATLAB to analyse the effect of fuzzy logic controller in damping small signal oscillations when implemented on single machine infinite bus system is shown in Figure 5.1.

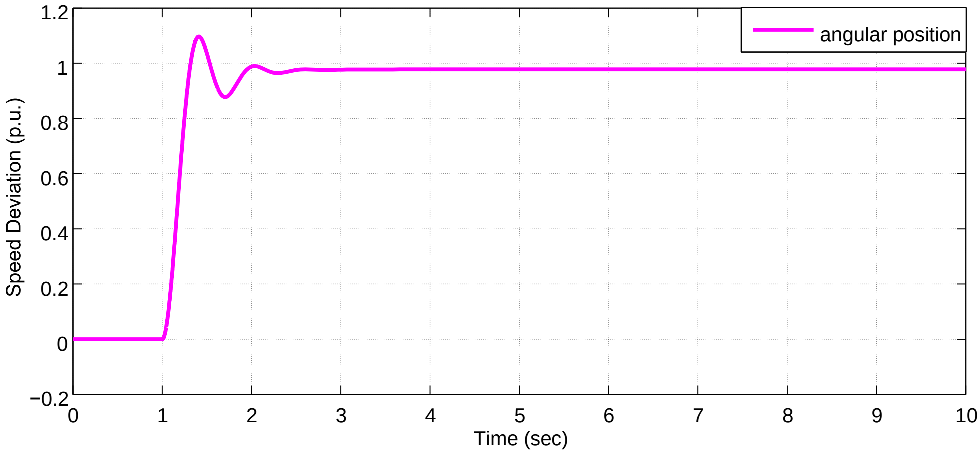

Figure 5.7: Variation of angular position with FLPSS for -ve K_5

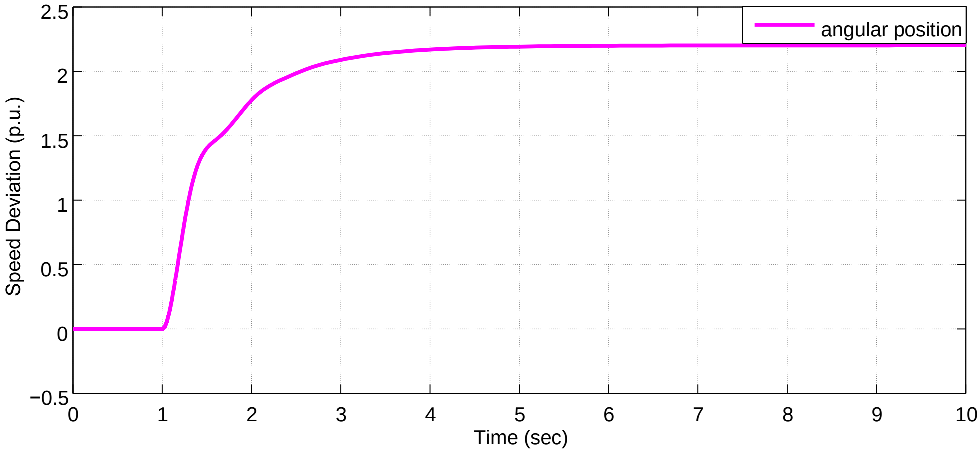

Figure 5.8: Variation of angular position with FLPSS for +ve K_5

The variation of angular position with fuzzy logic based PSS for negative and positive value of K_5 constant is shown in Figure 5.7 and Figure 5.8 respectively.

The variation of angular speed with fuzzy logic based PSS for negative and positive value of K_5 constant is shown in Figure 5.9 and Figure 5.10 respectively. Figure 5.7 and Figure 5.9 show that the angular position and angular speed stabilizes to a particular value with very few oscillations for negative value of K_5constant. For positive value of K_5 constant angular position attains higher value than conventional PSS.

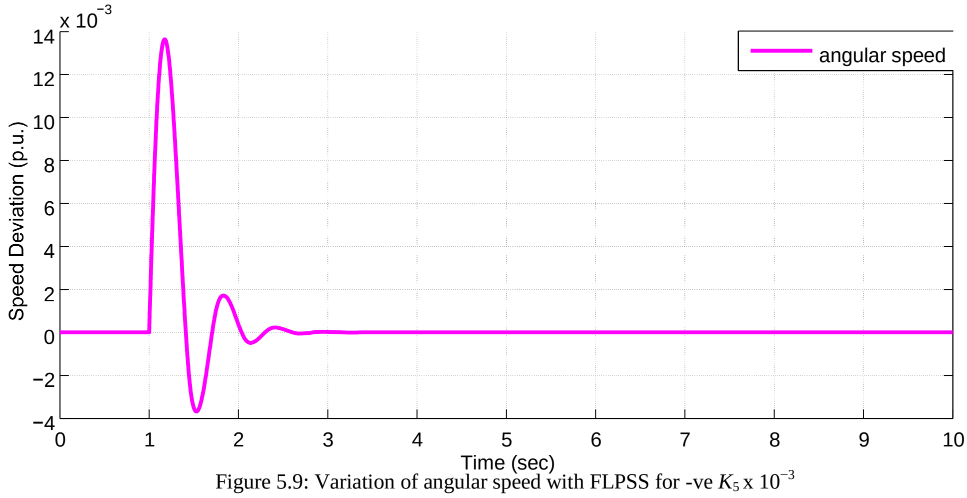

Figure 5.9: Variation of angular speed with FLPSS for -ve K_5 x 10^{-3}

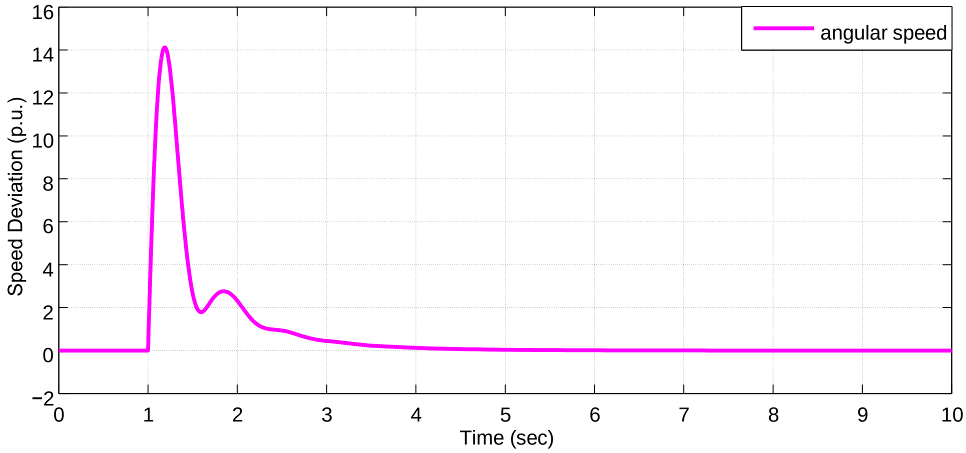

Figure 5.10: Variation of angular speed with FLPSS for +ve K_5

CHAPTER 6

CONCLUSION AND FUTURE WORK SCOPE

6.1 CONCLUSION

In this thesis work initially the effectiveness of PSS in damping oscillations is reviewed. For this a fuzzy logic controller based PSS 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. Fuzzy Logic PSS gives the better control performance than PSS with respect to settling time and damping effect. It has been observed that the performance of FLPSS is better than conventional PSS. Moreover, the selection of MF has a significant bearing on the damping of oscillations. From the simulation studies it shows that the oscillations are largely present in case of trapezoidal MF. The responses of gaussian membership functions and triangular MF are compared. It is seen that the performance of Fuzzy Logic PSS with triangular MF is better compared to other membership functions.

6.2 FUTURE WORK SCOPE

Having gone through the study of fuzzy logic based PSS for one machine infinite bus system, the scope of the work is

1. The fuzzy logic based PSS 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.
3. PSS testing can be carried out using more complex network models.

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APPENDIX

SYSTEM DATA

The Parameters of the synchronous machine, excitation system and conventional PSS are as follows.

[a] Synchronous machine constants:

- $x_d = 2.64$ pu,
- $x_d' = 0.28$ pu
- $x_q = 1.32$ pu
- $x_q' = 0.29$ pu
- $R_E = 0.004$ pu
- $X_E = 0.73$ pu
- $f = 50$ Hz
- $H = 4.5$ sec

[b] Excitation system constants:

- *KA = 100,*
- *TA = 0.05,*
- *TR = 0.015*
- *EFMAX = 5.0,*
- *EFMIN = -5.0*

[c] PSS constants:

- *KSTAB = 20,*
- *Tw = 1.4 sec*
- *T1= 0.154 sec,*
- *T2 = 0.033 sec*
- *VSMAX = 0.2,*
- *VSMIN = -0.2*