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Dynamic Stability Enhancement of Power System using Fuzzy Logic Based Power System Stabilizer

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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 signal derived from 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 stabilizer has become very common in operation of large electric power systems. The conventional PSS which uses lead-lag compensation, where gain setting 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.

Keywords:- Generator Excitation System, Synchronous Machine Model, Automatic Voltage Regulator (AVR), Power System Stabilizer, Fuzzy Logic Controller (FLC), PID, Controller Design, Robust control.

1. Introduction

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 0.1 to 0.8 Hz, these swings are due to the poor damping characteristics caused by modern voltage regulators with high gain. A high gain regulator through excitation control has an important effect of eliminating synchronizing torque but it affects the damping torque negatively. 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.

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.

2. System Modeling

The Mathematical Models needed for small signal analysis of Synchronous Machines, Excitation System and lead-lag power system stabilizer are briefly reviewed. The Guidelines for the selection of Power System Stabilizer parameters are also presented.

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 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. The Thevenin's equivalent circuit shown in Fig. 1.1

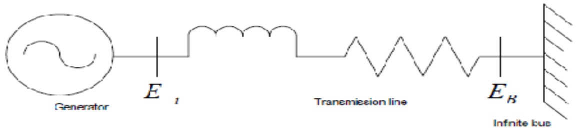

Fig. 1.1 The equivalent circuit of synchronous machine connected to infinite bus.

Classical System Model

The generator is represented as the voltage E' behind Xd' as shown in Fig. 1.2. The magnitude of E' is assumed to remain constant at the pre-disturbance value. Let d be the angle by which E' leads the infinite bus voltage EB. The d changes with rotor oscillation. The line current is expressed as –

$$I_t = \frac{E'\angle 0^0 - E_B\angle -\delta}{jX_T} = \frac{E' - (E_B\cos\delta - j\sin\delta)}{jX_T} \quad (1)$$

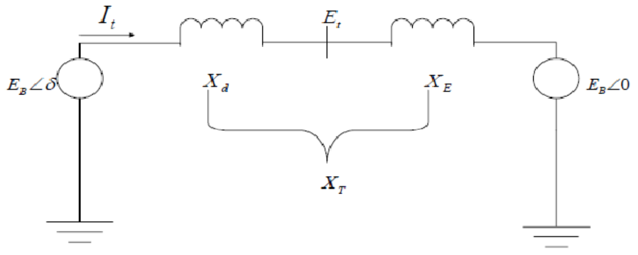

Fig. 1.2: Classical model of generator

The Complex Power behind Xd' is given by-

$$S = P + jQ = \frac{E'E_B\sin\delta}{X_T} + j\frac{E'(E' - E_B\cos\delta)}{X_T} \quad (2)$$

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

$$T_e = P = \frac{E'E_B}{X_T}\sin\delta \quad (3)$$

Linearising about an initial operating condition represented by δ = δ 0 yields

$$\Delta T_e = \frac{\partial T_e}{\partial\delta}\Delta\delta = \frac{E'E_B}{X_T}\cos\delta_0(\Delta\delta) = K_s\Delta\delta \quad (4)$$

Where, $K_s = \frac{E'E_B}{X_T}\cos\delta_0$

The equations of motion in per unit are:

$$p\Delta\omega_r = \frac{1}{2H}(T_M - T_e - K_D\Delta\omega_r)$$
$$p\delta = \omega_0\Delta\omega_r \quad (5)$$

Linearising Eqn. 5 and substitute for ΔT**e,** given by equation 4, result into:

$$p\Delta\omega_r = \frac{1}{2H}(\Delta T_M - K_s\Delta\delta - K_D\Delta\omega_r)$$
$$p\Delta\delta = \omega_0\Delta\omega_r \quad (6)$$

Writing equation 6 in Matrix form we obtain

$$\frac{d}{dt}\begin{pmatrix}\Delta\omega\\ \Delta\delta\end{pmatrix}=\begin{pmatrix}-\frac{K_D}{2H} & -\frac{K_s}{2H}\\ \omega_o & 0\end{pmatrix}\begin{pmatrix}\Delta\omega\\ \Delta\delta\end{pmatrix}+\begin{pmatrix}\frac{1}{2H}\\ 0\end{pmatrix}\Delta T_M \tag{7}$$

The equation 7 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 7 to describe small-signal performance is represented in block diagram as Fig. 1.3

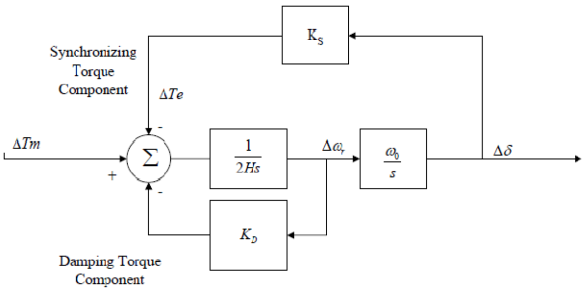

Fig. 1.3: Block diagram of single machine infinite bus system with classical model

From the block diagram we have:

$$\Delta\delta=\frac{\omega_0}{s}\left(\frac{1}{2Hs}\;(-K_s\Delta\delta-K_D\Delta\omega_r+\Delta T_M)\right)$$
$$=\frac{\omega_0}{s}\left(\frac{1}{2Hs}\;(-K_s\Delta\delta-K_D\frac{\Delta\delta}{\omega_0}s+\Delta T_M)\right) \tag{8}$$

Solving the block diagram we get the characteristics equation:

$$s^2+\frac{K_D}{2H}s+\frac{K_s\omega_0}{2H}=0 \tag{9}$$

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

$$\omega_n=\sqrt{\frac{K_s\omega_0}{2H}}$$

$$\xi=\frac{1}{2}\frac{K_D}{\sqrt{K_s 2H\omega_0}} \tag{10}$$

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. 1.4

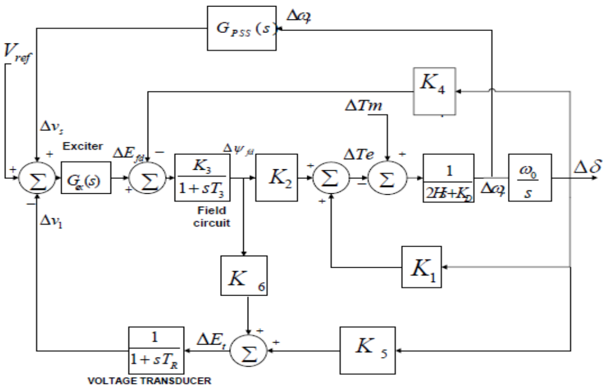

Fig. 1.4: Block diagram representation with AVR and PSS

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 Δωr. The PSS transfer function, GPSS(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.

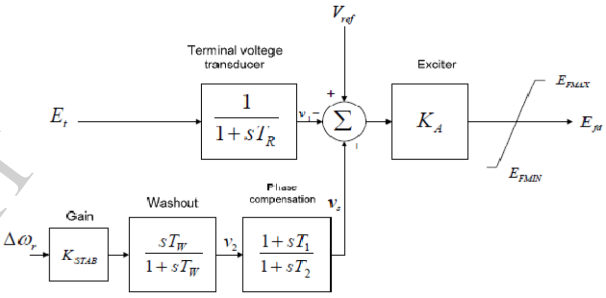

Fig. 1.5: Thyristor excitation system with AVR and PSS

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. 1.5 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 Tw high enough to allow signals associated with oscillations in wr 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 KSTAB 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.

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.

4. Power System Stabilizer Model-

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.

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.

5. 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. 1.6 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.

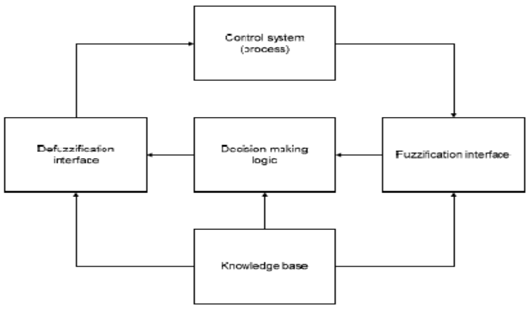

Fig. 1.6: The principle design of fuzzy logic controller

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.

6. 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.

Selection of input and output Variable

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

In Practice, only shaft speed is readily available. The acceleration signal can be derived from the speed signals measure at two successive instants using the following equations:

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

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.

The variables are normalized by multiplying with respective gains Kin1, Kin2, Kout 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. 1.7.

NB	NEGATIVE BIG
NM	NEGATIVE MEDIUM
NS	NEGATIVE SMALL
ZE	ZERO
PS	POSITIVE SMALL
PM	POSITIVE MEDIUM
PB	POSITIVE BIG

Table 1: Membership functions for fuzzy variables

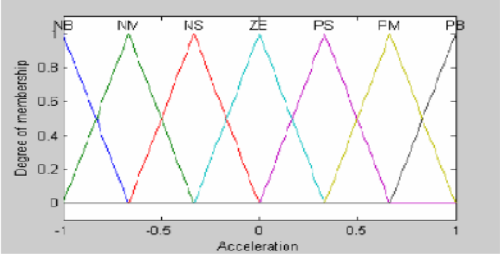

Fig. 1.7(a) Membership functions for acceleration

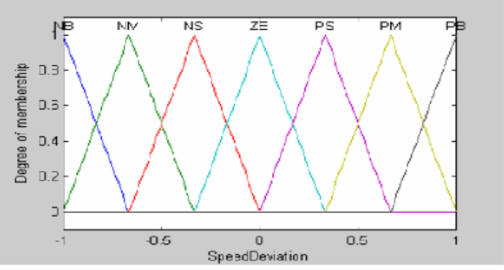

Fig. 1.7(b) Membership functions for speed deviation

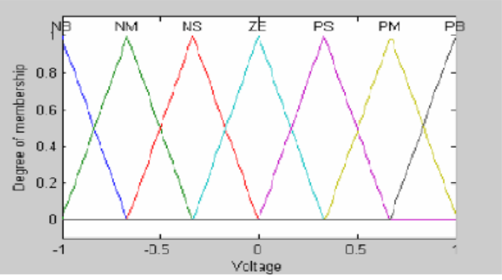

Fig. 1.7(c) Membership functions for voltage

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 2 where all the symbols are defined in the basic fuzzy logic terminology.

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

Table 2: Rule base of fuzzy logic controller

DEFUZZICATION

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:

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

7. Simulation Model and Result-

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. The machine data is taken from

TABLE-I

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} K_{sd}	0.153 0.8491
K_{sq}	0.8491
K_{sdI} K_{sqI}	0.434 0.434
A_{SAT}	0.031
B_{SAT} ψ_1	6.93 0.8
Frequency of oscillation (in rad/sec)	10

Performance with constant field voltage-

The model used in the simulink to study the response of the system with constant field voltage is shown in figure. In this representation the dynamic characteristics are represented in terms of K constant. The values of K constants are calculated using above parameters are-

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

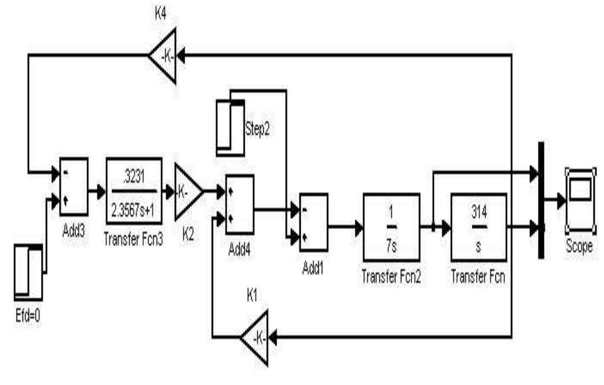

Fig 1.8: Simulink model for simulation of single machine infinite bus System with constant field voltage.

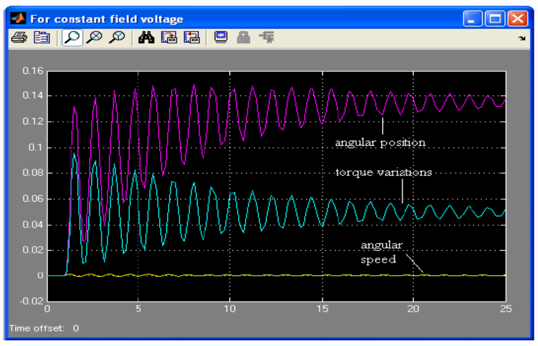

Fig 1.9: System response for a 5% change in mechanical input

Performance with Excitation System only-

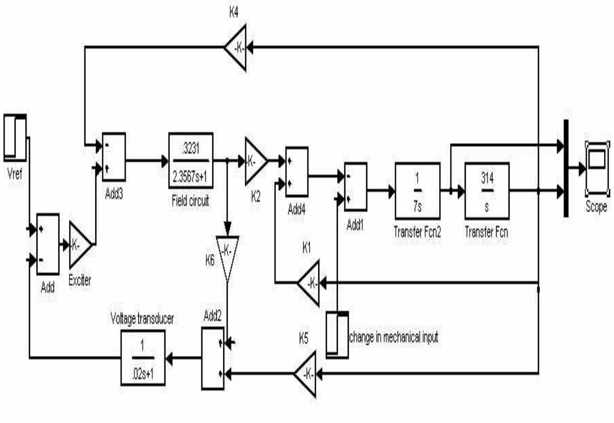

Fig 1.10: Simulink model for simulation of single machine infinite bus system with AVR only

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 1.10. The excitation system parameters are taken as K = 200 and TR = 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

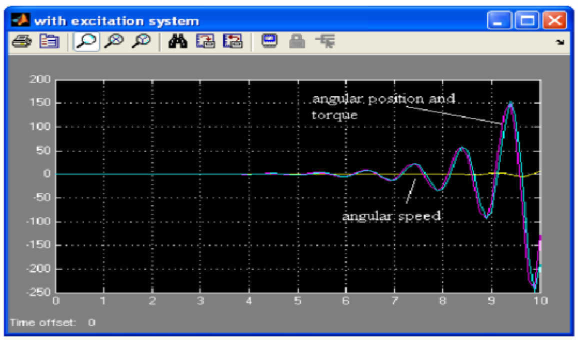

Fig 1.11: System response for a 5% change in mechanical input with K5 negative

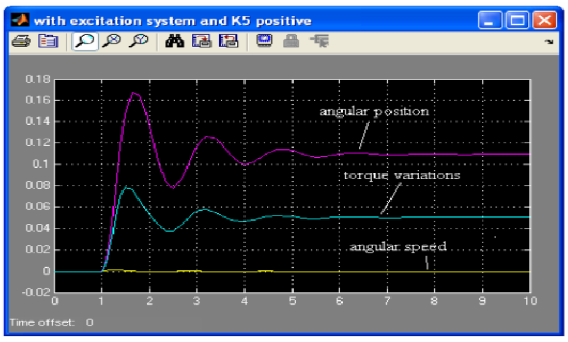

Fig 1.12: System response for a 5% change in mechanical input with K5 positive

Performance with Conventional PSS lead-lag-

The simulink model of lead-lag power system stabilizer is shown in Fig. 1.13

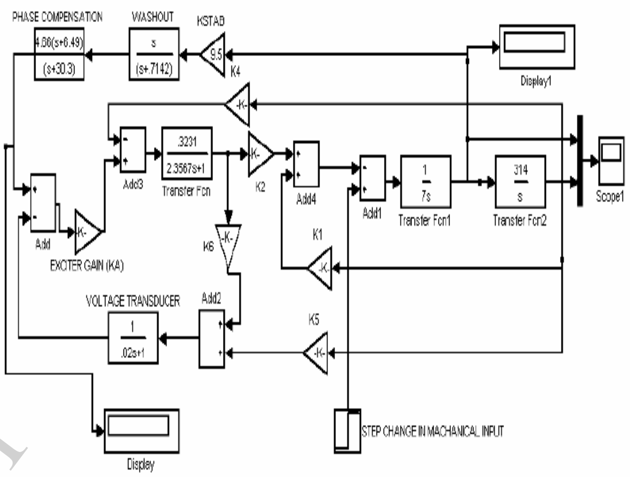

Fig 1.13 Simulink Model with AVR and PSS

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 1.14 and Fig.1.15 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.

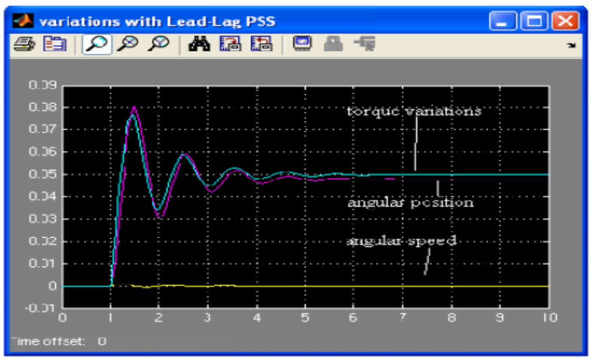

Fig 1.14: Variation of angular speed, angular position and torque when PSS (lead-lag) is applied with K5 negative.

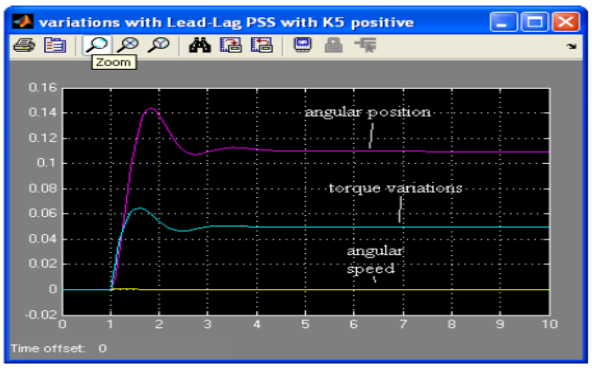

Fig 1.15: Variation of angular speed and angular position and torque when PSS (lead-lag) is applied with K5 positive

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.1.16 and the details of the fuzzy controller are shown in Fig. 1.17. As shown in Fig. 1.18, 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.

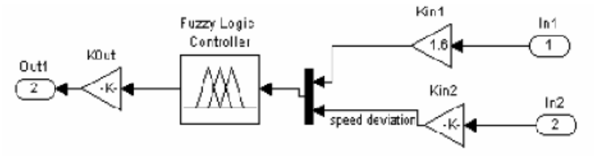

Fig 1.16: Fuzzy logic based PSS

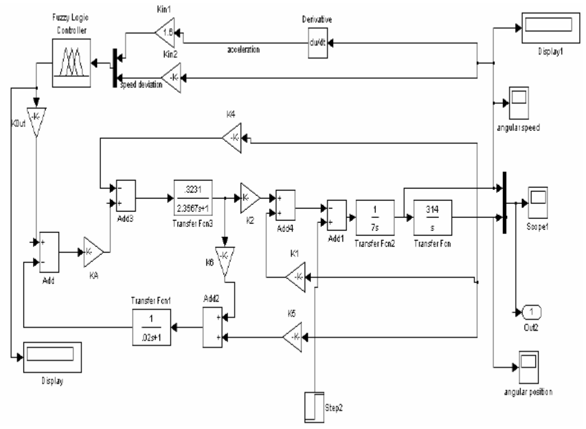

Fig 1.17: Simulink model with fuzzy logic based PSS

8. 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 1.17. This is implemented using following FIS (fuzzy Inference System) properties:
And Method: Min
Or Method: Max
Implication: Min
Aggregation: Max
Defuzzification: Centroid

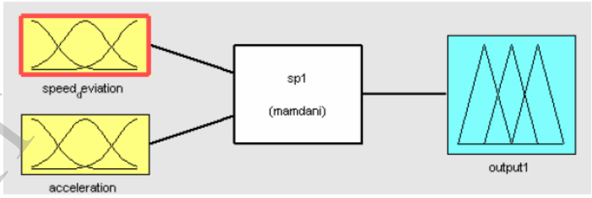

Fig 1.18: Fuzzy Inference System

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.

9. Comparison of Results-

To compare the performance of lead-lag PSS and fuzzy logic based PSS, the step response are shown in Fig. 1.19 and Fig. 1.20 for angular speed for the negative and the positive values of K5.

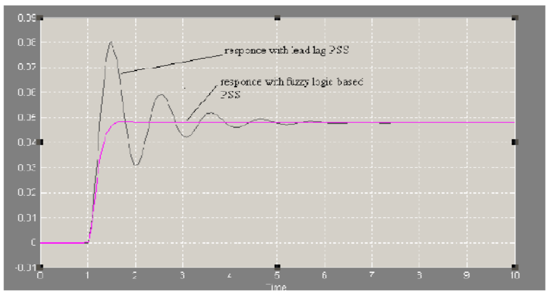

Fig 1.19: Comparison of angular position for a 5% change in mechanical input with conventional PSS (lead-lag) and fuzzy logic based PSS with K5 negative.

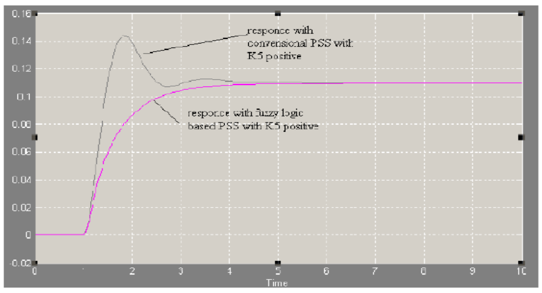

Fig 1.20: Comparison of angular position for a 5% change in mechanical input with conventional PSS (lead-lag) and fuzzy logic based PSS with K5 positive

These results are for 5% change in mechanical torque. From Fig. 1.19 and Fig. 1.20 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 (over damped response) characteristic is resulted and the settling time remains largely unchanged.

The step response characteristics for angular position for both lead-lag PSS and fuzzy logic based PSS are compared in Fig. 1.21 and Fig. 1.22 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. 1.22 with fuzzy logic the variation in angular speed reduces to zero in about 2seconds 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.

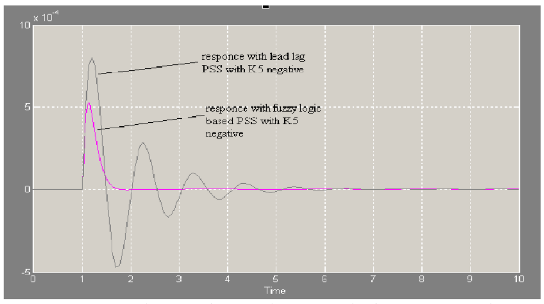

Fig 1.21: Comparison of angular speed for a 5% change in mechanical input with conventional PSS (lead-lag) and fuzzy logic based PSS with K5 negative.

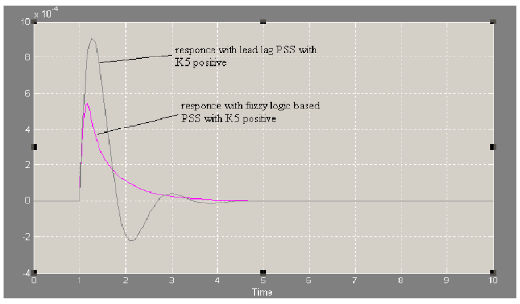

Fig 1.22: Comparison of angular speed for a 5% change in mechanical input with conventional PSS (lead-lag) and fuzzy logic based PSS with K5 positive.

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

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