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Improvement of Dynamic Stability of a SMIB using Fuzzy logic based Power System Stabilizer

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Abstract—In this paper a design of an optimal fuzzy Proportional Integral derivative (PID) power system stabilizer for single machine infinite bus power system (SMIB) is presented. The aim of the control is to enhance the stability and to improve the dynamic response of the SMIB operating at different conditions. Speed deviation and rate of change of speed deviation of the synchronous machines are chosen as input signals to the fuzzy controllers. These variables take significant effects on damping of the generator shaft mechanical oscillations. The three parameters (K_p, Ki, K_d) of PID controller are computed using the fuzzy membership functions depending on these variables. The inference mechanism of the fuzzy PID controller is represented by three (7x7) decision tables. Simulation results of Fuzzy PID power system stabilizer are compared with Conventional Power System Stabilizer (CPSS) and Fuzzy power system stabilizer in order to show effectiveness of the proposed controller.

Keywords— Fuzzy logic controller (FLC), PID, CPSS, SMIB, synchronous generator.

I. INTRODUCTION

The power system is a dynamic system. The electrical power systems today are no longer operated as isolated systems, but as interconnected systems which may include thousands of electric elements and be spread over vast geographical areas. There are many advantages of interconnected power systems. 1) To provide large blocks of power and increase reliability of the system. 2) To reduce the number of machines which are required both for operation at peak load and required as spinning reserve to take care of a sudden change of load. 3) To provide economical source of power to consumers. Low frequency oscillations are a common problem in large power system [7].

II. POWER SYSTEM STABILIZER

A power system stabilizer (PSS) can provide a supplementary control signal to the excitation system and/or the speed governor system of the electric generating unit to damp the oscillations. Due to their flexibility, easy implementation, and low cost PSSs have been extensively studied and successfully used in power systems for many years [4]. Most PSSs in use in electric power systems employ the classical linear control theory approach based on a linear model of a fixed configuration of the power system. Such a fixed-parameter PSS are called CPSS, is widely used in power systems and has made a great contribution in enhancing power system dynamics. The parameters of CPSS are determined based on a linearized model of the power system around a nominal operating point to obtain good performance. Because power systems are highly nonlinear systems, with configurations and parameters that change with time, the CPSS design based on the linearized model of the power systems cannot guarantee its performance in a practical operating environment [3].The Block diagram of the PSS is shown in the fig 2.1[3].

To improve the performance of CPSS, numerous techniques have been proposed for their design, such as using intelligent optimization methods (genetic algorithms, neural networks, fuzzy). It recent years, fuzzy logic control has emerged as a powerful tool and is starting to be used in various power system applications [3].The application of fuzzy logic control techniques are most suitable one whenever a suitable control objective cannot be specified, the system to be controlled is a complex one, or its exact mathematical model is not available. In this paper a new power system stabilizer with a fuzzy PID controller is presented. Comparison studies have been performed between the CPSS, the fuzzy controller and the fuzzy PID. The simulations results clearly demonstrate the superiority of the fuzzy PID in comparison to the fuzzy and CPSS.

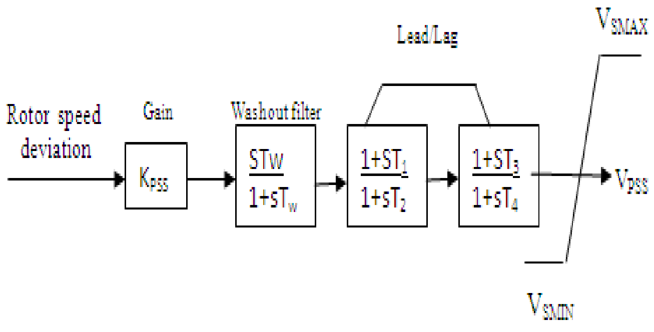

Fig 2.1 Block diagram of the power system stabilizer

III SMIB MODEL

The performance of a synchronous machine connected to a large system through transmission lines has shown in Fig 3.1. The general system configuration of synchronous machine connected to infinite bus through transmission network can be represented as the Thevenin's equivalent circuit [4].

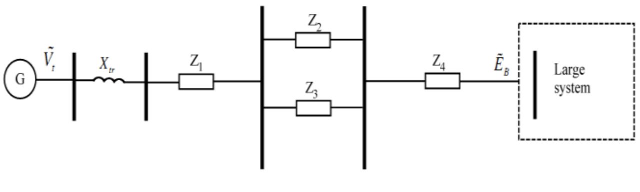

Fig 3.1 General Configuration of SMIB

The classical model representation of the generator [7] and with all the resistances neglected, the system representation is shown in Fig 3.2

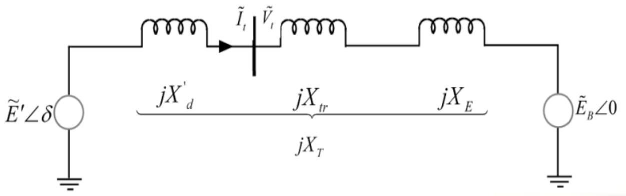

Fig 3.2: Classical model of the synchronous generator

In Fig 3.2, X'_d is the direct axis transient reactance of the generator. The magnitude of $\tilde{E}'$ is assumed to remain constant at the pre-disturbance value. Let δ b e the angle by which $\tilde{E}'$ leads the infinite bus voltage $\tilde{E}_B$ [5]. The complex power is given by

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

(3.1)

When a power system under normal load condition suffers a perturbance there is synchronous machine voltage angles rearrangement. If for each perturbance that occurs, an unbalance is created between the system generation and the load, a new operation point will be established and consequently there will be voltage angle adjustments [3]. The complete model is shown in Fig 3.3

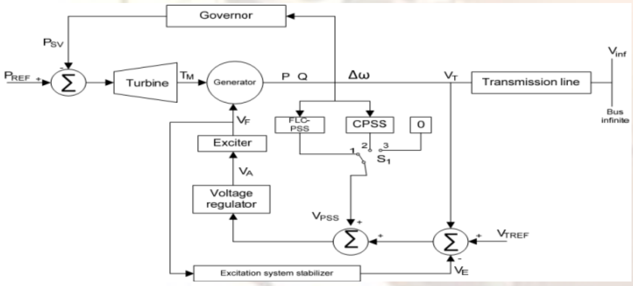

Fig 3.3 System model configuration

As a primitive definition, it can be said that the system oscillatory response during the transient period, shortly after the perturbance, is damped and the system goes in a definite time to a new operating condition, so the system is stable. This means that the oscillations are damped, that the system has inherent forces which tend to reduce the oscillations. In fig 3.3, P_{ref} is mechanical power reference, P_{sv} is feedback through the governor, T_m is turbine output torque, V_{inf} is infinite bus voltage, V_{tref} is terminal voltage reference, V_T is the terminal voltage, V_A is the voltage regulator output, ΔΩ is the speed deviation, V_{PSS} is the PSS output, V_F is field voltage, V_E is the excitation system stabilizing signal, P is the power active and Q is reactive power at the generator terminal[4], [7].

The instability in a power system can be shown in different ways, according to its configuration and its mode of operation, but it can be observed without synchronism loss.

The generating unit is modeled by the five first-order differential equations given below

$$\dot{\delta} = \omega - \omega_0 \,, \tag{3.2}$$

$$\dot{\omega} = \frac{\pi f}{H}(T_m - T_e) \,, \tag{3.3}$$

$$T_{d0}\dot{e}'_q = e_f - (x_d - x'_d)i_d - e'_q \,, \tag{3.4}$$

$$T''_{do}\dot{e}''_q = \left[e'_q - (x'_d - x''_d)i_d - e''_q\right] + T'_{d0}\dot{e}'_q \,, \tag{3.5}$$

$$T''_{q0}\dot{e}''_d = -(x_q - x''_q)i_q - e''_d \tag{3.6}$$

Here T_m is the mechanical Torque
T_e is electric torque output of the generator.

The turbine is used to drive the generator and the governor is used to control the speed and the real power. The block diagram of a separately excited turbine and a conventional governor is shown in Fig 3.4 [3].

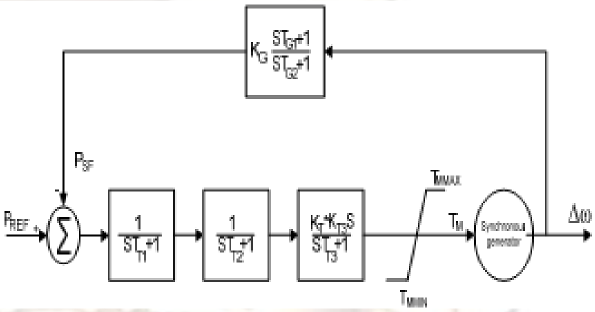

Fig 3.4 Block diagram of turbine and governor

EFECT OF EXCITATION SYSTEM

The main objective of the excitation system is to control the field current of the synchronous machine and thereby to regulate the terminal voltage of the machine. The rate of change of voltage should also be fast. Because of the high reliability required, unit exciter scheme is prevalent where each generating unit has its individual exciter. From the power system view point, the excitation system should contribute to effective control of voltage and enhancement of system stability. The block diagram of synchronous generator excitation system is shown in the Fig 3.5 [7].

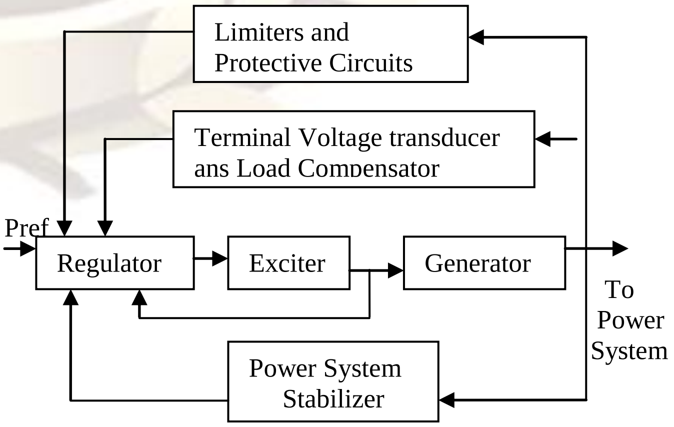

Fig 3.5: Block diagram of a synchronous generator excitation system

Automatic devices (Automatic Voltage Regulator & Governor) control the generator's output in voltage and frequency, in order to keep them constant according to pre-established values [7].

The function of the Automatic Voltage Regulator (AVR) is to control the terminal voltage by adjusting the excitation voltage of the generators. The AVR also controls the reactive power generated and the power factor of the machine. The quality of AVR influences the voltages level during steady state operation, and also reduces the voltage oscillations during transient periods, affecting the overall system stability.

IV. STRUCTURE OF FUZZY LOGIC CONTROLLER (FLC)

The fuzzy system is a popular computing frame-work based on the concept of fuzzy set theory, fuzzy if-then rules, and fuzzy reasoning. The fuzzy inference system basically consists of a formulation of the mapping from a given input set to an output set using fuzzy logic as shown in Fig 4.1

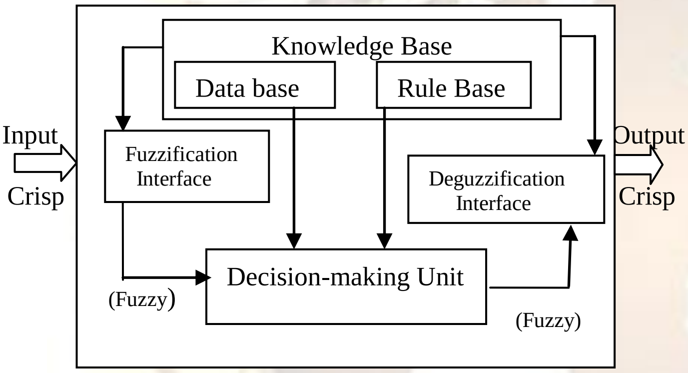

Fig 4.1 Block diagram of fuzzy logic controller

The mapping process provides the basis from which the inference can be made. The basic structure of fuzzy inference system consists of three conceptual components: a rule base, which contains a selection of fuzzy rules; a data base, which defines the membership functions used in the fuzzy rules; and a reasoning mechanism which performs the inference procedure up on the rules and given facts to derive a reasonable output or conclusion [4].

The fuzzy logic controller comprises 4 principle components: fuzzification interface, knowledge base, decision making logic, and defuzzification interface.

i. Fuzzification: In Fuzzification, the values of input variables are measured i.e. it converts the input data into suitable linguistic values.

ii. Knowledge base: The knowledge base consists of a database and linguistic control rule base. The database provides the necessary definitions, which are used to define the linguistic control rules and fuzzy data manipulation in an FLC. The rule base characterizes the control policy of domain experts by means of set of linguistic control rules.

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

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

The basic inference process consists of the following five steps:

Step 1: Fuzzification of input variables.
Step2: Application of fuzzy operator (AND, OR, NOT) in the IF (antecedent) part of the rule.
Step3: Implication from the antecedent to the consequent THEN part of the rule.
Step4: Aggregation of the consequents across the rules.
Step5: Defuzzification.

V.THE DESIGN OF FLC

The design process of an FLC may split into the five steps described as:

a. Selection of the control variables:

The selection of control variables (controlled inputs and outputs) depends on the nature of the controlled system and the desired output. Usually the output error (e) and the rate or derivatives of the output (de) are used as controller inputs [3].

b. Membership function definition:

Each of the FLC input signal and output signal, fuzzy variables ($X_j=\{e, de,u\}$), has the real line R as the universe of discourse. In practice, the universe of discourse is restricted to a comparatively small interval $[X_{minj}, X_{maxj}]$. The universe of discourse of each fuzzy variable can be quantized into a number of overlapping fuzzy sets (linguistic variables). The number of fuzzy sets for each fuzzy variable varies according to the application. The reasonable number is an odd number (3, 5, 7…). More fuzzy sets need more number of rules. Membership functions can be of a variety of shapes such as triangular, trapezoidal, singleton or an exponential.

i. Triangular Membership Function

A triangular membership function is specified by three parameters {a; b; c} as follows

$$f\,(x;\, a,\, b,\, c) = \begin{cases} 0\,, & x \leq a \\ \frac{x-a}{b-a}\,, & a \leq x \leq b \\ \frac{c-x}{c-b}\,, & b \leq x \leq c \\ 0, & c \leq x \end{cases} \qquad (5.1)$$

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

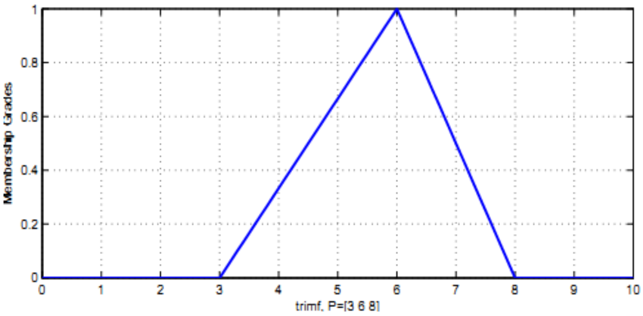

Fig 5.1 Triangular Membership Function

ii. Trapezoidal Membership Function

A Trapezoidal membership function is specified by four parameters

$$f(x;a,b,c,d)=\begin{cases}0, & x\le a\\ \frac{x-a}{b-a}, & a\le x\le b\\ 1, & a\le x\le b\\ \frac{d-x}{d-c}, & c\le x\le d\\ 0, & d\le x\end{cases} \qquad (5.2)$$

The parameters a and d locates the feet of the trapezoid and the parameters b and c locates the shoulders

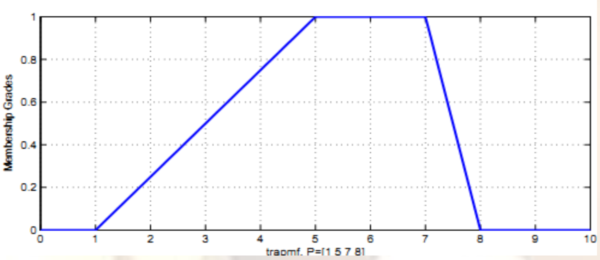

Fig 5.2 Trapezoidal Membership Function

The main part of the FLC is the Rule Base and the Inference Mechanism. The rule base is normally expressed in a set of Fuzzy Linguistic rules, with each rule triggered with varying belief for support. The "i" th linguistic control rule can be expressed as:

R_i: If e_i is A_i and de_i is B_i THEN u_i is C_i

Where A_i and B_i (antecedent), C_i (consequent) are fuzzy variables characterized by fuzzy membership functions. The set of fuzzy rule for a simple FLC is shown in table 1

de/e	N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

Table 1 Rule base for a simple FLC to calculate output.

The fig explains the fuzzy composition by MAX-MIN principle for two fired rules. Note that the output membership function of each rule is given by the MIN operator whereas

the combined fuzzy output is given by the MAX-operator. The composition operation can be expressed as:

$$\mu_B(u) = \mathrm{SUP}_x\,[\mathrm{MIN}\,(\mu_A(x), \mu_B(x,u))] \qquad (5.3)$$

Where A is the known fuzzy set for the input x and B is the inferred fuzzy set for the output. In the fig 5.3, there is only one input fuzzy subset (A) for each rule. µ1 is the minimal membership degree for the input fuzzy subsets (A) of the Rule 1; µ2 is the minimal membership degree for the input fuzzy subset (A) of the find Rule 2. B1 and B2 are the inferred fuzzy subset given by the MIN operator; B is the inferred output fuzzy subset given by the MAX operator [3].

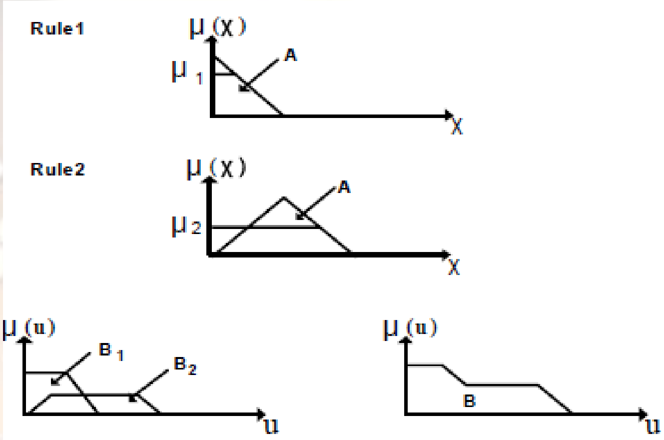

Fig 5.3 The MAX – MIN Fuzzy composition method

c. Defuzzification

Defuzzification is a process of converting the FLC inferred control actions from fuzzy to crisp values. This process depends on the output fuzzy set, which is generated from the fired rules.

The performance of the FLC depends very much on the defuzzification process. This is because the overall performance of the system under control is determined by the controlling signal

The various defuzzification methods have been proposed to convert the output of the fuzzy controller to a crisp value required by the plant. These methods are: Center of Area (COA), Center of Sum (COS), Mean of maxima (MOM)

i) Center of Area Method

Centroid method is also known as centre of gravity method, it obtains the centre of area z^* occupied by the fuzzy set A of universe of discourse Z. It is given by the expression for a continuous membership function

$$Z^* = \frac{\int_z \mu_A(z)zdz}{\int_z \mu_A(z)dz} \qquad (5.4)$$

ii) Center of Sums (COS) Method

In the centroid method, the overlapping area is counted once whereas in centre of sums, the overlapping area is counted twice. COS builds the resultant membership function by taking the algebraic sum of outputs from each of the

contributing fuzzy sets A1, A2, A3,etc. The defuzzified value z^* is given by

$$Z* = \frac{\sum_{i=1}^{N} z_i \sum_{k=1}^{n} \mu_{A_k}(z_i)}{\sum_{i=1}^{N} \sum_{k=1}^{n} \mu_{A_k}(z_i)} \qquad (5.5)$$

where n is the number of fuzzy sets and N is the number of fuzzy variables.

iii) Mean of Maxima (MOM) Method
MOM is the average of the maximizing z^* at which the MF reach maximum μ^*. In symbols,

$$Z^* = \frac{\sum_{z_i \varepsilon M} z_i}{|M|} \qquad (5.6)$$

where M = {z_i | $\mu(z_i)$ the height of the fuzzy set }and |M| is the cardinality of the set M. [1],[6]

VI. FUZZY PID CONTROLLER

Controllers based on the fuzzy logic give the linguistic strategies control conversion from expert knowledge in automatic control strategies [3],[4].

The development of the control system based on fuzzy logic involves 5 steps (Fuzzification, Data base building, Rule base elaboration, Inference machine elaboration and Defuzzification).

The fuzzy logic controller has the ability to improve the robustness of the synchronous generator. In the development of the fuzzy logic approach the input constraints were terminal voltage error and its variations; the output constraint was the increment of the voltage exciter.

The inputs of FLC are defined as the error $e_u(m)$ and change of error $de_u(m)$ .The fuzzy controller ran with the input and output normalized universe [-1,1].

Fuzzy sets are defined for each input and output variable. There are seven fuzzy levels (LN-large negative, MN-medium negative, SN-small negative, MN-medium negative, LN-large negative Z-zero, SP-small positive, MP-medium positive, LP-large positive) [3].The membership functions for input and output variable are triangular. The min-max method inference engine is used; the defuzzify method used in this FLC is centroid method. The complete set of control rules is shown in table 2 [3].

de/e	LN	MN	SN	Z	SP	MP	LP
LN	LP	LP	LP	MP	MP	SP	Z
MN	LP	MP	MP	MP	SP	Z	SN
SN	LP	MP	SP	SP	Z	SN	MN
Z	MP	MP	SP	Z	SN	MN	MN
SP	MP	SP	Z	SN	SN	MN	LN
MP	SP	Z	SN	MN	MN	MN	LN
LP	Z	SN	MN	MN	LN	LN	LN

Table 2 Rule base

Each of the 49 control rules represents the desired controller response to a particular situation. The block diagram presented in fig 6.1 shows a FLC controller in the Matlab simulation and in fig 6.2 the simulation of the surface control is presented [8].

Simulink diagrams of the SMIB system with PSS (Fig 6.3), with Fuzzy PSS (Fig 6.5) and Fuzzy PID PSS (Fig 6.7) are simulated and analyzed. The corresponding simulation results are shown in figs. 6.4, 6.6 and 6.8 respectively.

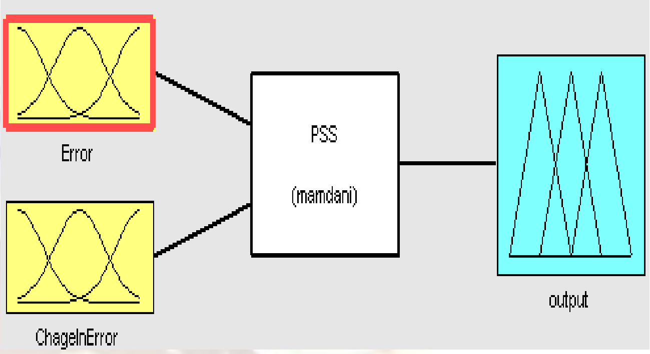

Fig 6.1 FIS editor for FLC

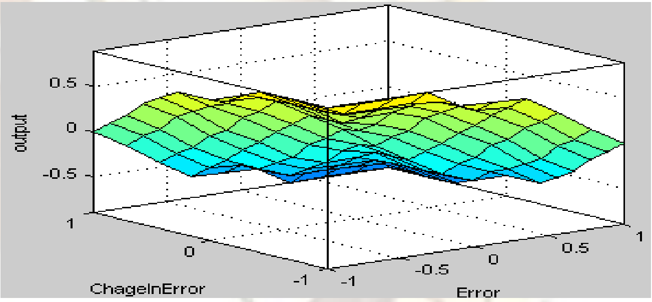

Fig 6.2 Surface view

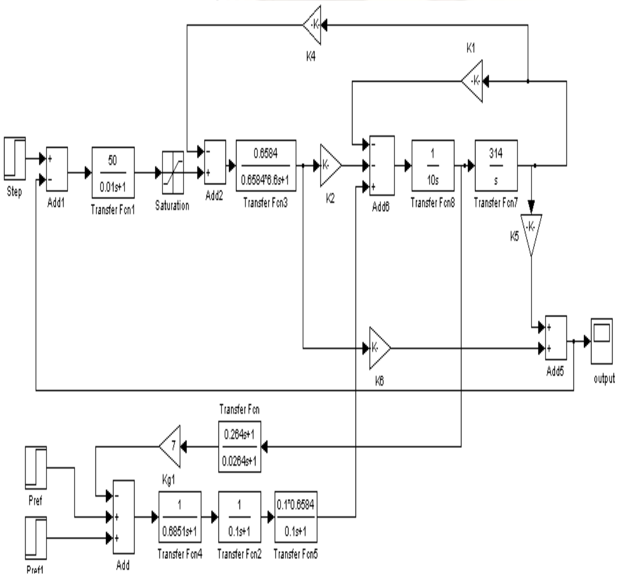

Fig.6.3 Simulink of synchronous machine with PSS

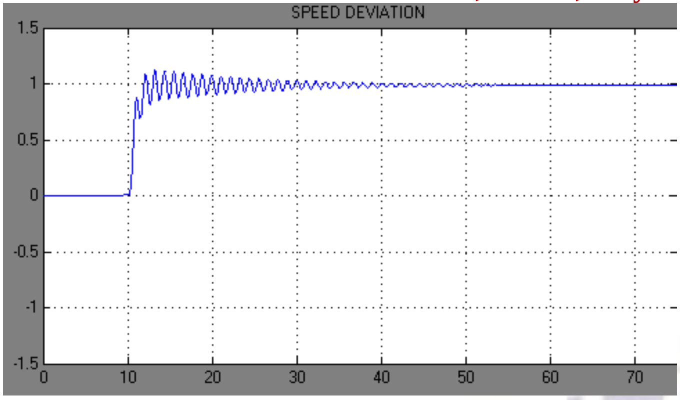

Fig 6.4 Output using CPSS

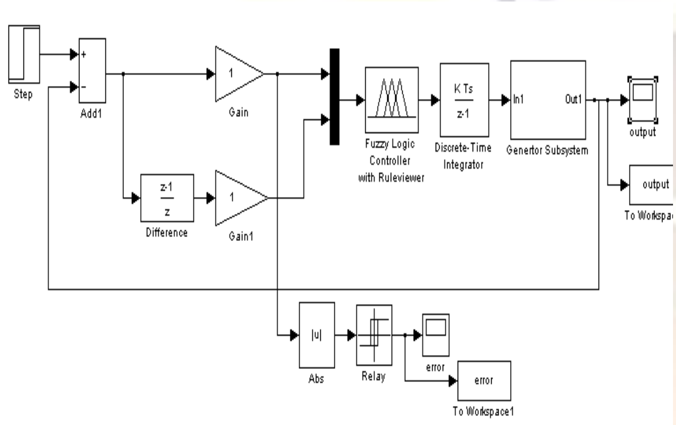

Fig 6.5 Simulink model of synchronous machine with the fuzzy control

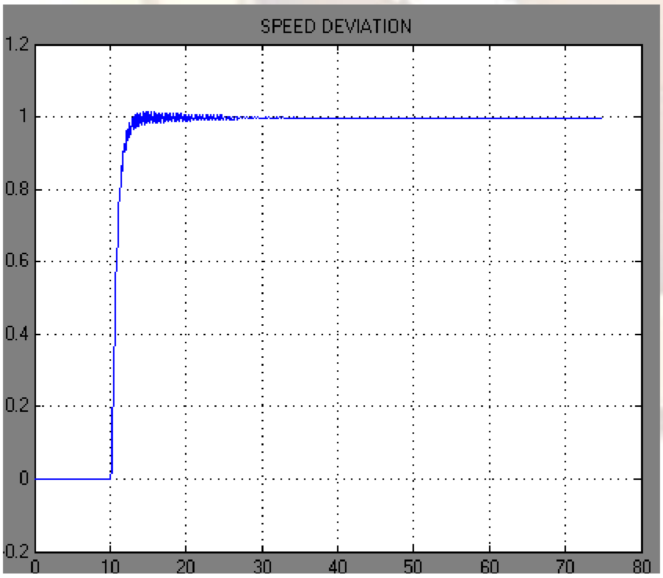

Fig 6.6 Output using fuzzy logic PSS

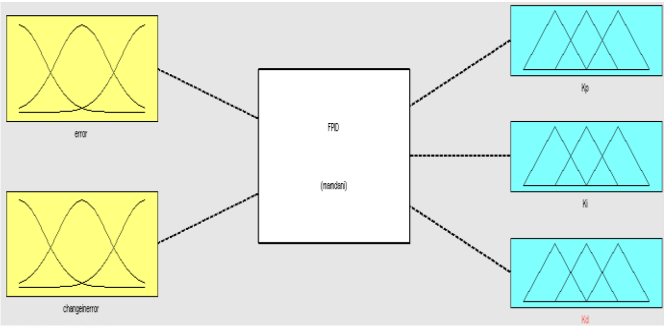

Fig 6.7 FPID editor

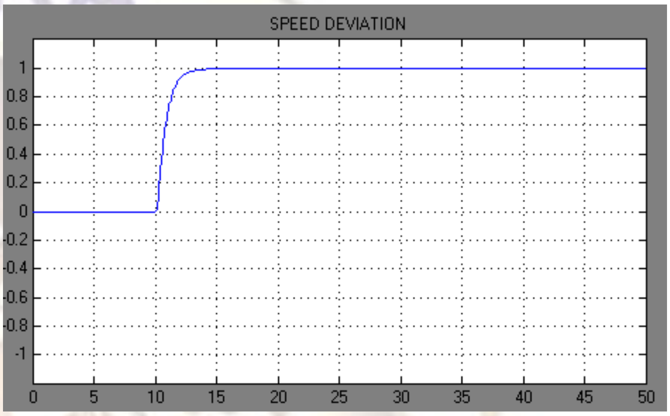

Fig 6.8 Output using fuzzy PID controller

VII.CONCLUSION

From the Matlab/Simulink simulation study, it is observed that the fuzzy PID controller has an excellent response with small oscillations, while the fuzzy and CPSS response shows a ripple and some oscillations before reaching the steady state operating point. It is also observed that a good performance of the fuzzy control in contrast to the CPSS for the excitation control of synchronous machines could be achieved.

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