FUZZY LOGIC BASED POWER SYSTEM STABILIZER

Thesis submitted in partial fulfillment of the requirements for the award of degree of

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in
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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, **"FUZZY LOGIC BASED POWER SYSTEM STABILIZER"**, in partial fulfillment of the requirements for the award of degree of Master of Engineering in ***Power Systems & Electric Drives*** submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Dr. Sanjay K. Jain, Assistant Professor, EIED.**

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

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This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

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There are times in a project when the clock beats our time and we run out of energy, wishing to finish it once and forever. My parents made me endure such times with their unconditional support and love.

Dated: **Neeraj Gupta**
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ABSTRACT

The power system is a dynamic system and it is constantly being subjected to disturbances. It is important that these disturbances do not drive the system to unstable conditions. For this purpose, additional signals derived from speed deviation, excitation deviation and accelerating power are injected into voltage regulators. The device to provide these signals is referred as power system stabilizer

The use of power system stabilizers has become very common in operation of large electric power systems. The conventional PSS which uses lead-lag compensation, where gain settings designed for specific operating conditions, is giving poor performance under different loading conditions. Therefore, it is very difficult to design a stabilizer that could present good performance in all operating points of electric power systems. In an attempt to cover a wide range of operating conditions, Fuzzy logic control has been suggested as a possible solution to overcome this problem, thereby using linguist information and avoiding a complex system mathematical model, while giving good performance under different operating conditions.

In this thesis, a systematic approach to fuzzy logic control design is proposed. The study of fuzzy logic power system stabilizer for stability enhancement of a single machine infinite bus system is presented. In order to accomplish the stability enhancement, speed deviation and acceleration of the rotor synchronous generator are taken as the inputs to the fuzzy logic controller. These variables take significant effects on damping the generator shaft mechanical oscillations. The stabilizing signals were computed using the fuzzy membership function depending on these variables. Simulink Block Design and Matlab-7.5 is utilized in implementing the study. The performance of the system with fuzzy logic based power system stabilizer is compared with the system having conventional power system stabilizer and system without power system stabilizer.

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CHAPTER-1

INTRODUCTION

1.1 OVERVIEW

The power system is a dynamic system. 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 01 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 effects the damping torque negatively. To compensate the unwanted effect of these voltage regulators, additional signals are 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 setup to provide 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 i.e. 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). 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. PSS have been added to the excitation systems to improve the oscillatory instability it is used to provide a supplementary signal to excitation system. The basic function of 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.

A typical PSS consists of phase compensation stage, a signal washout stage and gain block. To provide damping, PSS must provide a component of electrical torque on the rotor in phase with speed deviations. PSS input signal includes generator speed, frequency and power. For any input signal, the transfer function of PSS must compensate for gain and phase characteristics of the excitation system, the generator and the power system. These collectively determine the transfer function from the stabilizer output to the component of electrical torque which can be modulated via excitation control.

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 PSS attenuates the shaft torsional modes inherently and mitigates the requirements of the filtering in main stabilizing path.

1.2 LITERATURE REVIEW

After going through the literature in limited time duration during M.E. work, the various techniques used in power system stabilizer are classical [1]-[19], fuzzy logic [20]-[61], neural network [62]-[94], genetic algorithm [95]-[109], hybrid [110]-[118], swarm intelligence [119]-[121]. The classification of methods based on literature is shown in Fig. 1.1.

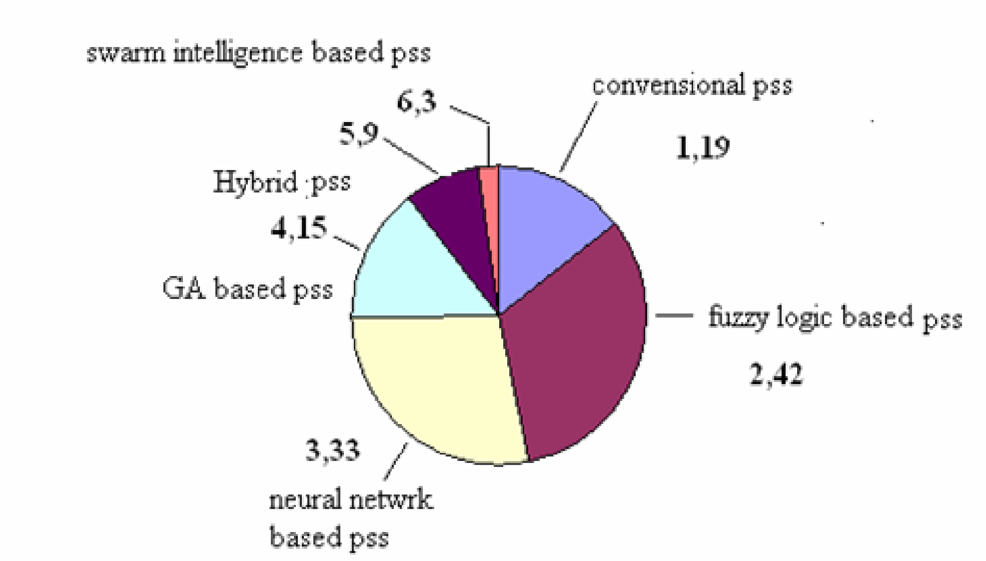

Fig. 1.1: Pie chart giving the review of different type of PSS

1.2.1 CONVENSIONAL PSS

Keay and South [19] proposed a power system stabilizer with frequency deviation as only input signal. Larsen and Swann [16]-[17] gives the overview of power system stabilizer practically from practical point of view. Chow and Sanchez-Gasca [15] proposes a power system stabilizer using pole placement techniques and this work is carried by Yu and Li [12] for a nine bus system. Hsu [11] proposes a proportional integral controller. Cai et al. [9] proposes a lapanov's approach for the design of power system stabilizer and Robak et al. [2] gives the comparison of different control structures. Radman and Smaili [8] proposes the PID based power system stabilizer and Wu and Hsu [7] proposes the self tuning PID power system stabilizer for a multi machine power system.

1.2.2 FUZZY BASED PSS

Fuzzy set theory is a mathematical concept proposed by Prof. L. A. Zadeh in 1965. Fuzzy logic is a kind of logic using graded or quantified statements rather than ones that are strictly true or false. The fuzzy sets represented by linguistic variables allow objects to have grade of membership from 0 to 1. A fuzzy set F in a universe of discourse U is characterized by a membership μ_f which takes values in the interval[0,1] and can be written as -

$$F = \left((u, \mu_F(u)) / u \in U\right)$$

The fuzzy logic controller comprises of four principle components: fuzzification, a knowledge base, decision making logic and defuzzification. In fuzzification the value of input variables are measured, scale mapping that transfers the range of values of input variables into corresponding universe of discourse is performed; it performs the function of fuzzification that converts input data into suitable linguistic values which may be viewed as label fuzzy sets. The knowledge base comprises knowledge of application domain and attendant control goals. It consists of a database and linguistic control rule base. The database provides the necessary definitions, which are used to define linguistic control rules and fuzzy data manipulation in an FLC. The rule base characterizes the control goals and control policy of domain experts by means of set of linguistic control rules. The decision making logic has the capability of simulating human decision making based on fuzzy concepts. The defuzzification performs scale mapping, which converts the range of values of output variables into corresponding universe of discourse, it yields a non-fuzzy control action from an inferred control action. The different methods of defuzzification are max criterion method, mean of maxima method and centriod method.

Metwally and Malik [54] describes a paper on fuzzy logic power system stabilizer using speed and power output variations as the controller input variables. Hiyama [37] obtained the required information i.e acceleration, speed deviation and phase deviation of generator from measured real power signal. Pasand and Malik [49] discussed fuzzy logic based PSS implement on an intel single board computer iSBC386/21. Majid et al. [30] presented a fuzzy logic controller in which speed deviation and acceleration of rotor synchronous generator were taken as input. Juan et al. [58] compares the fuzzy logic based and rule base power system stabilizer. Gupta et al. [22] proposed a robust PSS based on fuzzy logic. In this speed deviation and acceleration of the rotor of synchronous generator of multi machine power system taken as input to fuzzy logic controller, results a obtained using different defuzzification methods. Moodley et al. [46] investigates the effect of FLPSS in a multimachine environment. Ferreira et al. [39] proposed a fuzzy logic PSS including a fuzzy PI controller to improve steady state behaviour of a system. The PI controller as proposed uses only speed deviation as input and uses triangular membership functions with only small number of rules. Lim [52] proposed a new fuzzy logic control scheme using one input signal which is the linear combination of three signals, i.e. signal, its derivative and its integral. Hosseinzadeh and Kalam[60] proposed a fuzzy logic based adaptive PSS in which Lyapunov's direct method is proposed to make the fuzzy logic controller adaptive to changes in operating conditions of power systems. Park and Lee [45] proposed a self organizing power system stabilizer which doesn't use any reconstructed rule base of an expert or any plant model, with the input-output history. The rules are generated automatically and rule base updated online by self organizing procedure Lu et al. [61] proposed a fuzzy logic base adaptive power system stabilizer. The proposed stabilizer consists of a conventional lead-lag stabilizer and fuzzy logic based parameter tuner which adjusts the parameters of conventional stabilizer according to real time operating information and knowledge from the rule base prepared offline. Taliyat et al. [50] proposed an augmented fuzzy PSS in which the speed deviation and acceleration were taken as input to fuzzy logic controller in which an auxiliary stabilizing signal which is a function of accelerating power into the terminal voltage feedback loop is utilized, which is a difference between mechanical and electrical power. Lin [24] proposed a fuzzy logic power system stabilizer which could shorten the tuning process of fuzzy rules and membership functions. The proposed PSS has two stages, first stage develops a proportional derivative type PSS, in the second stage it is transformed into FLPSS. Matsuki et al. [56] described the process of determination of optimal fuzzy control parameters by trial and error. This paper does not concern with improvement of scheme but problems encountered with the practical settings when fuzzy logic controller is introduced. Bandal et al. [23] proposed a PSS based on fuzzy logic and output feedback sliding mode control which is a variable structure control that is designate to drive and constrain the system to lie within the neighborhood of switching function. Chung et al. [38] proposed the fuzzy PID controller in which three PID parameters of the controller are accurately tuned under a given active and reactive power conditions. Hussein et al. [20] proposed self tuning power system stabilizer in which two tuning parameters are introduced to tune fuzzy logic PSS, these parameters are the output of another fuzzy logic system which gets its input from operating condition of power system. Abdelazim and Malik [27] proposed a self learning fuzzy logic power system stabilizer in which for the continuous tracking of system, recursive least squares parameter identification method is used and a forgetting factor is used to discount the importance of older data.

1.2.3 NEURAL NETWORK BASED PSS

An artificial neural network (ANN) is an information processing paradigm that is inspired by the way biological nervous system, such as brain, process information. It is composed of a large no of highly interconnected processing elements working in unison to solve specific problems ANN like people learn by example. ANN is configured for specific application, such as pattern reorganization or data classification through learning process. Learning involves the adjustment to synaptic connections that exist between neurons. Neural networks with their remarkable ability to derive meaning from complicated or imprecise data, can be used to extract patterns and detect trends that are too complex to be noticed by either human or computer techniques.

The neural network based PSS is discussed by various researchers [62]-[94]. Bulic et al. [62] proposed the control of excitation system using neural network, Liu et al. [63] gives the comparison of adaptive neural network based controller and convensional power system stabilizer. Chaturvedi and Malik [66]-[69] proposes a generalized neuron based adaptive PSS. Chusanapiputt et al. [71] proposed a method to tune the parameters of PSS using neural network. Hu Zhijian et al. [72] proposed a PSS using neural network inverse system. Chusanapiputt et al. [75] proposed a hybrid RBF neural network adaptive PSS using tabu search algorithm. Zhang and Malik [78] conducted experimental studies based on neural network based PSS. Shijie cheng et al. [80] proposed the PSS based on neural network by using online learning. Shamsollahi and Malik [84] proposed an adaptive PSS in which neural networks are tuned online. Park et al. [83] proposed a neural network based PSS using power flow characteristics.

1.2.4 GENETIC BASED PSS

The genetic algorithm mimics the principle of natural genetics and selection to construct search and optimization procedures. The idea of evolutionary algorithm was introduced in 1960 by I. Rechenberg. Genetic algorithm are good at taking larger, potentially huge, search spaces and navigating them looking for optimal combination of things and solutions which we might not find in life time. Genetic algorithms need design space to be converted into genetic spaces, therefore it work with coding of variables. The advantage of working with coding of variable space is that coding discretizes the search space even though the function is continuous. It uses randomized operators which improve search space in an adaptive manner.

Abdel-Magid et al.[109] proposed a method for the stabilization of power systems using GA. Hasanovic and Feliachi [108] proposed a GA based controller design using MATLAB. Rashidi [106] proposed the method for tunning PSS using GA for stabilization of power systems. Huang et al. [105] proposed a sliding mode PSS using GA. Folly [102] proposed a multi machine PSS design based on GA. Karim [100] describes optimal location and tuning of PSS using GA. Dubey and Dubey [98] proposed GA based PSS for multi-machine system.

1.2.5 HYBRID PSS

Hybrid systems are those for which more than one technology is employed to solve the problem. Combining the above, neuro-fuzzy, neuro-genetic and fuzzy genetic hybrid systems are possible.

There are two ways of looking at neuro-fuzzy hybridization. One is to endow neural networks with fuzzy capabilities thereby increasing the networks expressiveness and flexibility to adapt to uncertain environments. The second aspect is to apply neural learning capabilities to fuzzy systems to make the fuzzy systems more adaptive to changing environments.

Neuro-genetic Hybrid combined GA-NN also known as GANN have the ability to ability to locate the neighborhood of optimal solution quicker than other search strategies But once in neighbour hood of an optimal solution GANN statergies tends to converge slower than conventional ones. Drawback is that a large amount of memory is required to handle and manipulate chromosomes for a given network

Fuzzy systems have been integrated with GA's called fuzzy-genetic Hybrid. The adjustment of system parameters that is called for in the process, so that system output matches the training data, has been tackled using GA. Parsa and Toyoda[118] gives the overview about the implementation of hybrid PSS. Sharaf and Lie [117] proposed a hybrid neuro-fuzzy PSS whearas Abido and Magid [116] proposed the same for a multimachine system. You et al.[115] proposed the neuro-fuzzy PSS with self organizing map. Venugopal et al. [113] proposed an adaptive hybrid PSS based on neuro-fuzzy.

The swarm intelligence is based on the collective behaviour of decentralized, self organized systems. Particle swarm optimization is a population based stochastic optimization technique inspired by social behavior of bird flocking or fish schooling. Abido [121] gives the optimal design of PSS using particle swarm optimization, which is taken forward by Abido [120] and Mukherjee and Ghoshal [119].

1.3 OBJECTIVE OF THE WORK

In this work a novel power system stabilizer for damping oscillations based on fuzzy logic theory is developed as the controller settings to be inadvertently changed due to nonlinear changes in generators and in transmission-lines operating conditions and the models based on original manufacturer information may not be accurate after few years. The simulation of the power system stabilizer based on fuzzy logic is carried out and its performance is compared using conventional (lead-lag) controller for a single machine infinite bus system when the system is subjected to disturbance.

1.4 ORGANIZATION OF THE THESIS

The thesis is organized into five Chapters. The first chapter describes the PSS, literature review; identify the objective and organization of thesis. The synchronous machine modeling, excitation system modeling and PSS modeling for controller simulation is summarized in Chapter 2. The Chapter 3 briefly discusses the fuzzy control theory, need for implementing fuzzy controller. It also describes the fuzzy logic based PSS. The results are discussed in Chapter 4 having various cases of a single machine to infinite bus system. The system without PSS, with PSS and with fuzzy logic based PSS and comparison of results is given in Chapter 4. The conclusion with the recommendation for future work are presented in Chapter 5.

CHAPTER-2

SYSTEM MODELLING

The mathematical models needed for small signal analysis of synchronous machine, excitation system and the lead-lag power system stabilizer are briefly reviewed. The guidelines for the selection of power system stabilizer parameters are also presented.

2.1 SYNCHRONOUS MACHINE MODEL

The synchronous machine is vital for power system operation. The general system configuration of synchronous machine connected to infinite bus through transmission network can be represented as the Thevenin's equivalent circuit shown in Fig. 2.1.

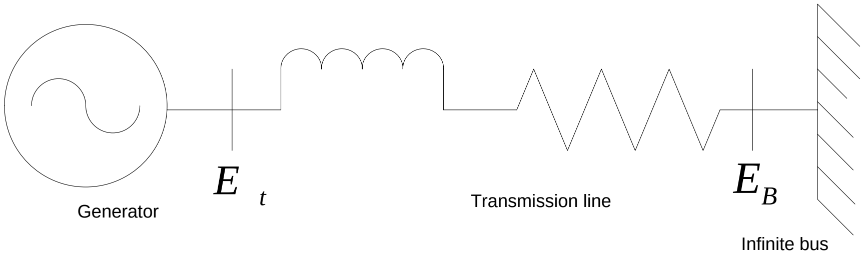

Fig. 2.1 : The equivalent circuit of synchronous machine connected to infinite bus

2.1.1 CLASSICAL MODEL

The generator is represented as the voltage E' behind Xd' as shown in Fig. 2.2. The magnitude of E' is assumed to remain constant at the pre-disturbance value. Let δ be the angle by which E' leads the infinite bus voltage E_B. The δ changes with rotor oscillation. The line current is expressed as -

$$I_t = \frac{E^{'}\angle 0^0 - E_B\angle -\delta}{jX_T} = \frac{E^{'} - (E_B\cos\delta - j\sin\delta)}{jX_T} \qquad (2.1)$$

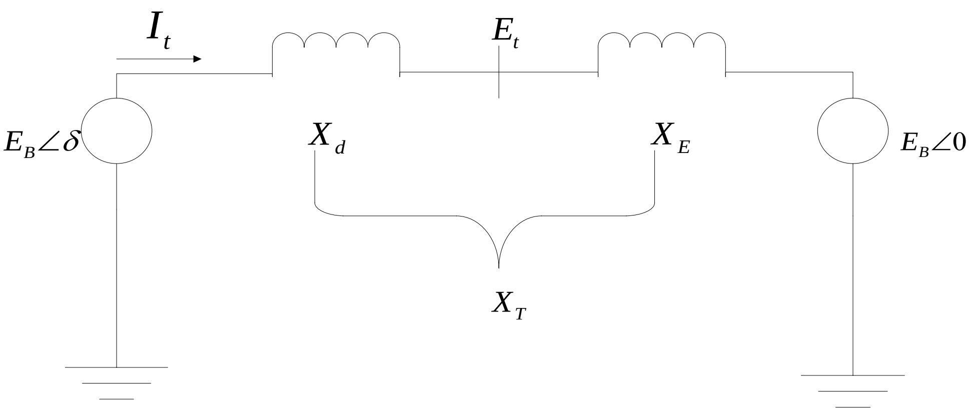

Fig. 2.2: Classical model of generator

The complex power behind Xd' is given by:

$$S = P + jQ = \frac{E^{'}E_B \sin\delta}{X_T} + j\frac{E^{'}(E^{'} - E_B\cos\delta)}{X_T} \tag{2.2}$$

With stator resistance neglected, the air-gap power (P_e) is equal to the terminal power (P). In per unit, the air-gap torque is equal to the air-gap power. Hence

$$T_e = P = \frac{E^{'}E_B}{X_T}\sin\delta \tag{2.3}$$

Linearizing about an initial operating condition represented by $\delta=\delta_o$ yields

$$\Delta T_e = \frac{\partial T_e}{\partial\delta}\ \Delta\delta = \frac{E^{'}E_B}{X_T}\cos\delta_0(\Delta\delta) = K_s\Delta\delta \tag{2.4}$$

$$\text{Where, } K_s = \frac{E^{'}E_B}{X_T}\cos\delta_0 \tag{2.5}$$

The equations of motion in per unit are:

$$\begin{aligned} \mathrm{p}\Delta\omega_r &= \frac{1}{2H}\ (T_M - T_e - K_D\Delta\omega_r) \\ \mathrm{p}\delta &= \omega_0\Delta\omega_\mathrm{r} \end{aligned} \tag{2.6}$$

Linearizing equation 2.6 and substituting for ΔT_e, given by Equation 2.4, results into:

$$\begin{aligned} \mathrm{p}\Delta\omega_r &= \frac{1}{2H}\ (\Delta T_M - K_s\Delta\delta - K_D\Delta\omega_r) \\ \mathrm{p}\Delta\delta &= \omega_0\Delta\omega_\mathrm{r} \end{aligned} \tag{2.7}$$

Writing equation 2.7 in matrix form we obtain

$$\frac{d}{dt}\begin{pmatrix}\Delta\omega\\ \Delta\delta\end{pmatrix}=\begin{pmatrix}-\frac{K_D}{2H} & -\frac{K_s}{2H}\\ \omega_o & 0\end{pmatrix}\begin{pmatrix}\Delta\omega\\ \Delta\delta\end{pmatrix}+\begin{pmatrix}\frac{1}{2H}\\ 0\end{pmatrix}\Delta T_M \tag{2.8}$$

The equation 2.8 is of the form of $\dot{x} = Ax + Bu$ The elements of the state matrix A are seen to be dependent on the system parameters K_D, H, X_T, and the initial operating condition represented by the value of E' and δ_0. The equation 2.8 to describe small-signal performance is represented in block diagram as Fig. 2.3.

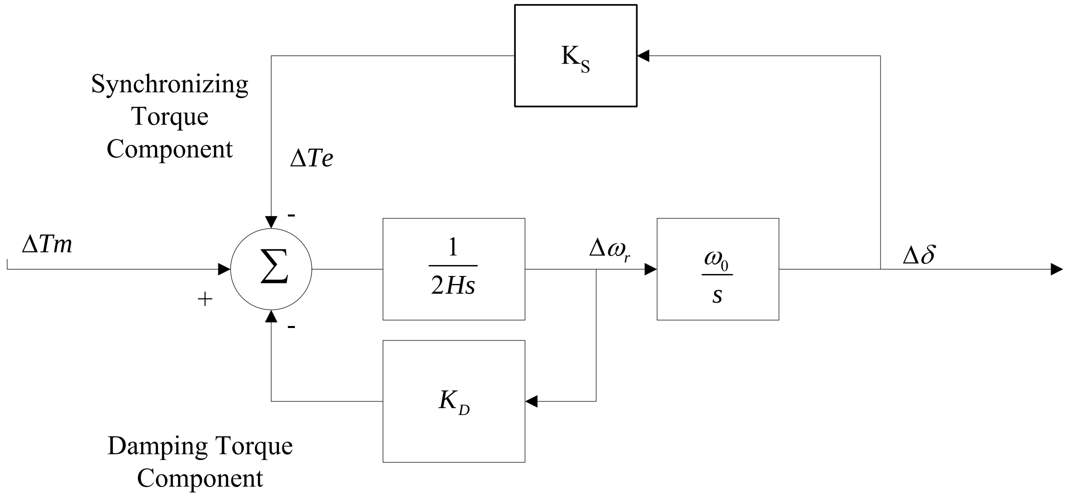

Fig. 2.3: Block diagram of single machine infinite bus system with classical model

From the block diagram we have:

$$\begin{aligned}\Delta\delta &= \frac{\omega_0}{s}\left(\frac{1}{2Hs}\;(-K_s\Delta\delta - K_D\Delta\omega_r + \Delta T_M)\right)\\ &= \frac{\omega_0}{s}\left(\frac{1}{2Hs}\;(-K_s\Delta\delta - K_D\frac{\Delta\delta}{\omega_0}s + \Delta T_M)\right)\end{aligned} \tag{2.9}$$

Solving the block diagram we get the characteristic equation:

$$s^2 + \frac{K_D}{2H}s + \frac{K_s\omega_0}{2H} = 0 \tag{2.10}$$

Comparing it with general form, the undamped natural frequency ω_n and damping ratio ξ are expressed as -

$$\omega_n = \sqrt{\frac{K_s \omega_0}{2H}}$$
$$\xi = \frac{1}{2} \frac{K_D}{\sqrt{K_s 2H \omega_0}} \qquad (2.11)$$

2.1.2 *EFFECT OF FIELD CIRCUIT DYNAMICS*

The synchronous generator field circuit dynamic equations are given by:

$$\begin{aligned} p\psi_{fd} &= \omega_0 (e_{fd} - R_{fd} i_{fd}) \\ &= \omega_0 \frac{R_{fd}}{L_{adu}} E_{fd} - \omega_0 R_{fd} i_{fd} \end{aligned} \qquad (2.12)$$

Where, E_{fd} is the exciter output voltage

The equivalent circuits relating the machine flux linkages and currents are shown in Fig. 2.4.

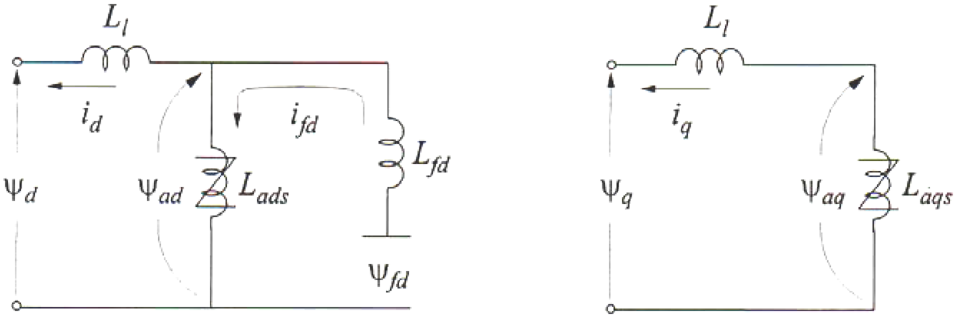

Fig. 2.4: Equivalent circuits relating the machine flux linkage and current

The stator and rotor flux linkage are given by:

$$\begin{aligned} \psi_d &= -L_l i_d + L_{ads}(-i_d + i_{fd}) = -L_l i_d + \psi_{ad} \\ \psi_q &= -L_l i_q + L_{aqs}(-i_q) = -L_l i_q + \psi_{aq} \\ \psi_{fd} &= L_{ads}(-i_d + i_{fd}) + L_{fd} i_{fd} = \psi_{ad} + L_{fd} i_{fd} \end{aligned} \qquad (2.13)$$

From equation 2.13, the field circuit may be expressed as:

$$i_{fd} = \frac{\psi_{fd} - \psi_{ad}}{L_{fd}} \tag{2.14}$$

The d-axis mutual flux linkage can be written in terms of ψ_{fd} and i_d as -

$$\begin{aligned} \psi_{ad} &= -L_{ads} i_d + L_{ads} i_{fd} \\ &= L_{ads} i_d + \frac{L_{ads}}{L_{fd}}(\psi_{fd} - \psi_{ad}) \\ &= L_{ads}^{'}(-i_d + \frac{\psi_{fd}}{L_{fd}}) \end{aligned} \tag{2.15}$$

$$\text{Where, } L_{ads}{'} = \frac{1}{\frac{1}{L_{ads}} + \frac{1}{L_{fd}}}$$

Since there are no rotor circuits considered in the q-axis, the mutual flux linkage is given by:

$$\psi_{aq} = -L_{aqs} i_q \tag{2.16}$$

The air-gap torque is:

$$T_e = \psi_d i_q - \psi_q i_d = \psi_{ad} i_q - \psi_{aq} i_d \tag{2.17}$$

With $p\psi_{fd}$ terms and speed variation neglected the stator voltage equations are:

$$\begin{aligned} e_d &= -R_a i_d - \psi_q = -R_a i_d + (L_l i_q - \psi_{aq}) \\ e_q &= -R_a i_q + \psi_d = -R_a i_q - (L_l i_d - \psi_{ad}) \end{aligned} \tag{2.18}$$

Machine terminal and infinite bus voltage expressed in term of d-axis and q-axis components is given as follows:

$$\tilde{E}_t = e_d + je_q$$
$$\tilde{E}_B = E_{Bd} + jE_{Bq} \tag{2.19}$$

The network constraint equation for the system shown in Fig. 2.1 is

$$\tilde{E}_t = \tilde{E}_B + (R_E + jX_E)\tilde{I}_t$$

$$(e_d + je_q) = (E_{Bd} + jE_{Bq}) + (R_E + jX_E)(i_d + ji_q) \tag{2.20}$$

Resolving into d and q components give

$$\begin{aligned} e_d &= R_E i_d - X_E i_q + E_{Bd} \\ e_q &= R_E i_q - X_E i_d + E_{Bq} \end{aligned} \tag{2.21}$$

where

$$\begin{aligned} E_{Bd} &= E_B \sin\delta \\ E_{Bq} &= E_B \cos\delta \end{aligned}$$

Using equations 2.18 and 2.21, the expression for i_d and i_q are obtained as :

$$\begin{aligned} i_d &= \frac{X_{Tq}\left[\psi_{fd}\left(\dfrac{L_{ads}}{L_{ads} + L_{fd}}\right) - E_B \cos\delta\right] - R_T E_B \sin\delta}{D} \\ i_q &= \frac{R_T\left[\psi_{fd}\left(\dfrac{L_{ads}}{L_{ads} + L_{fd}}\right) - E_B \cos\delta\right] - X_{Td} E_B \sin\delta}{D} \end{aligned} \tag{2.22}$$

where

$$\begin{aligned} R_T &= R_a + R_E \\ X_{Tq} &= X_E + (L_{aqs} + L_l) = X_E + X_{qs} \\ X_{Td} &= X_E + (L^{'}_{ads} + L_l) = X_E + X^{'}_{ds} \\ D &= R_T^2 + X_{Tq} X_{Td} \end{aligned} \tag{2.23}$$

Expressing equation 2.22 in linearized form yields:

$$\begin{aligned}\Delta i_d &= m_1\Delta\delta + m_2\Delta\psi_{fd}\\ \Delta i_q &= n_1\Delta\delta + n_2\Delta\psi_{fd}\end{aligned} \qquad (2.24)$$

where

$$\begin{aligned} m_1 &= \frac{E_B(X_{Tq}\sin\delta_0 - R_T\cos\delta_0)}{D}\\ n_1 &= \frac{E_B(R_T\sin\delta_0 + X_{Td}\cos\delta_0)}{D}\\ m_2 &= \frac{X_{Tq}}{D}\frac{L_{ads}}{(L_{ads}+L_{fd})}\\ n_2 &= \frac{R_T}{D}\frac{L_{ads}}{(L_{ads}+L_{fd})}\end{aligned} \qquad (2.25)$$

By linearising equation 2.15 and 2.16 -

$$\begin{aligned}\Delta\psi_{ad} &= L'_{ads}\left(-\Delta i_d + \frac{\Delta\psi_{fd}}{L_{fd}}\right) = \left(\frac{1}{L_{fd}} - m_2\right)L'_{ads}\Delta\psi_{fd} - m_2L'_{ads}\Delta\delta\\ \Delta\psi_{aq} &= -L_{aqs}\Delta i_q = n_2L_{aqs}\Delta\psi_{fd} - n_1L_{aqs}\Delta\delta\end{aligned} \qquad (2.26)$$

Linearizing equation 2.14 and substituting for $\Delta\psi_{ad}$ from equation 2.26 gives

$$\begin{aligned}\Delta i_{fd} &= \frac{\Delta\psi_{fd} - \Delta\psi_{ad}}{L_{ad}}\\ &= \frac{1}{L_{fd}}\left(1 - \frac{L'_{fd}}{L_{fd}} + m_2L'_{ads}\right)\Delta\psi_{fd} + \frac{1}{L_{fd}}m_1L'_{ads}\Delta\delta\end{aligned} \qquad (2.27)$$

The linearized form of equation is

$$\Delta T_e = \Delta\psi_{ad0}\Delta i_q + i_{q0}\Delta\psi_{ad} - \Delta\psi_{aq0}\Delta i_d - i_{d0}\Delta\psi_{aq} \qquad (2.28)$$

Substituting Δi_d , Δi_q , $\Delta\psi_{ad}$, $\Delta\psi_{aq}$ from equations 2.24, 2.26 and2.27 we obtain

$$\Delta T_e = K_1\Delta\delta + K_2\Delta\psi_{fd} \qquad (2.29)$$

Where

$$K_1 = n_1(\psi_{ad0} + L_{aqs}i_{d0}) - m_1(\psi_{aq0} + L'_{aqs}i_{q0})$$

$$K_2 = n_2(\psi_{ad0} + L_{aqs} i_{d0}) - m_2(\psi_{aq0} + L'_{aqs} i_{q0}) + \frac{L'_{aqs}}{L_{fd}} i_{q0}$$

By substituting the eqution 2.29 for electric torque in eqution 2.7 results as -

$$\begin{aligned} &\mathrm{p}\Delta\omega_r = \frac{1}{2H}\ (\Delta T_M - K_1\Delta\delta - K_2\Delta\psi_{fd} - K_D\Delta\omega_r) \\ &\mathrm{p}\Delta\delta = \omega_0\Delta\omega_{\mathrm{r}} \end{aligned} \qquad (2.30)$$

By linearizing equation 2.12 and substituting the expressions for Δi_{fd} from equations 2.27 and using equation 2.30, the system equations in the desired final form are obtained as:

$$\begin{bmatrix} \Delta\dot{\omega} \\ \Delta\dot{\delta} \\ \Delta\dot{\psi}_{fd} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & 0 & 0 \\ 0 & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} \Delta\omega \\ \Delta\delta \\ \Delta\psi_{fd} \end{bmatrix} + \begin{bmatrix} b_{11} & 0 \\ 0 & 0 \\ 0 & b_{32} \end{bmatrix} \begin{bmatrix} \Delta T_m \\ \Delta E_{fd} \end{bmatrix} \qquad (\ 2.31)$$

Where,

$$\begin{aligned} a_{11} &= -\frac{K_D}{2H} \\ a_{12} &= -\frac{K_1}{2H} \\ a_{12} &= -\frac{K_1}{2H} \\ a_{13} &= -\frac{K_2}{2H} \\ a_{21} &= \omega_0 = 2\pi f_0 \\ a_{32} &= -\frac{\omega_0 R_{fd}}{L_{fd}} m_1 L'_{ads} \\ a_{33} &= -\frac{\omega_0 R_{fd}}{L_{fd}}\left(1 - \frac{L'_{ads}}{L_{fd}} + m_2 L'_{ads}\right) \\ b_{11} &= \frac{1}{2H} \\ b_{32} &= \frac{\omega_0 R_{fd}}{L_{adu}} \end{aligned} \qquad (2.32)$$

And ΔT_m and ΔE_{fd} depends on prime-mover and excitation controls. The mutual inductance L_{ads} and L_{aqs} in the above equations are saturated values. The method of accounting for saturation for small signal analysis is described below.

2.1.3 REPRESENTATION OF SATURATION IN STABILITY STUDIES

The following assumptions are made in the representation of magnetic saturation for stability studies-

(a) The leakage inductances are independent of saturation and only elements that saturate are the mutual inductances L_{ad} and $L_{aq.}$

(b) The leakage fluxes do not contribute to the iron saturation and the saturation is determined by the air-gap flux linkage.

(c) The saturation relationship between the resultant air-gap flux and the mmf under loaded conditions is the same as under no-load conditions.

(d) There is no magnetic coupling between the d- and q-axes.

With the above assumptions, the effects of saturation may be represented using open circuit characteristic as shon in Fig. 2.5 as -

$$\begin{aligned} L_{ad} &= K_{sd} L_{adu} \\ L_{aq} &= K_{sq} L_{aqu} \end{aligned} \qquad (2.33)$$

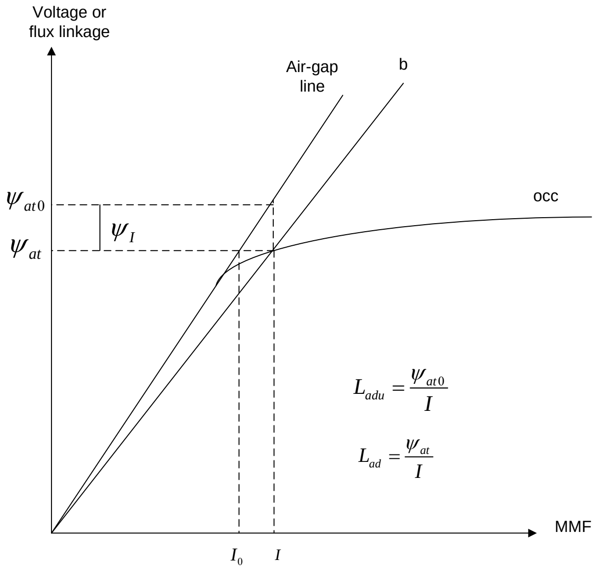

Fig. 2.5: Open-circuit characteristics showing the effect of saturation

Where L_{adu} and L_{aqu} are the unsaturated values of L_{ad} and L_{aq} The saturation factor K_{sd} and K_{sq} identifies the degrees of saturation in the d-axis and q-axis respectively. The saturation curve may be divided into three segments:

I. Unsaturated segment
II. Nonlinear segment
III. Fully saturated linear segment.

The threshold values of ψ_{T1} and ψ_{T2} defines the boundaries of the three segments as shown in Fig. 2.6. The total saturation is associated with total values of flux linkages and currents. Incremental saturation is associated with perturbed values of flux linkages and currents. Therefore the incremental slope of the saturation curve is used in computing the incremental saturation as shown in Fig. 2.6. using incremental saturation factor we have:

$$L_{ads(incr)} = K_{sd(incr)}\, L_{adu} \qquad (2.34)$$

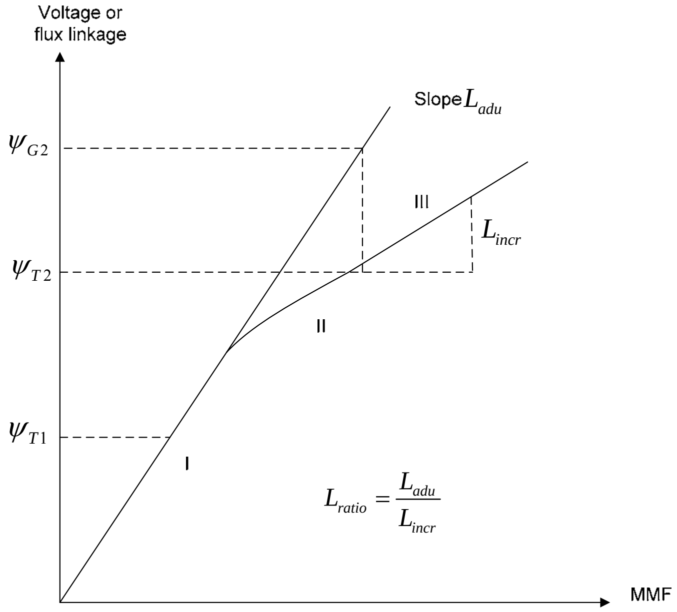

Fig. 2.6: Representation of saturation in stability studies

Where,

$$K_{sd(incr)} = \frac{1}{1 + B_{sat} A_{sat} e^{B_{sat}(\psi_{ato} - \psi_{TI})}}$$

Such that A_{sat} and B_{sat} are saturation constants depending on the saturation characteristics in the segment II portion in Fig. 2.7.

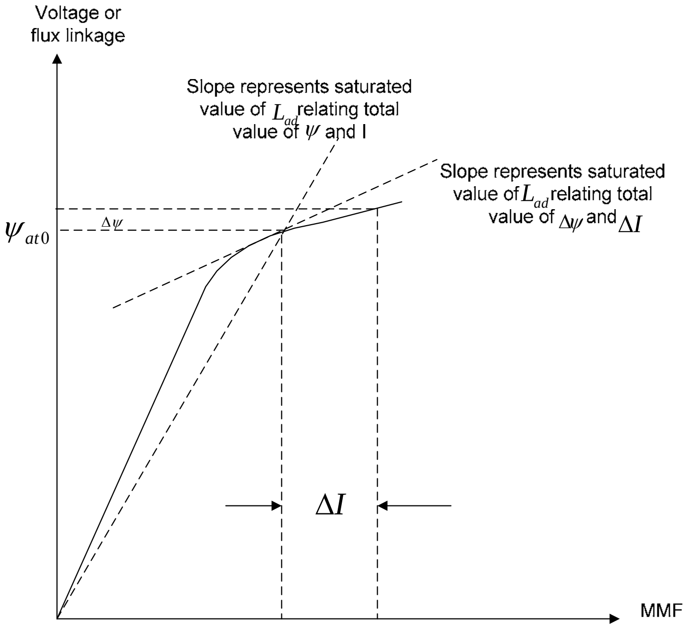

Fig. 2.7: Distinction between incremental and total saturation

For computing the initial values of system variable, total saturation is used whereas for relating the perturbed values the incremental saturation factor is used. The Fig. 2.8 shows the block diagram representation of the small signal performance of the system.

In this representation, the dynamic characteristics of the system are expressed in terms of the K-constants. From equation 2.29, we may express the change in air-gap torque as a function of $\Delta\delta$ and $\Delta\psi_{fd}$ as follows:

$$\Delta T_e = K_1\Delta\delta + K_2\Delta\psi_{fd} \tag{2.35}$$

Where:

$$K_1 = \frac{\Delta T_e}{\Delta\delta} \text{ with constant } \Delta\psi_{fd}$$

$$K_2 = \frac{\Delta T_e}{\Delta\psi_{fd}} \text{ with constant } \Delta\delta$$

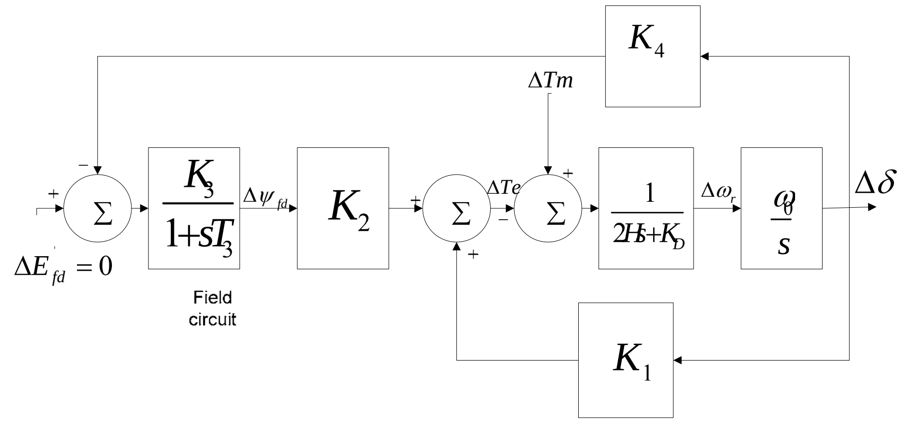

Fig. 2.8:Block diagram representation with constant E_{fd}

The variation of $\Delta\psi_{fd}$ is determined by the field circuit dynamic equation:

$$p\Delta\psi_{fd} = a_{32}\Delta\delta + a_{33}\Delta\psi_{fd} + b_{32}\Delta E_{fd} \tag{2.36}$$

By grouping terms involving $K_2\Delta\psi_{fd}$ and rearranging -

$$\Delta\psi_{fd} = \frac{K_3}{1+pT_3}\left[\Delta E_{fd} - K_4\Delta\delta\right] \tag{2.37}$$

Where

$$K_3 = -\frac{b_{32}}{a_{33}}$$

$$K_4 = -\frac{a_{32}}{b_{32}}$$

$$T_3 = -\frac{1}{a_{33}} = K_3 T'_{d0}\frac{L_{adu}}{L_{ffd}}$$

The constants K_2, K_3 and K_4 are usually positive. As long as K_4 is positive, the effect of field flux variation due to armature reaction is to introduce a positive damping torque component. However, there can be situation where K_4 is negative. K_4 is negative when a hydraulic generator without damper windings is operating at light load and is connected by a line of relatively high resistance to reactance ratio to a large system.

Also K_4 can be negative when a machine is connected to a large local load, supplied partly by the generator and partly by the remote large system. Under such conditions, the torques produced by induced currents in the field due to armature reaction has components out of phase with Δω, and produce negative damping.

2.2 EXCITATION SYSTEM MODEL

The input control signal to the excitation system is normally the generator terminal voltage E_t may be expressed in complex form:

$$\tilde{E}_t = e_d + je_q$$

$$E_t^2 = e_d^2 + e_q^2$$

Appling a small perturbation, we may write

$$(E_{t0} + \Delta E_t)^2 = (e_{d0} + \Delta e_d)^2 + (e_{q0} + \Delta e_q)^2$$

By neglecting higher order terms in above expression, the above equation reduced to

$$E_{t0}\Delta E_t = e_{d0}\Delta e_d + e_{q0}\Delta e_q$$

Therefore,

$$\Delta E_t = \frac{e_{d0}}{E_{t0}}\Delta e_d + \frac{e_{q0}}{E_{t0}}\Delta e_q \tag{2.38}$$

In terms of the perturbed values, equations 2.18 may be written as:

$$\begin{aligned} \Delta e_d &= -R_a \Delta i_d - (L_l \Delta i_q - \Delta \psi_{aq}) \\ \Delta e_q &= -R_a \Delta i_q - (L_l \Delta i_d - \Delta \psi_{ad}) \end{aligned} \tag{2.39}$$

Using equations 2.24 and 2.26, we get

$$\Delta E_t = K_5 \Delta \delta + K_6 \Delta \psi_{fd} \tag{2.40}$$

Where

$$K_5 = \frac{e_{d0}}{E_{t0}}\left[-R_a m_1 + L_1 n_1 + L_{aqs} n_1\right] + \frac{e_{q0}}{E_{t0}}\left[-R_a n_1 - L_1 m_1 - L_{ads}^{'} m_1\right] \tag{2.41}$$

$$K_6 = \frac{e_{d0}}{E_{t0}}\left[-R_a m_2 + L_1 n_2 + L_{aqs} n_2\right] + \frac{e_{q0}}{E_{t0}}\left[-R_a n_2 - L_1 m_2 + L'_{ads}(\frac{1}{L_{fd}} - m_1\right]$$

For the small scale analysis, the thyristor excitation system as shown in Fig. 2.9 is considered. The nonlinearity associated with the ceiling on the exciter output voltage represented by E_{FMAX} and E_{FMIN}, which is ignored for small-disturbance studies.

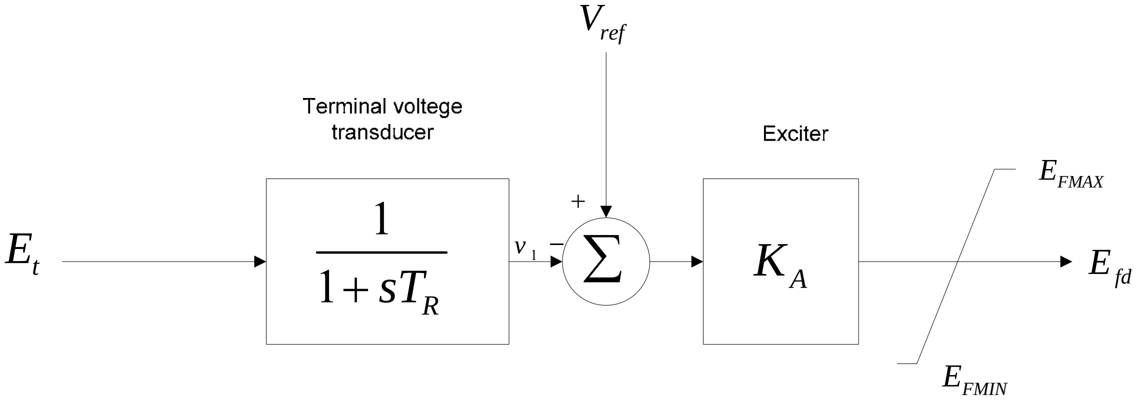

Fig. 2.9: Thyristor excitation system with AVR

From block of Fig. 2.9, using perturbed values, we have

$$\Delta v_1 = \frac{1}{1+pT_R}\Delta E_t$$

Hence,

$$p\Delta v_1 = \frac{1}{T_R}(\Delta E_t - \Delta v_1)$$

Substituting for ΔE_t from 2.40 we get:

$$p\Delta v_1 = \frac{1}{T_R}(K_5\Delta\delta + K_6\Delta\psi_{fd} - \Delta v_1) \tag{2.42}$$

From block 2 of Fig. 2.9 we get

$$E_{fd} = K_A(V_{ref} - v_1)$$

In terms of perturbed values we have

$$\Delta E_{fd} = K_A(-\Delta v_1) \tag{2.43}$$

The field circuit dynamic equation shown in equation 2.36 becomes:

$$p\psi_{fd} = a_{31}\Delta\omega_r + a_{32}\Delta\delta + a_{33}\Delta\psi_{fd} + a_{34}\Delta v_1 \tag{2.44}$$

Where,

$$a_{34} = -b_{32}K_A = -\frac{\omega_0 R_{fd}}{L_{adu}} K_A \tag{2.45}$$

The expressions for a_{31}, a_{32} and a_{33} remain unchanged as before and since we have a first order-order model for the exciter, the order of the overall system is increased by 1; the new state variable added is ΔV_1

$$\Delta v_1 = a_{41}\Delta\omega_r + a_{42}\Delta\delta + a_{43}\Delta\psi_{fd} + a_{44}\Delta v_1 \tag{2.46}$$

$$\begin{aligned} a_{41} &= 0 \\ a_{42} &= \frac{K_5}{T_R} \\ a_{43} &= \frac{K_6}{T_R} \\ a_{44} &= -\frac{1}{T_R} \end{aligned} \tag{2.47}$$

The complete state-space model for the power system, including the excitation system of Fig. 2.8 has the following form:

$$\begin{bmatrix} \Delta\dot{\omega}_r \\ \Delta\dot{\delta} \\ \Delta\dot{\psi}_{fd} \\ \Delta\dot{v}_1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 \\ a_{21} & 0 & 0 & 0 \\ 0 & a_{32} & a_{33} & a_{34} \\ 0 & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \\ \Delta\psi_{fd} \\ \Delta v_1 \end{bmatrix} + \begin{bmatrix} b_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \Delta T_m \tag{2.48}$$

The Fig. 2.10 shows the block diagram obtained by extending Fig. 2.8 to include voltage transducer and automatic voltage regulator/exciter block. The representation is applicable to any type of exciter, with G(s) representing transfer function of AVR and exciter. For a thyristor exciter –

$G(s) = K_A$

The terminal voltage error signal, which forms the input to the voltage transducer block is given by -

$$\Delta E_t = K_5\Delta\delta + K_6\Delta\psi_{fd}$$

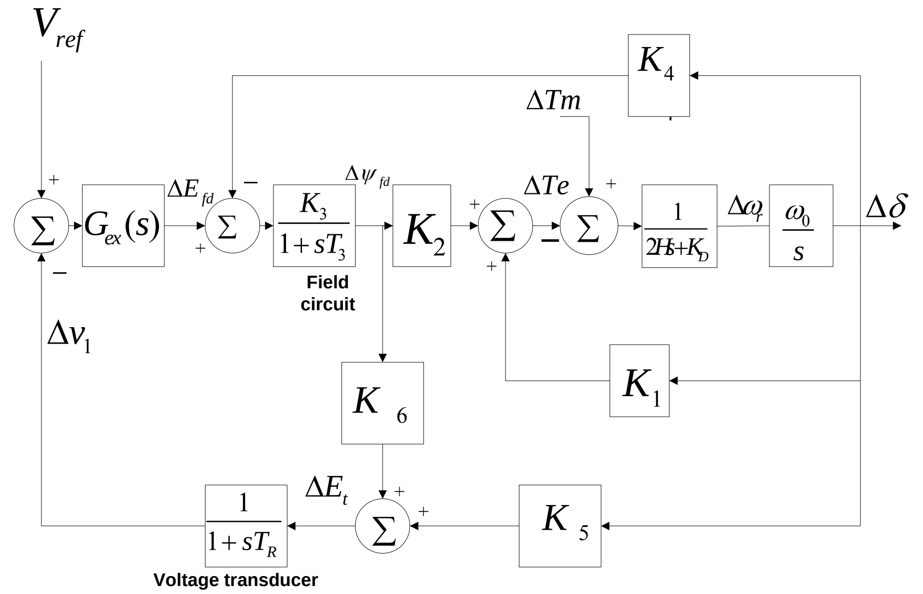

Fig. 2.10. Block diagram representation with exciter and AVR

The coefficient K6 is always positive whereas K_5 can be positive or negative depending upon operating condition. And external network impedance R_E + jX_E. The value of K_5 has a significant bearing on influence of AVR on the damping of system oscillations.

2.3 POWER SYSTEM STABILIZER MODEL

The basic function of power system stabilizer is to add damping to the generator rotor oscillations by controlling its excitation using auxiliary stabilizing signals. To provide damping, the stabilizer must produce a component of electrical torque in phase with rotor speed deviations. The theoretical basis for PSS may be illustrated with the aid of block diagram as shown in Fig. 2.11.

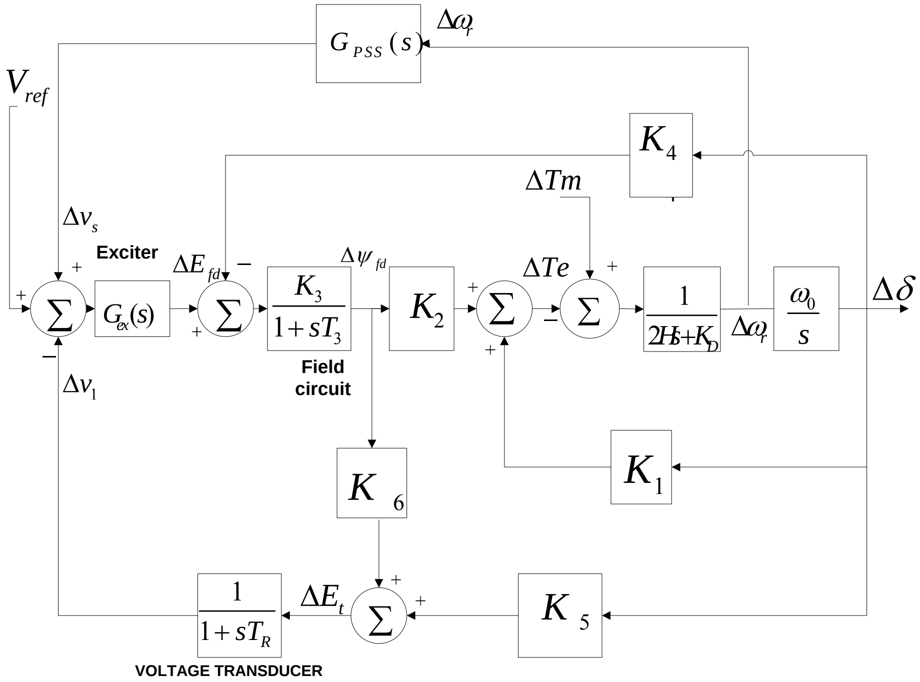

Fig. 2.11: Block diagram representation with AVR and PSS

Since the purpose of PSS is to introduce a damping torque component. A logical signal to use for controlling generator excitation is the speed deviation $\Delta\omega_r$. The PSS transfer function, $G_{PSS}(s)$, should have appropriate phase compensation circuits to compensate for the phase lag between exciter input and electrical torque. The following is a brief description of the basis for the PSS configuration and consideration in selection of parameters.

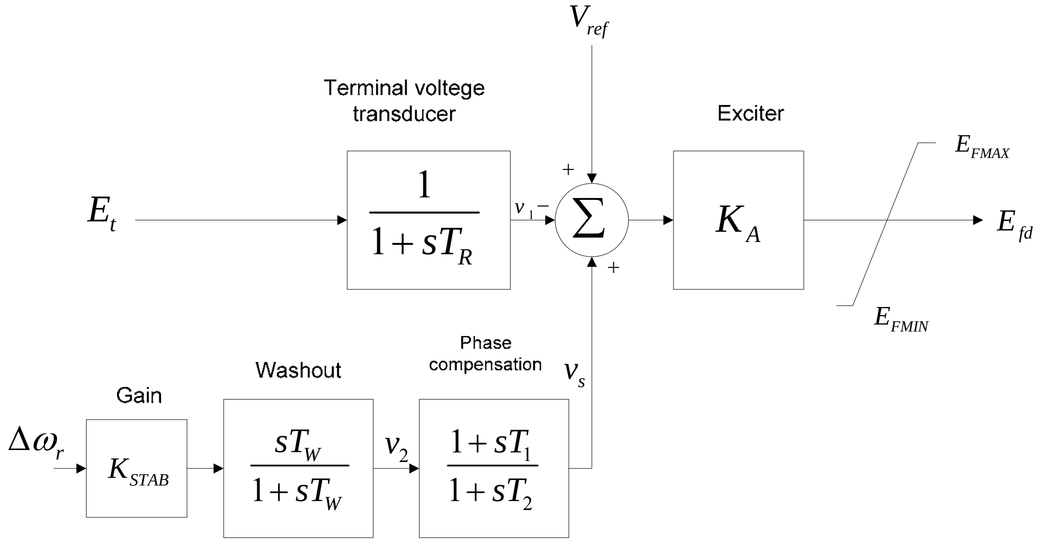

Fig. 2.12: Thyristor excitation system with AVR and PSS

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 Fig. 2.12 or having two or more first order blocks or second order blocks with complex roots.

The signal washout block serves as high pass filter, with time constant T_w high enough to allow signals associated with oscillations in ω_r to pass unchanged, which removes d.c. signals. Without it, steady changes in speed would modify the terminal voltage. It allows PSS to respond only to changes in speed.

The stabilizer gain K_{STAB} determines the amount of damping introduced by PSS. Ideally, the gain should be set at a value corresponding to maximum damping; however, it is limited by other consideration.

From block 4 of Fig. 2.12, using perturbed values, we have

$$\Delta v_1 = \frac{pT_W}{1+pT_W}(K_{STAB}\Delta\omega_r)$$

Hence,

$$p\Delta v_2 = K_{STAB}\,p\Delta\omega_r - \frac{1}{T_W}\Delta v_2 \tag{2.49}$$

Substituting for $p\Delta\omega_r$ given by Equation 2.31, we obtain the following expression for $p\Delta v_2$ in terms of the state variables:

$$\begin{aligned} pv_2 &= K_{STAB}\left[a_{11}\Delta\omega_r + a_{12}\Delta\delta + a_{13}\Delta\psi_{fd} + \frac{1}{2H}\Delta T_m\right] - \frac{1}{T_W}v_2 \\ &= a_{51}\Delta\omega_r + a_{52}\Delta\delta + a_{53}\Delta\psi_{fd} + a_{54}\Delta v_2 + \frac{K_{STAB}}{2H}\Delta T_m \end{aligned} \tag{2.50}$$

Where,

$$\begin{aligned} a_{51} &= K_{STAB}a_{11} \\ a_{52} &= K_{STAB}a_{12} \\ a_{53} &= K_{STAB}a_{13} \\ a_{54} &= \frac{1}{T_W} \end{aligned} \tag{2.51}$$

From block 5,

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

$$\Delta v_s = \frac{T_1}{T_2}p\Delta v_2 + \frac{1}{T_2}\Delta v_2 - \frac{1}{T_2}\Delta v_s$$

Substitution for $p\Delta v_2$, given by equation 2.50, yields

$$p\Delta v_s = a_{61}\Delta\omega_r + a_{62}\Delta\delta + a_{63}\Delta\psi_{fd} + a_{64}\Delta v_1 + a_{65}\Delta v_2 + a_{66}\Delta v_s + \frac{T_1}{T_2}\frac{K_{STAB}}{2H}\Delta T_m \tag{2.52}$$

Where,

$$\begin{aligned} a_{61} &= \frac{T_1}{T_2}a_{51} \\ a_{62} &= \frac{T_1}{T_2}a_{52} \\ a_{63} &= \frac{T_1}{T_2}a_{53} \\ a_{65} &= \frac{T_1}{T_2}a_{55} + \frac{1}{T_1} \\ a_{66} &= -\frac{1}{T_2} \end{aligned} \tag{2.53}$$

From block 2 we get,

$$\Delta E_{fd} = K_A(\Delta v_s - \Delta v_1)$$

The field circuit equation, with PSS included, becomes

$$p\Delta \psi_{fd} = a_{32}\Delta\delta + a_{33}\Delta\psi_{fd} + a_{34}\Delta v_2 + a_{36}\Delta v_s \qquad (2.54)$$

Where

$$a_{36} = \frac{\omega_0 R_{fd}}{L_{adu}} K_A$$

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

$$\begin{bmatrix} \Delta\dot{\omega}_r \\ \Delta\dot{\delta} \\ \Delta\dot{\psi}_{fd} \\ \Delta\dot{v}_1 \\ \Delta\dot{v}_2 \\ \Delta\dot{v}_S \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 & 0 & 0 \\ a_{21} & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{32} & a_{33} & a_{34} & 0 & a_{36} \\ 0 & a_{42} & a_{43} & a_{44} & 0 & 0 \\ a_{51} & a_{52} & a_{53} & 0 & a_{55} & 0 \\ a_{61} & a_{62} & a_{63} & 0 & a_{65} & a_{66} \end{bmatrix} \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \\ \Delta\psi_{fd} \\ \Delta v_1 \\ \Delta v_2 \\ \Delta v_S \end{bmatrix} \qquad (2.55)$$

The PSS parameters should be such that the control system results into the following-

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

CHAPTER 3

FUZZY LOGIC BASED POWER SYSTEM STABILIZER

In this chapter the concepts of fuzzy control system are briefly reviewed and the modeling of the fuggy logic based power system stabilizer is explained.

3.1 FUZZY CONTROL SYSTEM

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 i.e. [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 –

- A simpler and faster methodology.
- It reduces the design development cycle.
- It simplifies design complexity.
- An alternative solution to non-linear control.
- Improves the control performance.
- Simple to implement
- Reduces hardware cost

A typical fuzzy system consists of a rule base, membership functions and an inference procedure which are explained in the following sections.

3.1.1 FUZZY MEMBERSHIP

In classical set theory, a subset U of asset S can be defined as a mapping from the elements of S to the elements the subset {0, 1},

$$U: S \rightarrow \{0.1\}$$

The mapping may be represented as a set of ordered pairs, with exactly one ordered pair present for each element of S. The first element of the ordered pair is an element of the set S, and second element is an element of the set (0, l). The value zero is used to represent non-membership, and the value one is used to represent complete membership. The truth or falsity of the statement 'X is in U' is determined by finding the ordered pair whose first element is X. The statement is true if the second element of the ordered pair is 1, and the statement is false if it is 0.

The fuzzy set can be defined mathematically by assigning to each possible individual in the universe of discourse, a value representing its grade of membership in fuzzy set. This grade corresponds to the degree to which that individual is similar or compatible with the concept represented by the fuzzy set. In a fuzzy set many degree of membership (between 0 and 1) are allowed. Thus, a membership function $\mu(a)$ is associated with a fuzzy set A such that the function maps every element of the universe of discourse X to the interval [0,1]. 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.

3.2 FUZZY CONTROLLER

The fuzzy control systems are rule-based systems in which a set of fuzzy rules represent a control decision mechanism to adjust the effects of certain system stimuli. With an effective rule base, the fuzzy control systems can replace a skilled human operator. The fuzzy logic controller provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. The Fig. 3.1 illustrates the schematic design of a fuzzy logic controller which consists of a fuzzification interface, a knowledge base, decision making logic, and a defuzzification interface.

In fuzzification the value of input variables are measured, scale mapping that transfers the range of values of input variables into corresponding universe of discourse is performed; it performs the function of fuzzification that converts input data into suitable linguistic values which may be viewed as label fuzzy sets. The knowledge base comprises knowledge of application domain and attendant control goals. It consists of a database and linguistic control rule base. The database provides the necessary definitions, which are used to define linguistic control rules and fuzzy data manipulation in an FLC. The rule base characterizes the control goals and control policy of domain experts by means of set of linguistic control rules. The decision making logic has the capability of simulating human decision making based on fuzzy concepts. The defuzzification performs scale mapping, which converts the range of values of output variables into corresponding universe of discourse, it yields a non-fuzzy control action from an inferred control action. The different methods of defuzzification are max criterion method, mean of maxima method and centriod method etc.

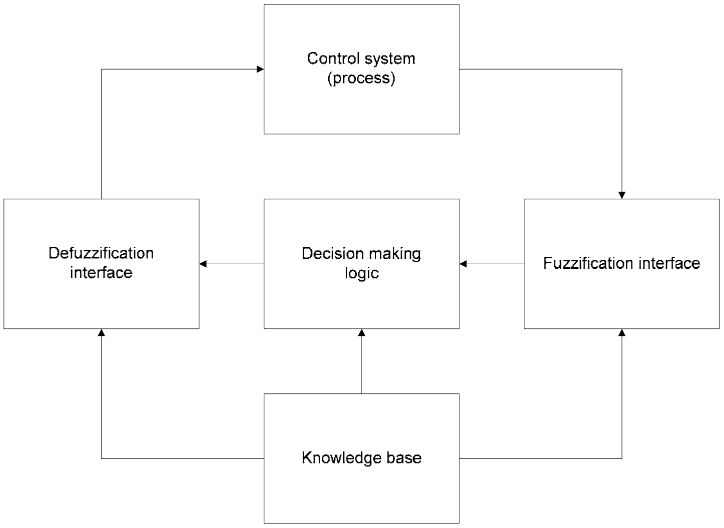

Fig. 3.1 : The principle design of fuzzy logic controller

3.2.1 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, i.e. establishing fuzzification method and fuzzy membership functions.

4) Selection of the compositional rule of inference.

5) Defuzzification method, i.e., 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.

3.3 FUZZY LOGIC BASED PSS

The power system stabilizer is used to improve the performance of synchronous generator. However, it results into poor performance under various loading conditions when implemented with conventional PSS. 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. The stabilizing signals are computed using the standard fuzzy membership functions depending upon these variables.

3.3.1 SELECTION OF INPUT AND OUTPUT VARIABLES

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.

In practice, only shaft speed is readily available. The acceleration signal can be derived from the speed signals measured at two successive sampling instants using the following equation:

$$\Delta\dot{\omega}(k) = \frac{((\Delta\omega(k) - \Delta\omega(k-1))}{\Delta T}$$

3.3.2 MEMBERSHIP FUNCTION

The variables chosen for this controller are speed deviation, acceleration and voltage. In this, the speed deviation and acceleration are the input variables and voltage is the output variable. The number of linguistic variables describing the fuzzy subsets of a variable varies according to the application. Usually an odd number is used. A reasonable number is seven. However, increasing the number of fuzzy subsets results in a corresponding increase in the number of rules. Each linguistic variable has its fuzzy membership function. The membership function maps the crisp values into fuzzy variables. The triangular membership functions are used to define the degree of membership. It is important to note that the degree of membership plays an important role in designing a fuzzy controller.

Each of the input and output fuzzy variables is assigned seven linguistic fuzzy subsets varying from negative big (NB) to positive big (PB). Each subset is associated with a triangular membership function to form a set of seven membership functions for each fuzzy variable.

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 variables are normalized by multiplying with respective gains K_{in1}, K_{in2}, K_{out} so that their value lies between -1 and 1. The membership functions of the input output variables have 50% overlap between adjacent fuzzy subsets. The membership function for acceleration, speed and voltage are shown in Fig. 3.2.

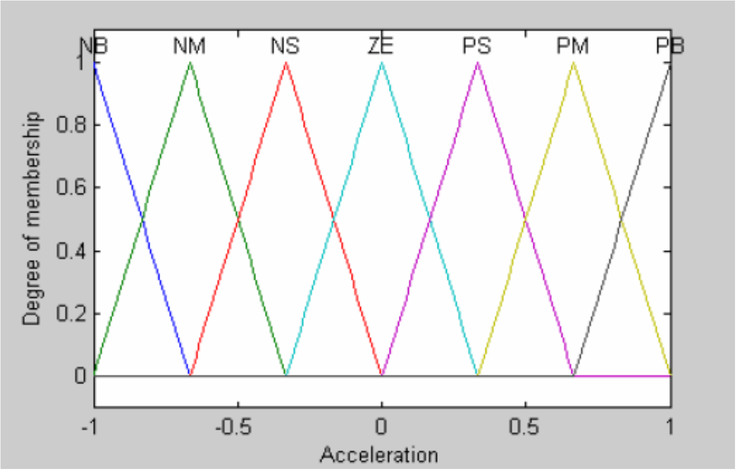

Fig. 3.2(a) Membership functions for acceleration

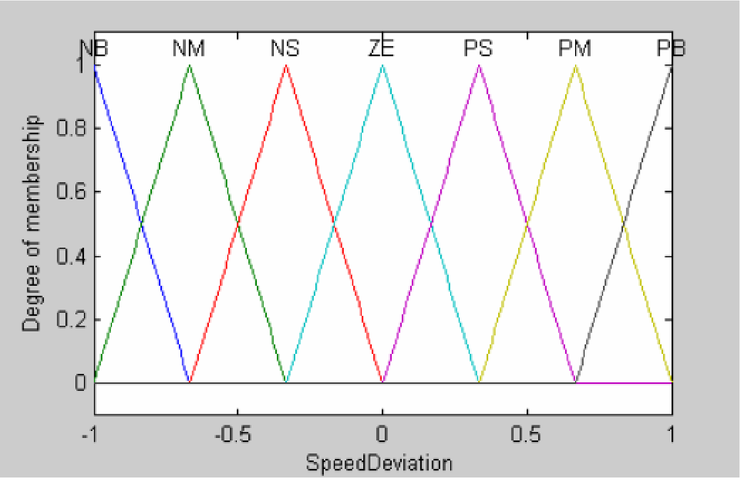

Fig. 3.2(b) Membership functions for speed deviation

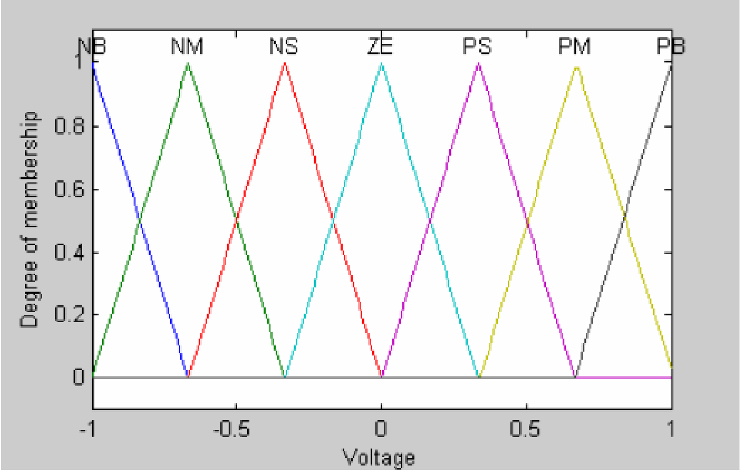

Fig. 3.2(c) Membership functions for voltage

3.3.3 FUZZY RULE BASE

A set of rules which define the relation between the input and output of fuzzy controller can be found using the available knowledge in the area of designing PSS. These rules are defined using the linguistic variables. The two inputs, speed and acceleration, result in 49 rules for each machine. The typical rules are having the following structure:

Rule 1**:** If speed deviation is NM (negative medium) AND acceleration is PS (positive small) then voltage (output of fuzzy PSS) is NS (negative small).
Rule 2**:** If speed deviation is NB (negative big) AND acceleration is NB (negative big) then voltage (output of fuzzy PSS) is NB (negative big).
Rule 3**:** If speed deviation is PS (positive small) AND acceleration is PS (positive small) then voltage (output of fuzzy PSS) is PS (positive small). And so on….

All the 49 rules governing the mechanism are explained in Table 3.2 where all the symbols are defined in the basic fuzzy logic terminology.

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 stabilizer output is obtained by applying a particular rule expressed in the form of membership functions. Finally the output membership function of the rule is calculated. This procedure is carried out for all of the rules and with every rule an output is obtained.

Using min-max inference, the activation of the ith rule consequent is a scalar value (Vs) which equals the minimum of the two antecedent conjuncts’ values. For example if speed deviation belongs to NB with a membership of 0.3 and acceleration belongs to NM with a membership of 0.7 then the rule consequence i.e. Voltage signal (Vs) will be 0.3.

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. However, it has been noticed in practice that, 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.

3.3.4 DEFUZZIFICATION

The input for the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output is a single crisp number. As much as fuzziness helps the rule evaluation during the intermediate steps, the final desired output for each variable is generally a single number. However, the aggregate of a fuzzy set encompasses a range of output values, and so must be defuzzified in order to resolve a single output value from the set. The most popular defuzzification method is the centroid calculation, which returns the center of area under the curve and therefore is considered for defuzzification.

For a discretised output universe of discourse

$$Y = \left(y_1, \ldots\ldots. y_p\right)$$

Which gives the discrete fuzzy centroid, the output of the controller is given by following expression:

$$u_k = \frac{\sum_{i=1}^{p} y_i w_i}{\sum_{i=1}^{p} w_i}$$

3.3.5 IMPLEMENTATION OF FUZZY LOGIC

The block diagram representation of fuzzy logic controller implemented on single machine infinite bus system is shown in the Fig. 3.5.

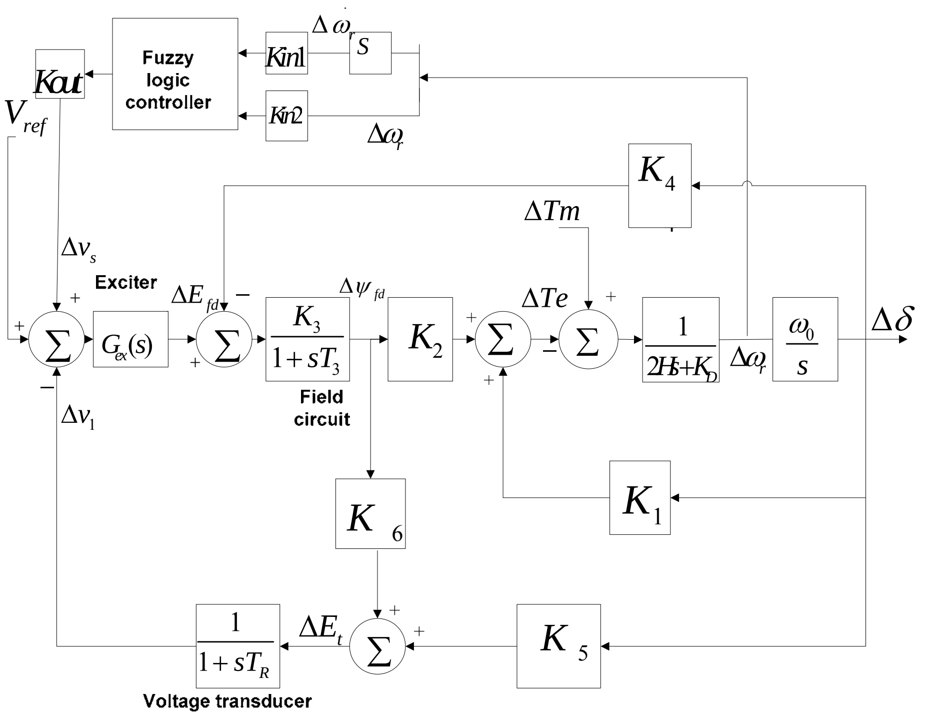

Fig. 3.5: Implementation of fuzzy logic controller

The only difference in application of fuzzy controller to single machine infinite bus and conventional power system stabilizer is that in former case the PSS block is replaced by the fuzzy logic controller block.

The fuzzy module has two inputs namely the angular velocity and its derivative i.e. angular acceleration and output parameter as voltage. These are normalized by gains K_{in1}, K_{in2} and K_{out} respectively in order to match the range on which the membership functions are defined. Seven fuzzy subsets are defined for each input and output. The main problem that was faced now is the tuning of these fuzzy logic parameters K_{in1}, K_{in2} and K_{out}. These parameters were tuned using the following procedure.

Initially set the value of K_{in1} and K_{in2} equal to unity and study the effect of variation of third parameter on the response of the system and among them select the most suitable value then vary other variables keeping two parameter constant. Follow this procedure to investigate the effect of all three constants on the system. Then after studying the effect of these parameters on system, suitable selection can be made following the similar procedure until the desired response is obtained. Previous experience with the controlled system is helpful in selecting these parameters.

CHAPTER-4

RESULTS AND DISCUSSION

The performance of single machine infinite bus system has been studied without excitation system, with excitation system only, with conventional PSS (lead-lag) and with fuzzy logic based PSS. The dynamic models of synchronous machine, excitation system and conventional PSS are described in Chapter 2. The machine data is taken from [122].

Parametres	**Numerical values**
P	0.9
Q	0.3
E_t	1.0
F	50
Xd	1.81
Xq	1.76
Xd1	0.3
XL	0
Xe	0.65
Ra	0.003
Tdo1	8.0
H	3.5
Ωo	314
K_D	0
T_R	0.02
E_{Tmag}	1.0
L_{adu}	1.65
L_{adu}	1.60
R_{fd}	.0006
L_{fd}	0.153
K_{sd}	0.8491
K_{sq}	0.8491
K_{sdI}	0.434
K_{sqI}	0.434
A_{SAT}	0.031
B_{SAT}	6.93
ψ_1	0.8
Frequency of oscillation (in rad/sec)	10

4.1 PERFORMANCE WITH CONSTANT FIELD VOLTAGE

The model used in simulink to study the response of the system with constant field voltage is shown in Fig 4.1. In this representation the dynamic characteristics of the system are expressed in terms of so called K constants. The values of K constants calculated using above parameters are:

K1=0.7636, K2=0.8644, K3=0.3231, K4=1.4189

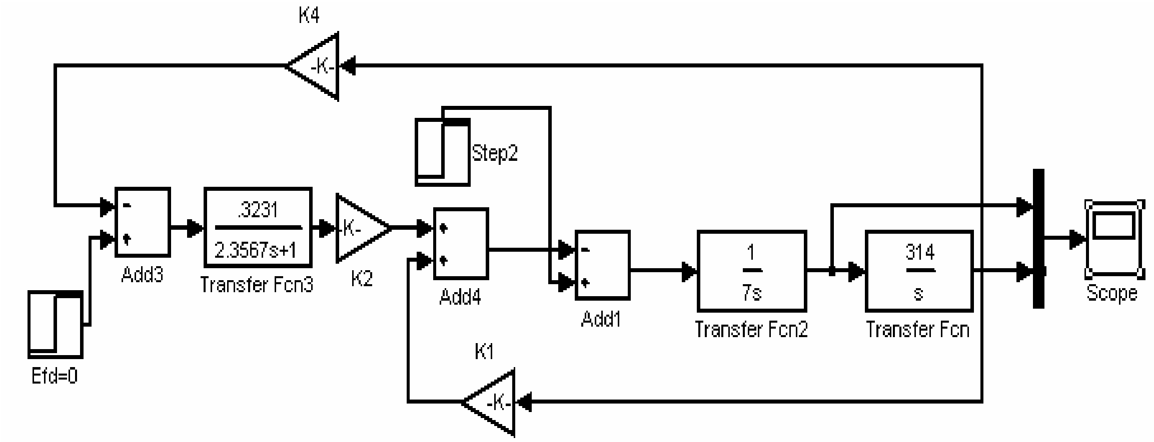

Fig 4.1: Simulink model for simulation of single machine infinite bus system with constant field voltage

The characteristics showing the variation in speed, angular position and the electric torque are shown in Fig 4.2.

The above response depicts that the oscillations are more pronounced when a system is perturbed with constant field voltage after which it becomes stable. It is taking very large time (more then 25 sec) to settle to steady value even with 0.05 pu increase in the input value. Therefore, the performance of the system with excitation system is analyzed to find the suitability of the excitation system in removing these oscillations.

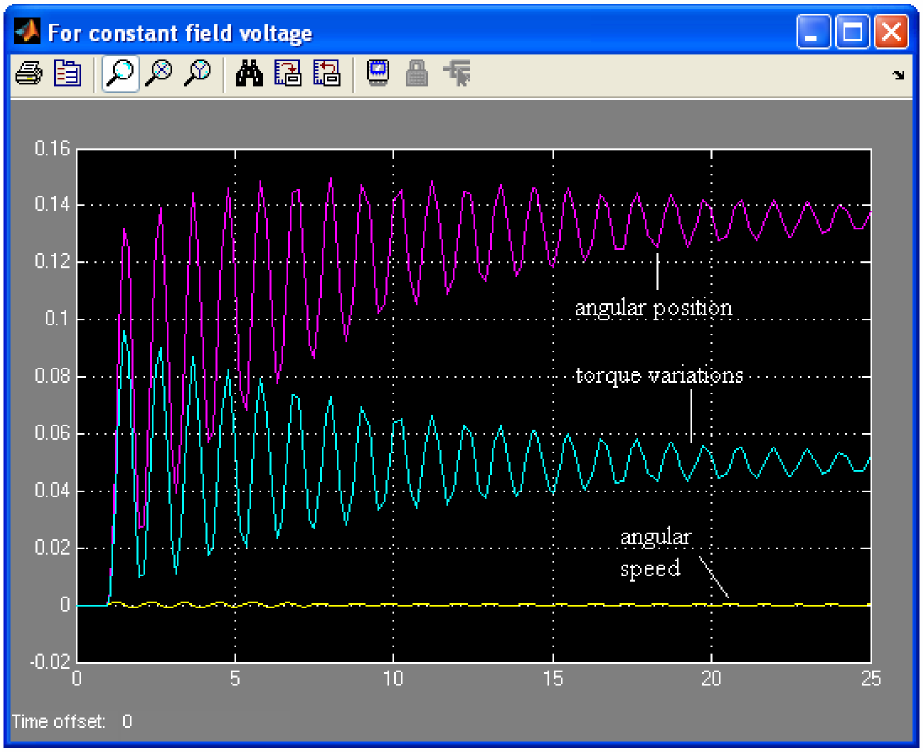

Fig 4.2: System response for a 5% change in mechanical input

4.2 PERFORMANCE WITH EXCITATION SYSTEM ONLY

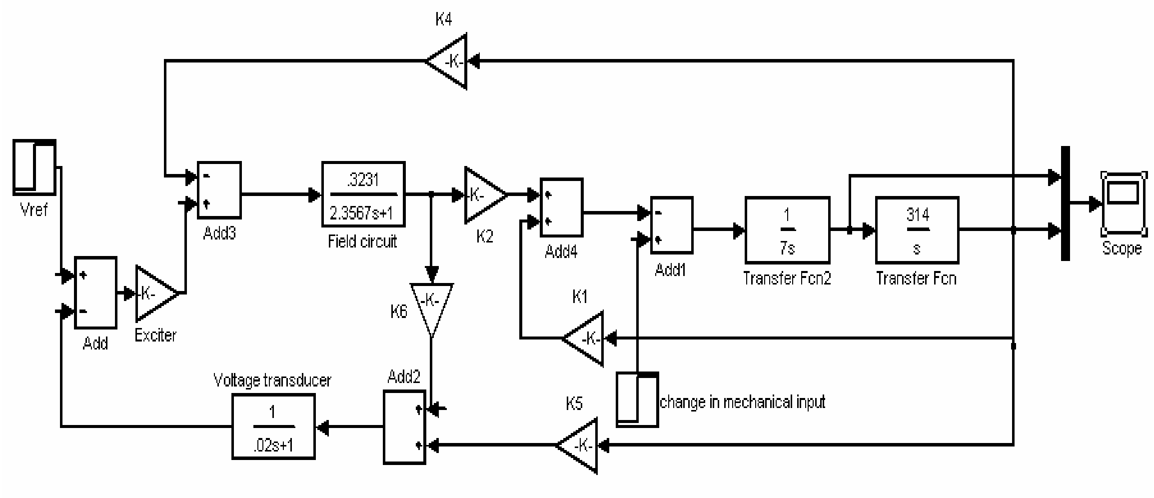

Fig 4.3: Simulink model for simulation of single machine infinite bus system with AVR only

The standard IEEE type ST1A excitation system model has been considered for the study and integrated it with the single machine infinite bus system. Correspondingly, the simulink model is shown in Fig 4.3. The excitation system parameters are taken as $K_A = 200$ and $T_R = 0.02$.

The values of 'K' constants calculated using above parameters:
K1=0.7636, K2=0.8644, K3=0.3231, K4=1.4189, K5 = -0.1463, K6=0.4167

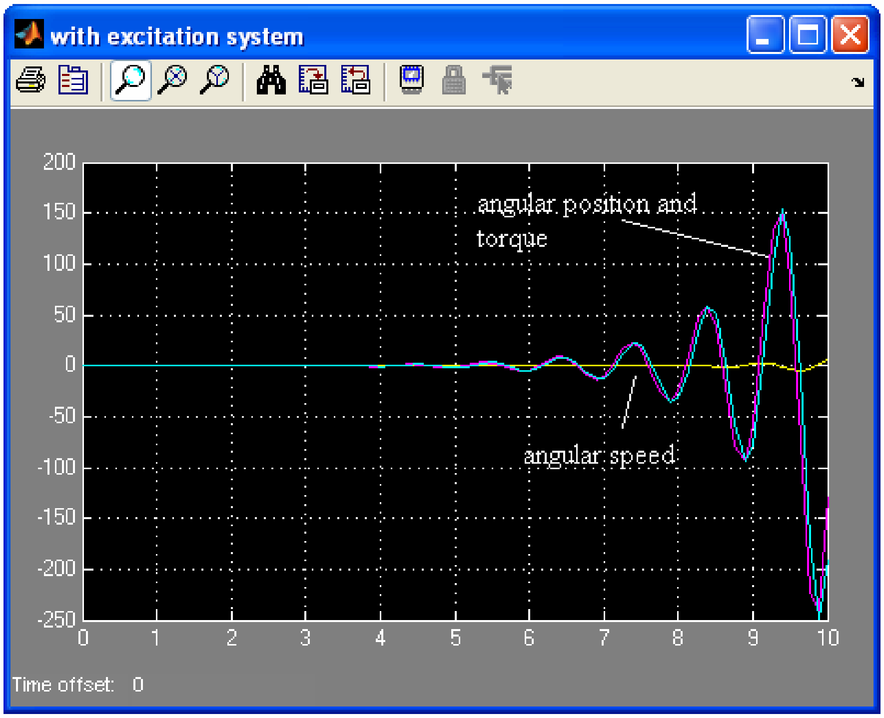

Fig 4.4: System response for a 5% change in mechanical input with K5 negative

The time response of the angular speed and angular position for a 5% step chance in mechanical input is shown in Fig 4.4. The performance characteristics shows that under damped oscillations are resulted. The Fig 4.4 depicts that it has negative damping due to the fact that K5 constant calculated above is negative which is true for high values of external system reactance and high generator outputs. The performance when analyzed with positive K5, as shown in Fig. 4.5, is coming out to be stable. The positive K5, which is possible for low value of external system reactance and low generator outputs, the damping is positive and thus the system is stable. The variation in the K5 value with the change in active power is shown in Fig. 4.6. As the active power increases, it attains negative value. With AVR, constant K_5 may have either negative or positive values which influence the damping and synchronizing torque coefficient and the stable or unstable behaviour of the system.

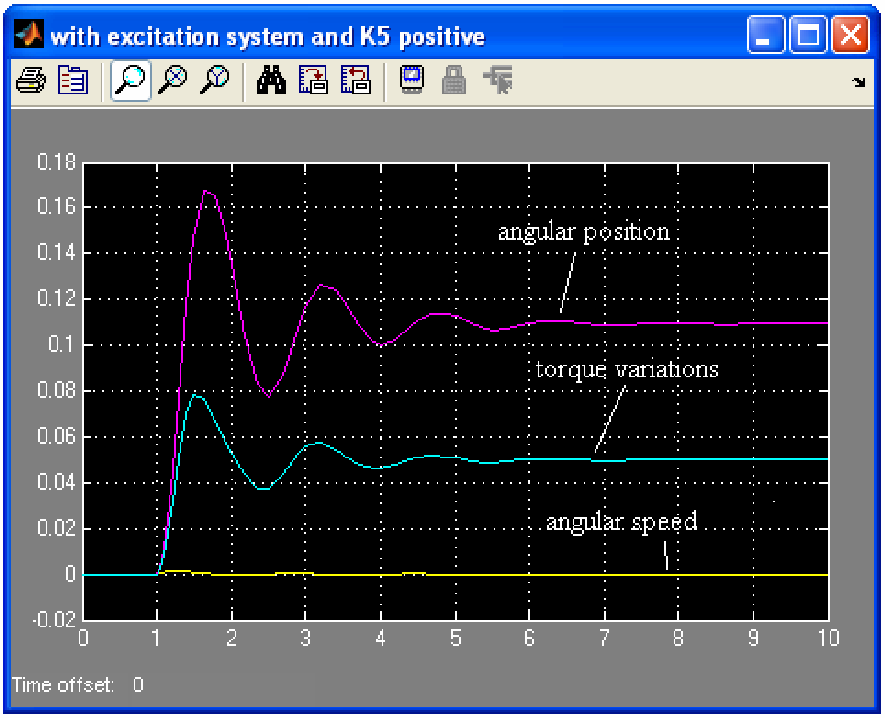

Fig 4.5: System response for a 5% change in mechanical input with K5 positive

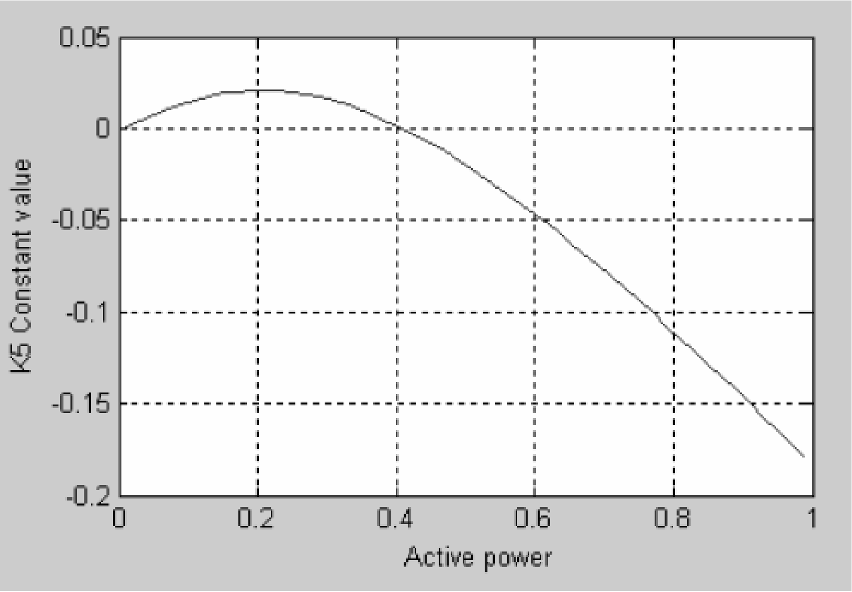

Fig 4.6: Variation of K_5 with per unit active power

For the system with AVR, the increase in active power introduces negative damping coefficient and positive synchronizing coefficient as evident from Fig 4.7 and 4.8 respectively.

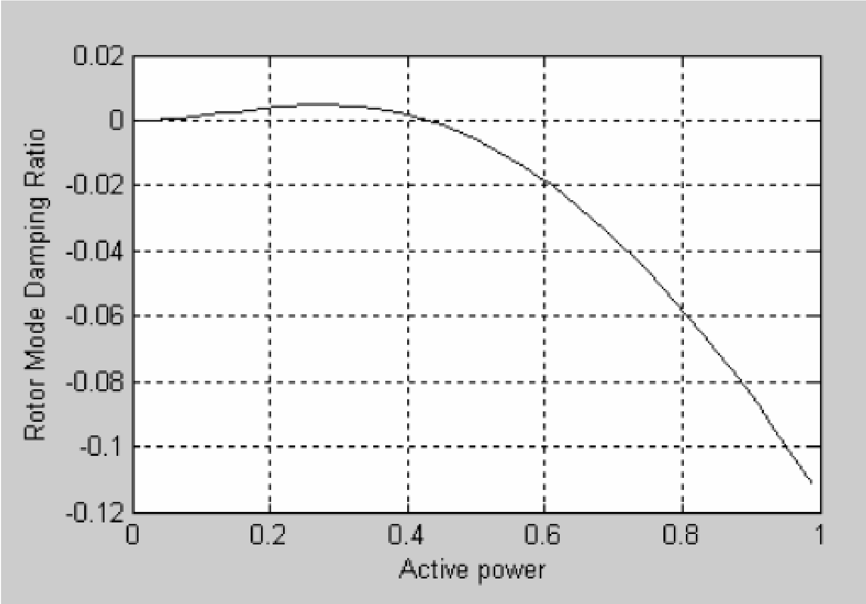

Fig 4.7: Variation of damping torque coefficient with per unit power

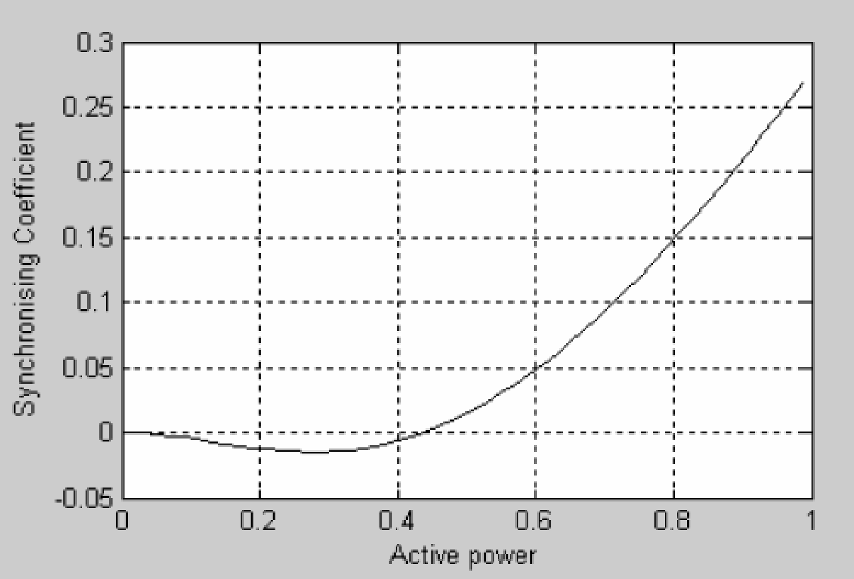

Fig 4.8: Variation of synchronizing torque coefficient with per unit power

Now effect of variation of excitation on stability will be portrayed. Values of excitation to the system are controlled by gain K_A. The effect of change in K_A on synchronizing torque coefficient and damping torque coefficient is shown in Fig. 4.9 and Fig. 4.10 respectively. The K_5 remains unaffected with the change in K_A.

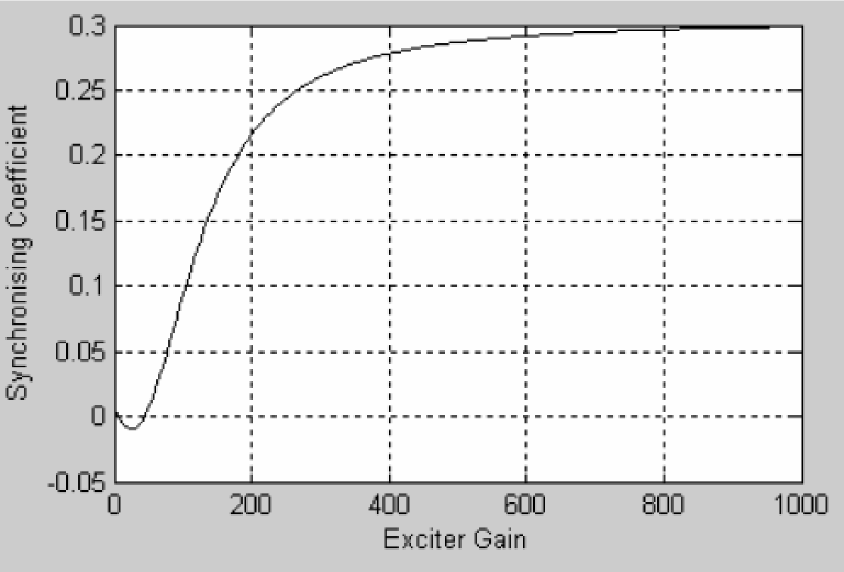

Fig 4.9: Variation of synchronizing torque coefficient with K_A

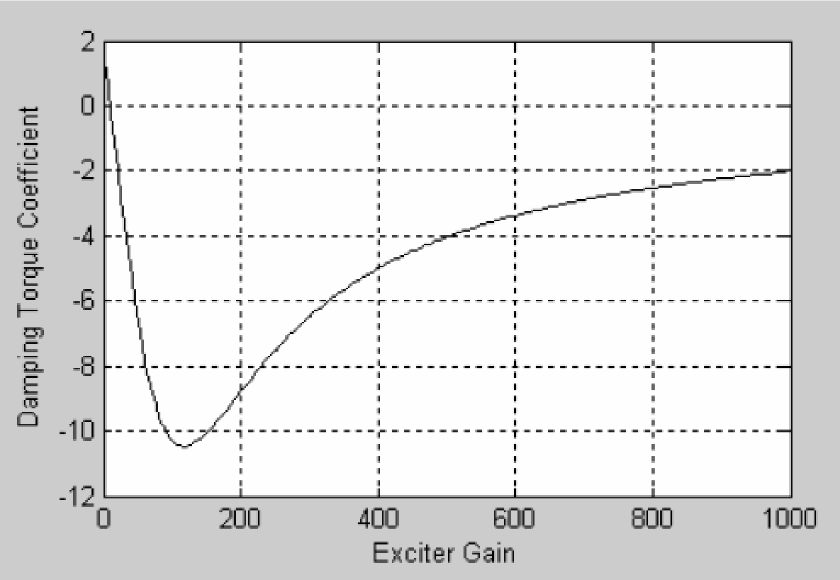

Fig 4.10: Variation of damping torque coefficient with K_A

For lower excitation the damping torque coefficient is more negative. The net damping is smallest when K_A is 110(approx.) and will increase with increase in exciter gain. But there is a certain limit up to which exciter gain can be increased. The high response exciter is beneficial in increasing synchronizing torque but in doing so it introduces a negative damping this is evident from Fig 4.9 and 4.10.

From the above analysis, we concluded that the effect of AVR on damping and synchronizing torque component is thus primarily influenced by constant K_5 and exciter gain K_A. With constant K_5 negative, the AVR action introduces a positive synchronizing torque and negative damping torque component. This effect is more pronounced as the exciter response increases. The main cause of instability of the system is negative damping coefficient; this effect of low damping should be removed by adding damping to the system. So these under damped oscillations call for a new approach i.e. power system stabilizer and later fuzzy logic based power system stabilizer.

4.3 PERFORMANCE WITH COVENSIONAL PSS (lead-lag)

The simulink model of lead-lag power system stabilizer is shown in Fig. 4.11.

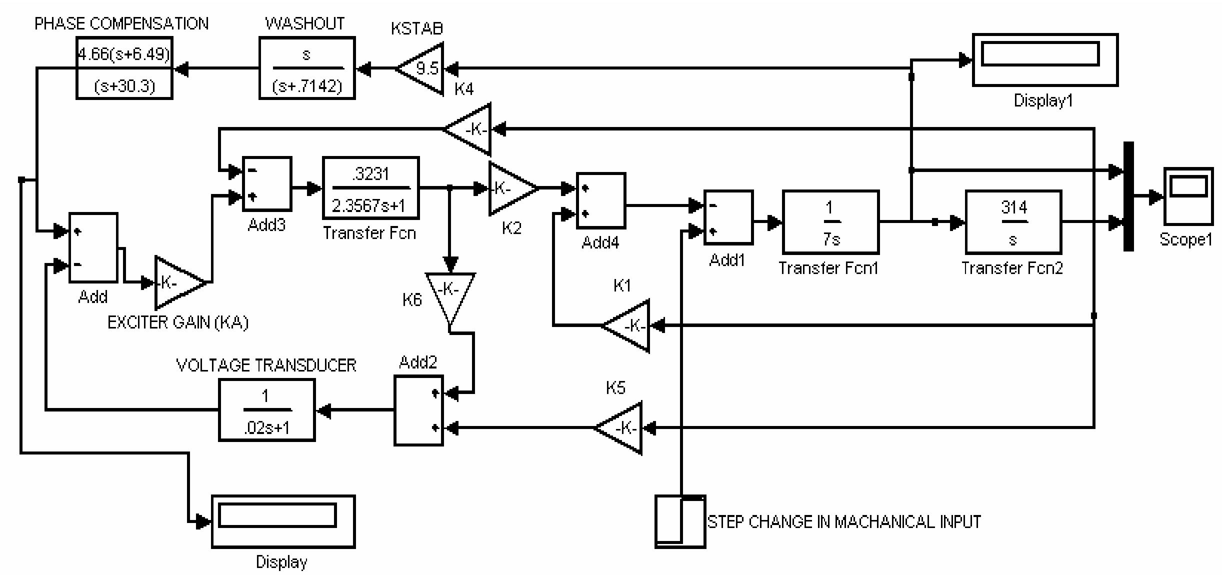

Fig 4.11: Simulink model with AVR and PSS

The parameters of PSS are:-

Parameters	Numerical values
T_1	0.154
T_2	0.033
T_W	1.4
K_{STAB}	9.5

The variation of angular position and angular speed with time for 0.05 pu increase in torque for negative and positive value of K5 are shown in Fig 4.12 and Fig.4.13 respectively. The system is coming out to be stable in both the cases, however, the transients are more with negative K5 whereas the higher angular position is attained with positive K5.

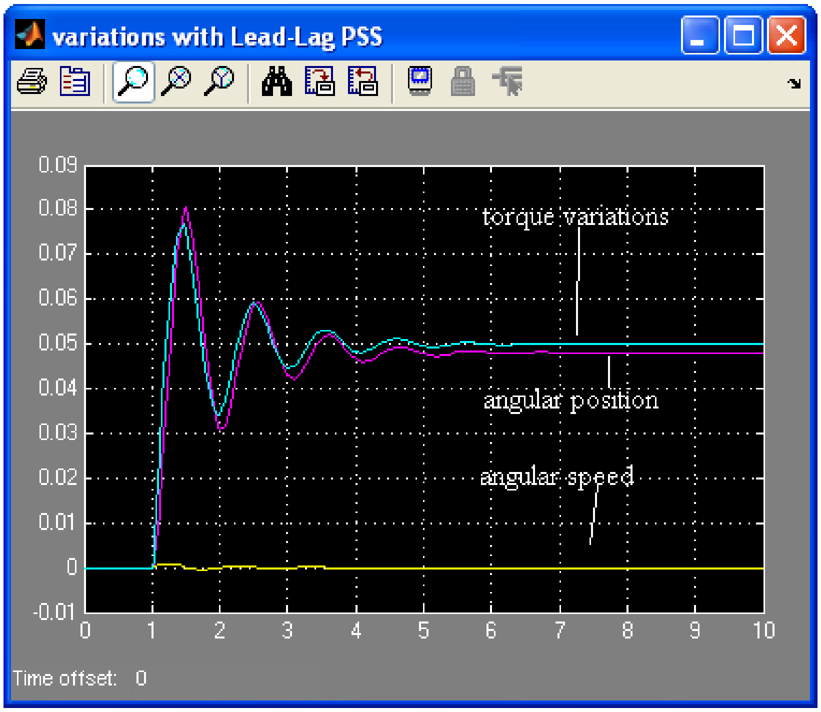

Fig 4.12: Variation of angular speed, angular position and torque when PSS (lead-lag) is applied with K5 negative

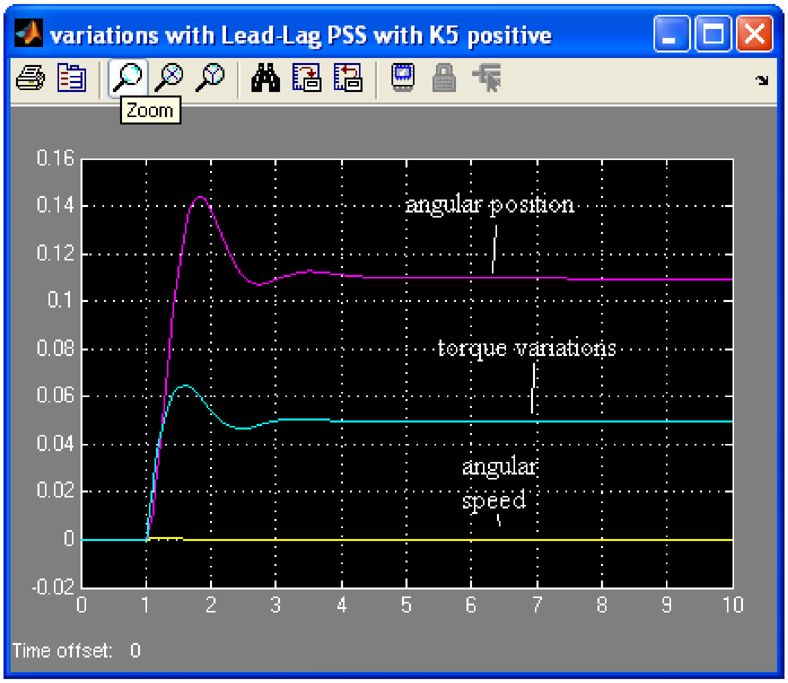

Fig 4.13: Variation of angular speed and angular position and torque when PSS (lead-lag) is applied with K5 positive

As, the system is stable with both positive and negative K5, the limitation of AVR are take taken care by applying power system stabilizer (The unstable behaviour is resulted with negative K5 with AVR only, as shown in Fig. 4.4). With Power system stabilizer the rotor mode damping ratio and damping coefficient increases with increase in exciter gain. These variations are shown in Fig 4.14 and 4.15 respectively.

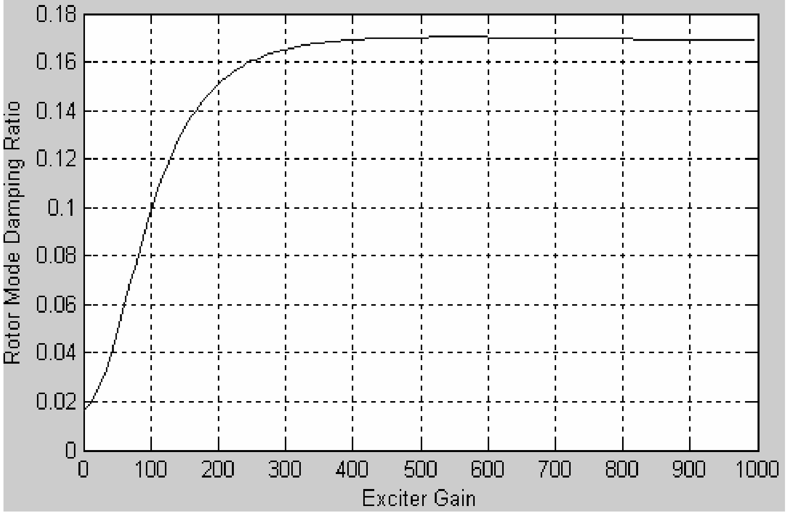

Fig 4.14: Variation of damping ratio with exciter gain

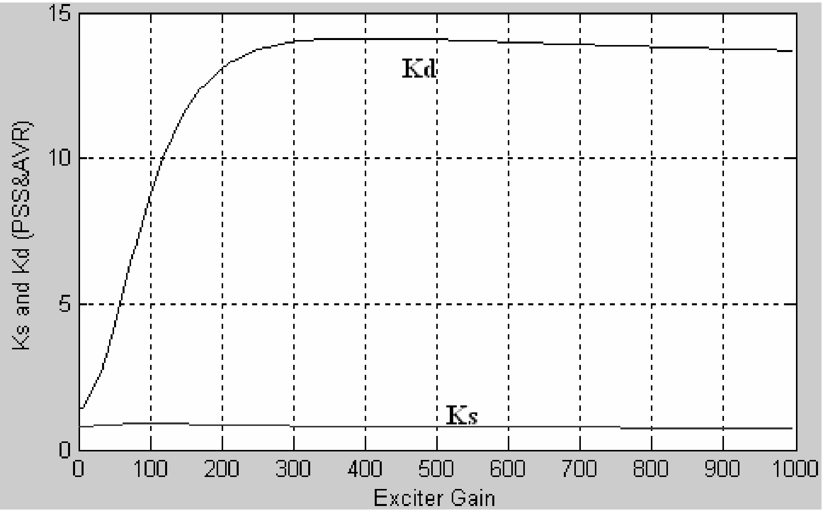

Fig 4.15: Variation of synchronizing torque coefficient and damping torque coefficient with exciter gain

The Fig 4.15 reveals that with increase in exciter gain synchronizing coefficient was positive as was with AVR (Fig. 4.9) but the main difference due to power system stabilizer is judged in damping torque coefficient which also becomes positive from negative (Fig. 4.10) thus providing increased damping to the system. And thus improve the stability.

4.4 PERFORMANCE WITH FUZZY LOGIC 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 below in Fig.4.16 and the details of the fuzzy controller are shown in Fig. 4.17.

As shown in Fig. 4.17, the fuzzy logic controller block consists of fuzzy logic block and scaling factors. The input scaling factors are two, one for each input and one scaling factor for output which determine the extent to which controlling effect is produced by the controller. The performance of fuzzy logic controller is studied for the scaling factors having the values as Kin1=1.6, Kin2=29.56, Kout=1.06.

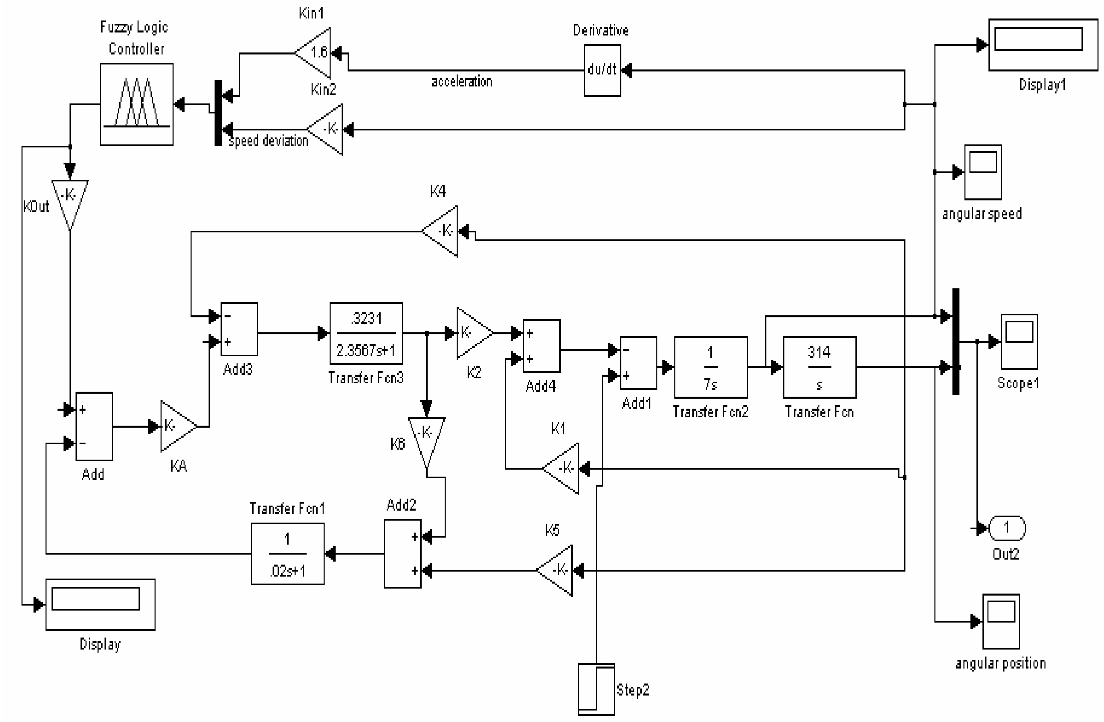

Fig 4.16: Simulink model with fuzzy logic based PSS

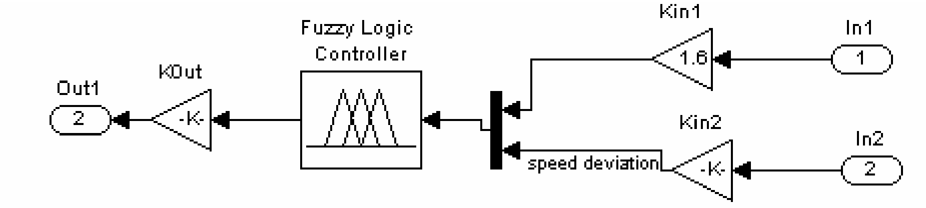

Fig 4.17: Fuzzy logic based PSS

4.4.1 FUZZY INFERENCE SYSTEM

Fuzzy logic block is prepared using fis file in Matlab 7.5 and the basic structure of this file is as shown in Fig 4.18. This is implemented using following FIS (fuzzy Inference System) properties:

And Method: Min

Or Method: Max

Implication: Min

Aggregation: Max

Defuzzification: Centroid

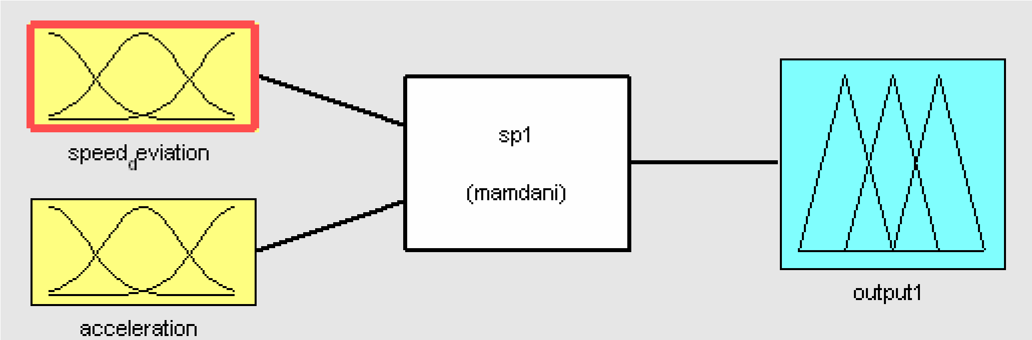

Fig 4.18: Fuzzy inference system

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 i.e. 49 rules. Fig 4.19 shows these rules using rule viewer.

The Rule Viewer displays a roadmap of the whole fuzzy inference process. The first two columns of plots show the membership functions referenced by the antecedent, or the if-part of each rule. The third column of plots shows the membership functions referenced by the consequent, or the then-part of each rule. The yellow color (or shading) in first two plots represents the antecedent rules fired for a particular value and blue color (or shading) in third column represents the consequence of the antecedent on the output. Blue color line in the last block of third column represents the final precise value calculated using centroid defuzzification method.

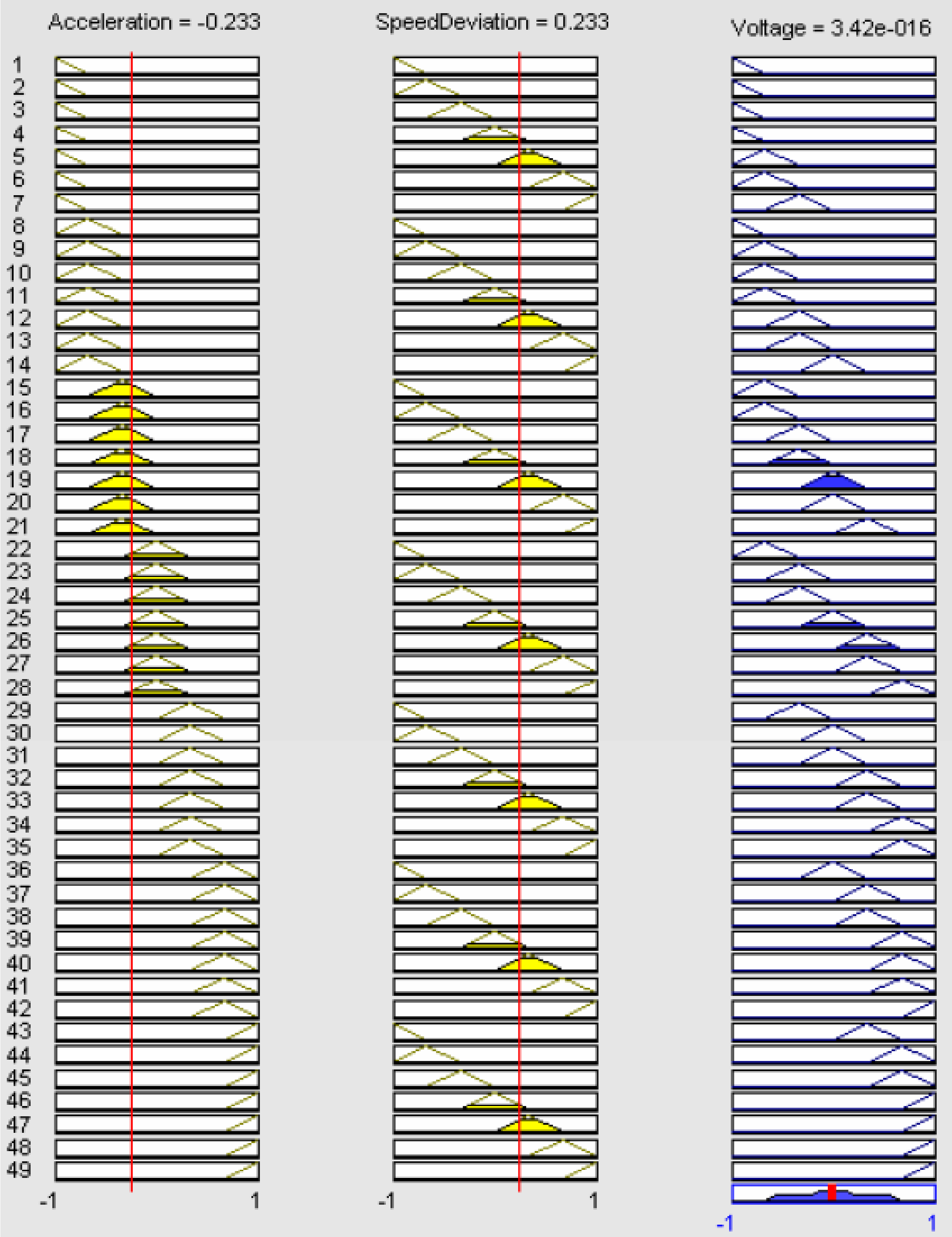

Fig 4.19: Rule viewer of fuzzy logic controller

The Rule Viewer shows one calculation at a time and in great detail. In this sense, it presents a sort of micro view of the fuzzy inference system. If the entire output surface of system is to be viewed, that is, the entire span of the output set based on the entire span of the input set, The Surface Viewer is required. Fig 4.20 shows the surface view of the system under consideration.

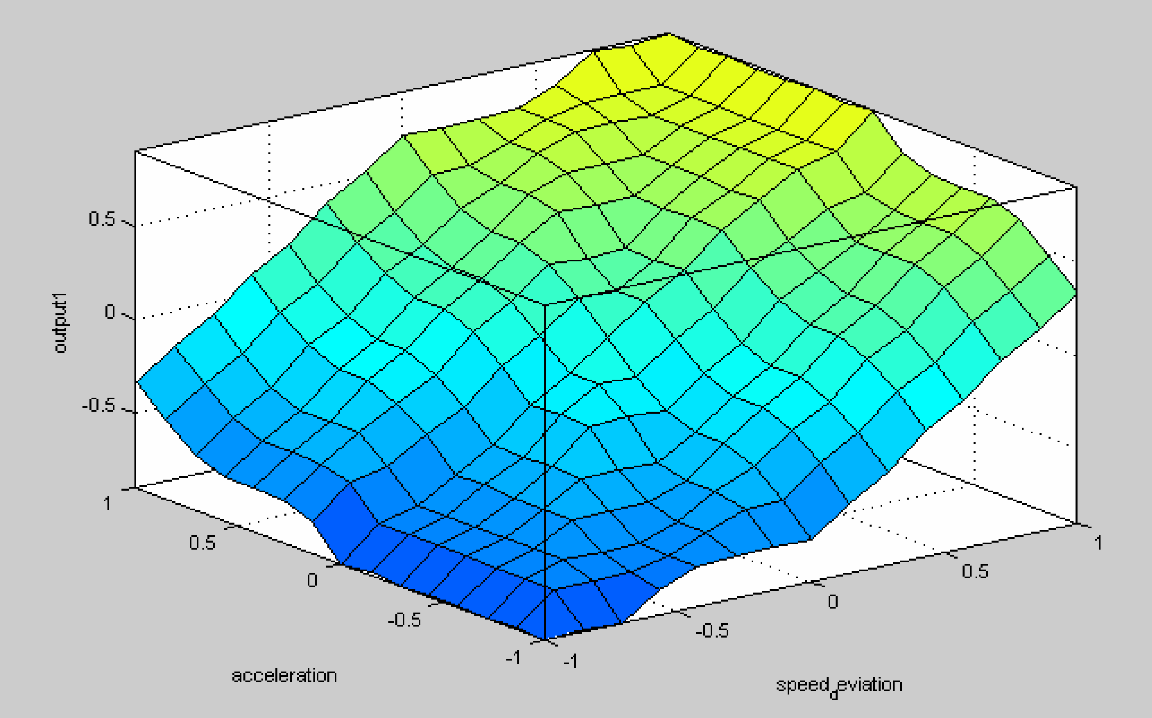

Fig 4.20: Surface viewer of fuzzy logic controller

The Surface Viewer has a special capability that is very helpful in cases with two (or more) inputs and one output: you can actually grab the axes and reposition them to get a different three-dimensional view on the data.

The variation of angular position and angular speed for a 5% step increase in mechanical input is shown in Fig 4.21 and 4.22 for the negative K5. It depicts that angular speed and angular position stabilizes to a particular value with very few oscillations.

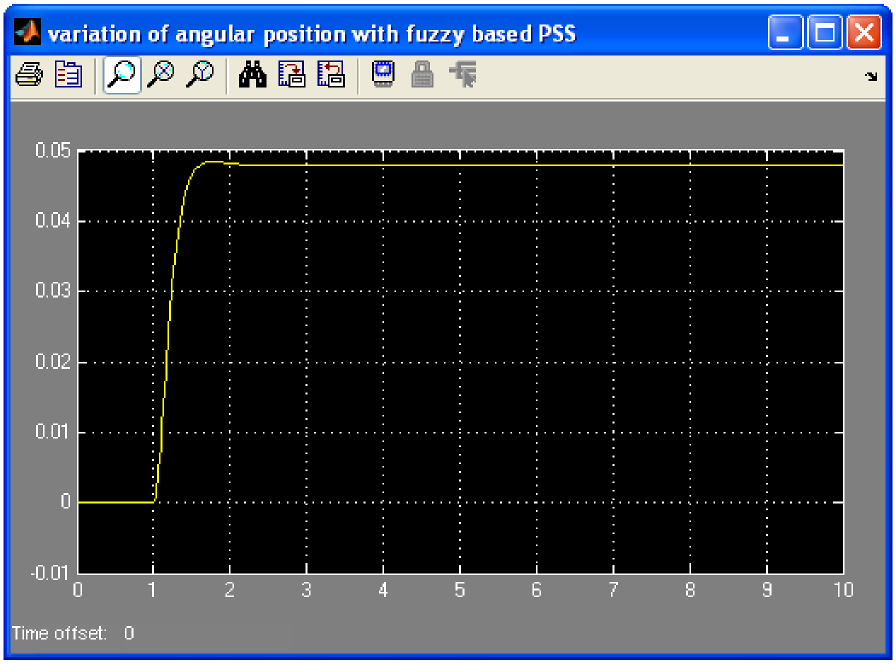

Fig 4.22: Variation of angular position for a 5% step change in mechanical input with fuzzy logic based PSS

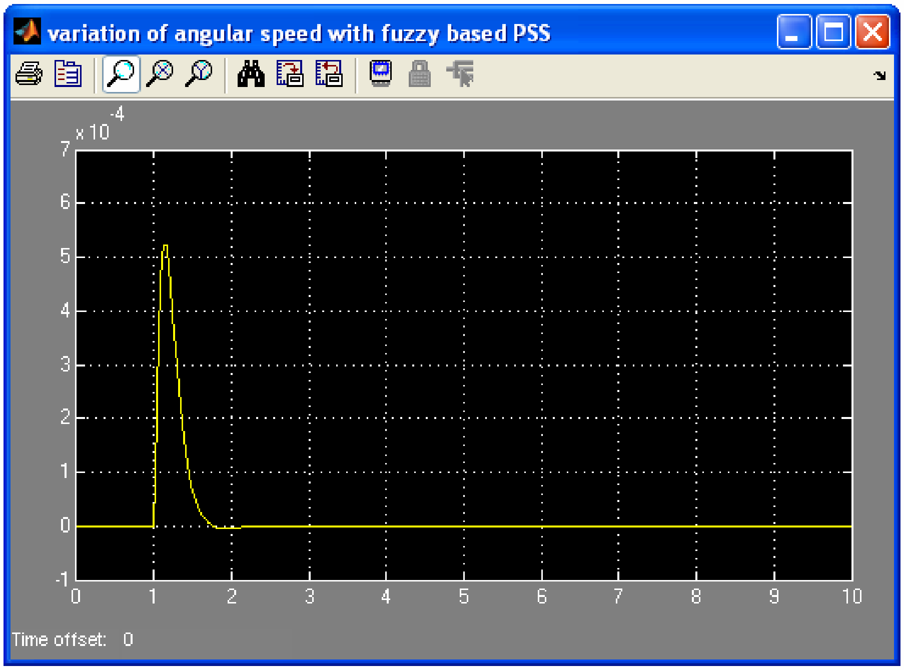

Fig 4.23: Variation of angular speed for a 5% step change in mechanical input with fuzzy logic based PSS

The results for 5% step increase in torque with K5 positive are obtained and are depicted in Fig. 4.24 and Fig. 4.25. With positive K5, the angular position attains higher value as was with conventional lead-lag PSS as demonstrated in Fig. 4.13.

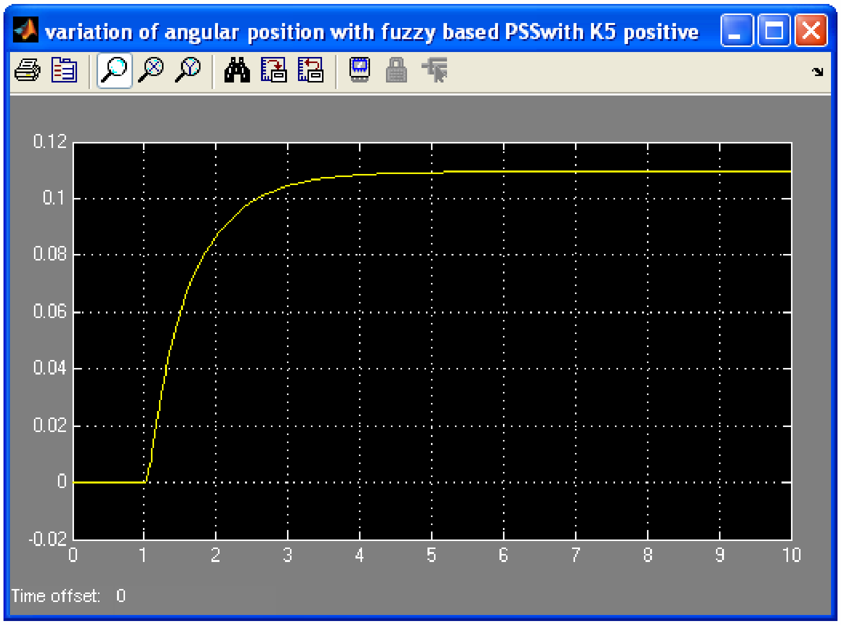

Fig 4.24: Variation of angular speed for a 5% step change in mechanical input with fuzzy logic based PSS with K5 positive

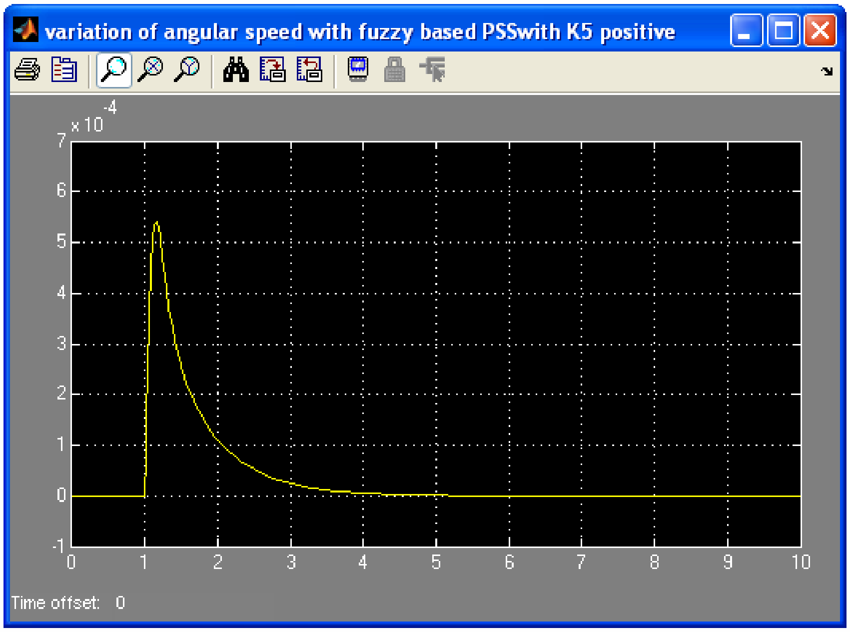

Fig 4.25: Variation of angular speed for a 5% step change in mechanical input with fuzzy logic based PSS

4.4.2 COMPARISON OF RESULTS

To compare the performance of lead-lag PSS and fuzzy logic based PSS, the step response are shown in Fig. 4.26 and Fig. 4.27 for angular speed for the negative and the positive values of K5.

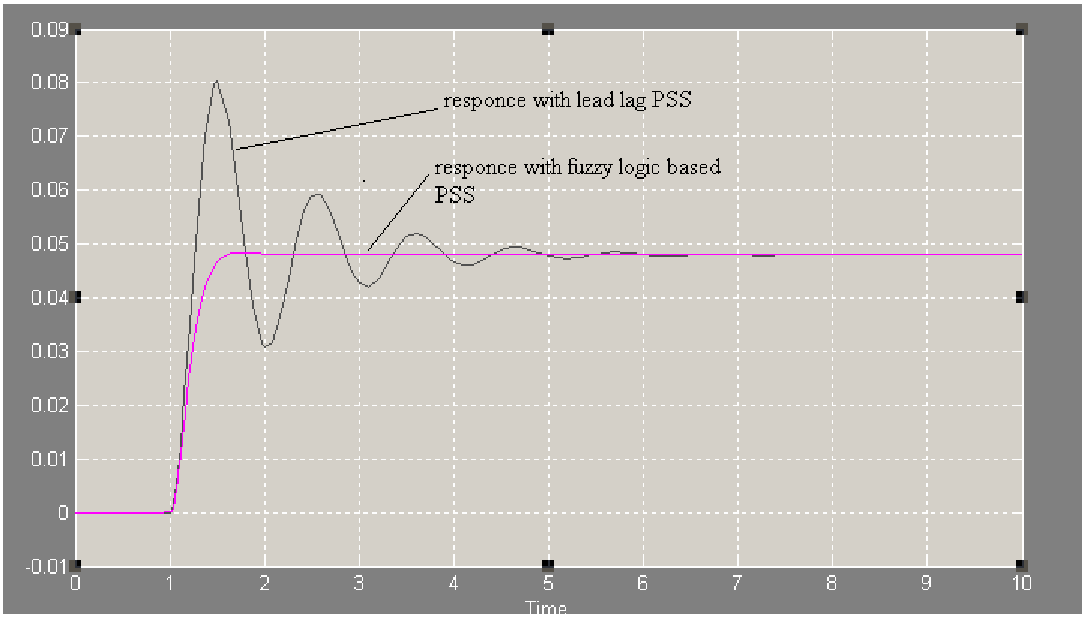

Fig 4.26: Comparison of angular position for a 5% change in mechanical input with conventional PSS (lead-lag) and fuzzy logic based PSS with K5 negative

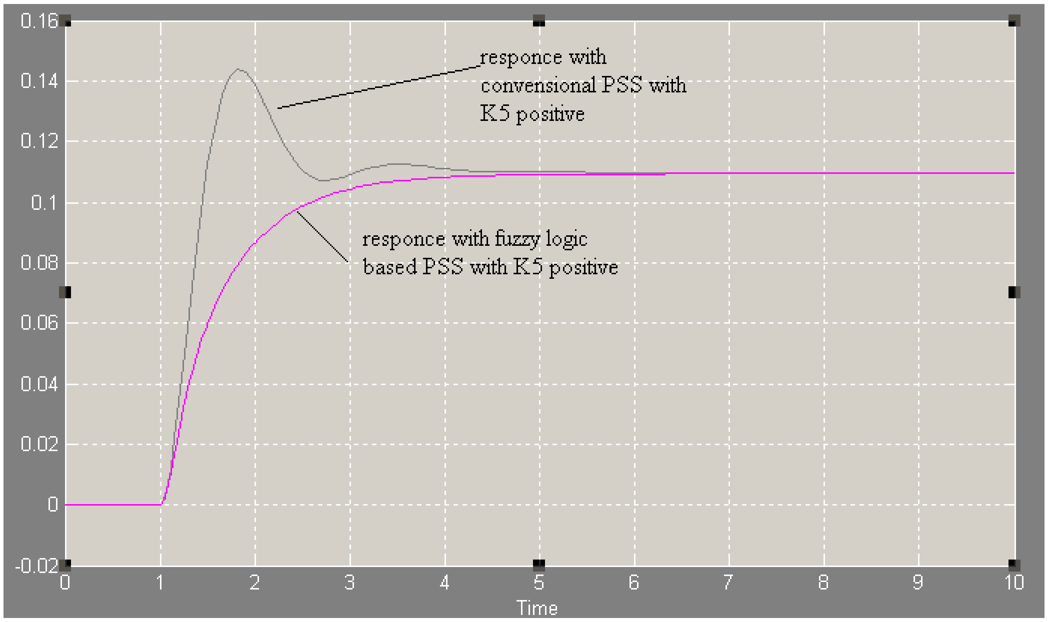

Fig 4.27: Comparison of angular position for a 5% change in mechanical input with conventional PSS (lead-lag) and fuzzy logic based PSS with K5 positive

These results are for 5% change in mechanical torque. From Fig. 4.26 and Fig. 4.27 it can be perceived that with the application of fuzzy logic the rise time and the settling time of the system decreases. The system reaches its steady state value much earlier with fuzzy logic power system stabilizer compared to conventional power system stabilizer for negative K5. For the positive value of K5, the sluggish response (overdamped response) characteristic is resulted and the settling time remains largely unchanged.

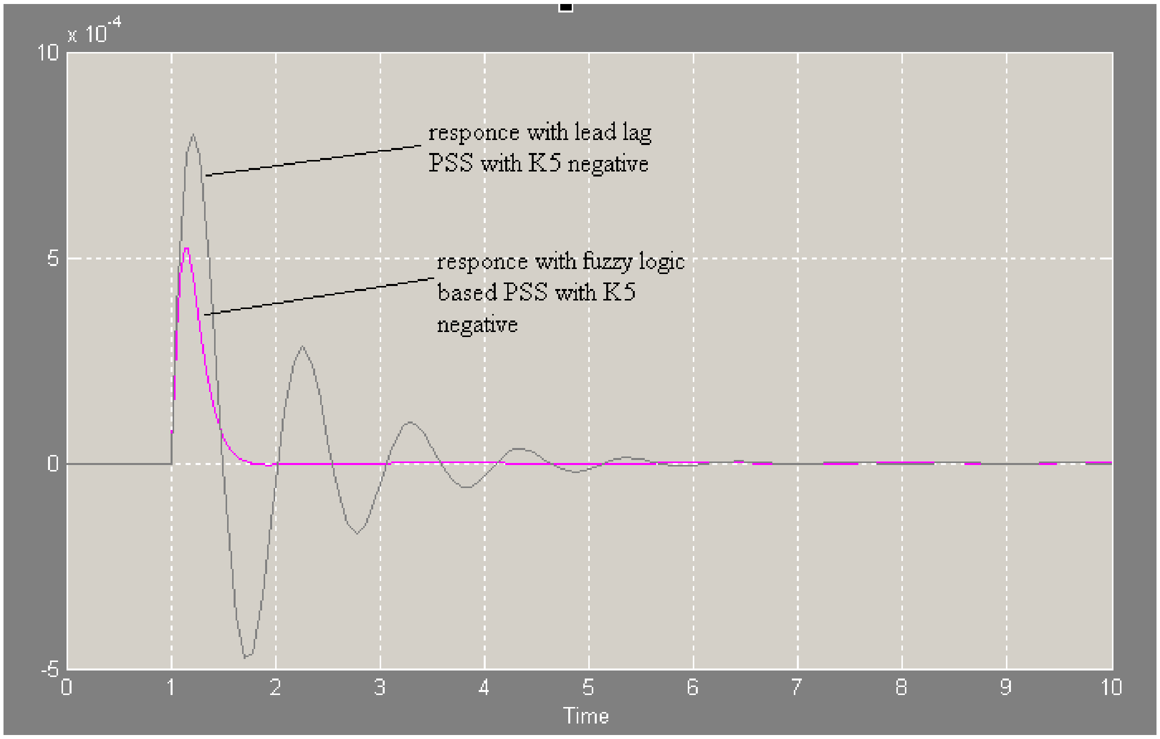

Fig 4.28: Comparison of angular speed for a 5% change in mechanical input with conventional PSS (lead-lag) and fuzzy logic based PSS with K5 negative

The step response characteristics for angular position for both lead-lag PSS and fuzzy logic based PSS are compared in Fig. 4.28 and Fig. 4.29 for negative and positive values of K5. From relative plots it can be retrieved that oscillations in angular speed reduces much faster with fuzzy logic power system stabilizer than with conventional power system stabilizer for both the cases i.e. when K5 positive and negative. As shown in Fig. 4.28 with fuzzy logic the variation in angular speed reduces to zero in about 2 seconds, but with conventional power system stabilizer it takes about 6 seconds to reach to final steady state value and also the oscillations are less pronounced in fuzzy logic based PSS. Similar is the case with K5 positive.

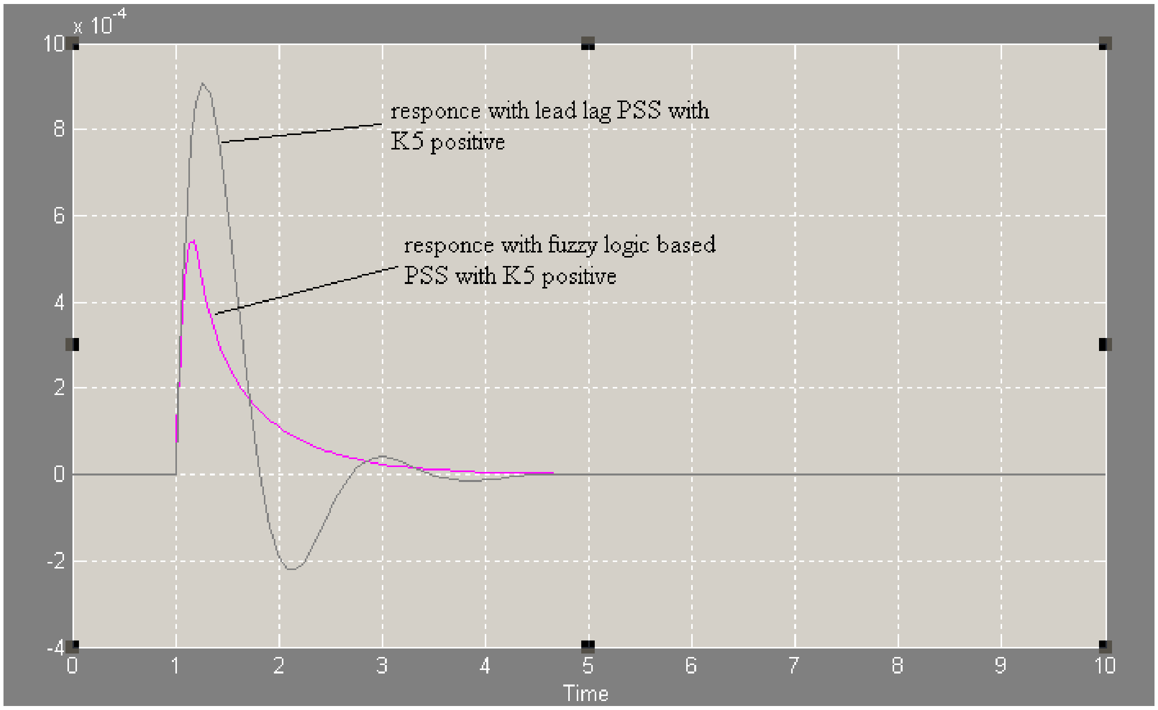

Fig 4.29: Comparison of angular speed for a 5% change in mechanical input with conventional PSS (lead-lag) and fuzzy logic based PSS with K5 positive

Therfore, it can inferred that the fuzzy controller does not require any complex mathematical support and the response is much improved than with conventional power system stabilizer.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE OF WORK

CONCLUSIONS

The target of the developed work is the damping of oscillations related to power system using a controller based on fuzzy logic theory on a single machine to infinite bus system. The purposed controller provides a more robust control over a large excursion of the operating points versus an optimal controller and lead-lag stabilizer. The conventional lead-lag PSS is not giving desired performance under wide range of operating conditions. A methodology to site the proposed controller doesn’t depend on the eigenvalue analysis approach. In this thesis work initially the effectiveness of power system stabilizer in damping power system stabilizer is reviewed then fuzzy logic power system stabilizer is introduced after taking speed deviation and acceleration of synchronous generator as the input signals to the fuzzy controllers and voltage as the output signal. FPSS shows the better control performance than power system stabilizer in terms of settling time and damping effect. The proposed FPSS produces better damping effect than PSS. It is thus possible to realize the controller efficiently. The overdamped response is resulted with positive K5, which is normally not encountered in practical situations. Therefore, it can be concluded that the performance of the proposed FPSS is much better and the oscillations are damped out much quicker.

SCOPE FOR FURTHER WORK

Having gone through the study of fuzzy logic PSS for single machine infinite bus system, the scope of the work has been identified as –

- Extend the fuzzy logic based PSS to truly multimachine interconnected system having non-linear industrial loads which may introduce phase shift.
- The work done in this thesis is focused on rotor speed as an input variable. The fuzzy logic 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.

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