Design of Hybrid Intelligent Power System Stabilizer for a Multi-Machine System

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***Abstract*—** In this project a coordinated design of Fuzzy Power System Stabilizer (FPSS) and TCSC based power oscillation damping (POD) controller to improve power system small-signal stability need to be designed. Two controllers are used for optimizing the system for a better result. Conventional power system stabilizer is replaced by a Fuzzy PSS and the Particle Swarm Optimization (PSO) algorithm tries to minimize an eigenvalue-based multi-objective function by optimizing the parameters of the POD controller. Time domain simulations in MATLAB/SIMULINK performed on a two area four machine (2A4M) power system reveals that superior enhancement in damping of oscillations is achieved by employing coordinated control of FPSS-POD controller in comparison with conventional PSS-POD controller.

Keywords: *Fuzzy power system stabilizer (FPSS), TCSC, power oscillation damping (POD) controller, Particle Swarm Optimization (PSO) algorithm.*

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I. INTRODUCTION

In an integrated power system network, improvement of transient and dynamic stability has been one of the major issues in power system control and operation. Oscillations of low frequencies in the range of 0.3-2 Hz persist in large interconnected power systems for large duration which leads to significant dynamic problems that occur due to the lack of sufficient damping in electromechanical modes. This long oscillation can result in loss of synchronism of machines. Power system stabilizer can be used to damp these oscillations and to enhance the dynamics of the system [1].

Power system stabilizer generate supplementary signal given to the excitation system to damp these oscillations produced. Power system stabilizer can be categorized according to the different types of inputs given. Generally conventional PSS have change in rotor speed (ΔW) and accelerating power (P_e) as input to the PSS. Multi band PSS and PSS with multiple inputs are also being used for better damping performance and to enhance dynamics of the system.
To improve robustness, achieve adaptive real time tuning, stabilizer's optimal performance under all sorts of system operating conditions and configurations etc. a lot of research works for controllers based on Conventional Lead- Lag type, PID, Pole placement, Artificial Neural Network, GA-Fuzzy, Hybrid Neuro-fuzzy etc. have been carried out in recently. Disadvantage of some of these techniques is that they suffer from computational burden, complexity in algorithm, and memory storage requirement.

In the recent years, with the advancement in power electronics, FACTS devices such as static var compensator (SVC), static compensator (STATCOM), and thyristor controlled series compensator (TCSC) are employed in power systems for different purposes such as power flow, reactive power, and voltage controls in transmission systems. Apart from these primary functions, FACTS devices are utilized to damp oscillations.

This paper mainly deals with coordinated control of fuzzy logic and TCSC-based POD controller to enhance multi-machine small-signal stability. Fuzzy power system stabilizer has two inputs, rotor speed deviation and derivative of change in rotor speed. Particle swarm optimization (PSO) algorithm is used to fine tune the adjustable parameter like time constants of the POD controller. The adjustable parameters are tuned by minimizing the Eigen value based target function in which effects of different operating points and proposed controllers are regarded simultaneously. In order to evaluate the robustness and effectiveness of designed FPSS-POD controllers with the CPSS-POD, simulations in time domain and eigenvalue analysis are carried out on a two area four machine (2A4M) system in MATLAB/SIMULINK.

II. POWER SYSTEM MODEL

This part explains about the two area four machine system including all its components and equipment's.

1. Two Area Four Machine power system

Test system consists of two completely symmetrical areas linked together by two 230 kV lines of 220 km length, one 230kV line can be taken in an out using the circuit breaker provided. It was specifically designed to study low frequency electromechanical oscillations in a large power systems. Even though the system seems small in size, it shadows the behavior of typical systems in operation very closely. Each area consist of two identical generators of 20 kV/900 MVA. All the parameters of the generators are identical, except for inertia constants. Inertia constant of area 1 is H = 6.5s and for area 2 is H = 6.175s. 413MW is exported from area 1 to area 2. Even during steady-state condition the system is stressed since each line is having surge impedance loading (SIL) of about 140 MW. Each generators are generating about 700 MW, with generator 2 considered as the slack machine. 187 Mvar capacitors are installed to improve the load voltage (made closer to unity) in each area.

$$\dot{\delta}_i = \omega_b(\omega_i - 1) \tag{1}$$

$$\dot{\omega}_i = \frac{1}{M}(P_{mi} - P_{ei} - D_i(\omega_i - 1)) \tag{2}$$

$$\dot{E}'_{qi} = \frac{1}{T'_{doi}}(E_{fdi} - (x_{di} - x'_{di})i_{di} - E'_{qi}) \tag{3}$$

where E_{fdi} is field voltage; T'_{doi} is field open circuit transient time constant, P_{mi} and P_{ei} are mechanical and electrical powers of the ith generator both in per-unit, δ_i, ω_i, and ω_b are rotor angle in electrical radians, angular speed in per-unit, and system base speed ($2\pi f$) in rad/s, M_i and D_i are inertia constant in second and damping coefficient, x_{di} and x'_{di} are d-axis reactance and d-axis transient reactance of the generator, respectively.

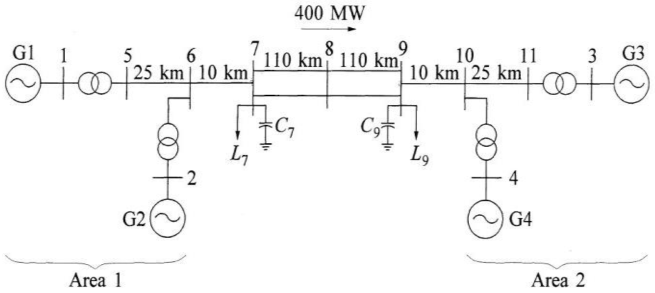

Figure 1.. Two area four machine system

B. Excitation Model

An excitation system have a great part in stability of an interconnected system as it can rapidly cause a high initial response to changes or variations in network operating condition. In this project a simplified form of IEEE type ST1A excitation system is used to generate the dc excitation field requirements of the generators. The Excitation model is showed in figure 2.

$$\dot{E}'_{fd} = \frac{1}{T_A}(K_A(V_{ref} - v + U_{pss}) - E'_{fd}) \tag{4}$$

Where K_A is the gain and T_A is the time constant of voltage regulator; V_{ref} is reference voltage; U_{PSS} is supplementary signal from PSS; and v is terminal voltage.

C. PSS Modelling

1. Rotor speed based PSS

Feedback of terminal voltage for the purpose of voltage regulation results in negative damping. The negative damping can be neutralized if we can somehow superimpose on it a sufficient positive damping torque. The positive damping torque can be produced by feeding back the speed deviation signal at the excitation input after providing to it appropriate gain and phase advance. The required gain and phase advance characteristics to the speed deviation signal are provided by the PSS.

The power system stabilizer mainly consist of three major blocks namely a Gain, phase compensation and signal washout blocks. Block diagram of PSS is shown in figure 3. K_S and T_w sets the gain and washout time constant of CPSS. T1 to T4 time constants provide the required phase compensation.

The signal washout block is a high pass filter to let rotor oscillation without magnitude reduction. The value of T_w is fixed anywhere between 1 to 20 seconds.

2. Fuzzy logic based PSS

In Fuzzy PSS two inputs are given to the fuzzy logic controller, change in rotor speed and derivative of change in rotor speed. Conventional PSS is replaced by a Fuzzy controller block with the above mentioned inputs. Fuzzy controller, tuning of parameters and functions will be explained in the next section.

III. IMPLEMENTATION

A. Fuzzy logic controller (FLC)

Fuzzy logic can be termed as the superset of Boolean logic that has been extended to handle the concept of partial truth values between ‘completely false’ and ‘completely true’. For controlling non-linear systems, fuzzy logic is ideal since it can handle information in an orderly way. The controller has a knowledge base, a fuzzification and defuzzification interface and a decision-making logic, Figure 2 illustrates the basic block of the fuzzy logic controller (FLC). Information’s about all the input and output partitions are contained in the knowledge base module. The algorithm to convert the linguistic control scheme into an automatic control scheme is provided by the FLC.

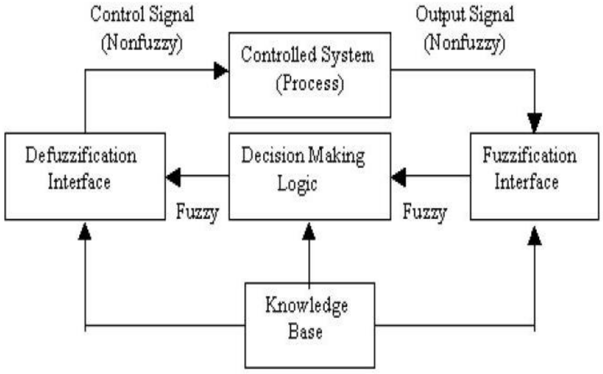

Figure 2.. Fuzzy logic controller

1. Input variables

Choice of input variables is an important factor that contribute to the performance of fuzzy control system. Generally speed deviation of the rotor, accelerating power and derivative of rotor speed deviation are taken as input signals to fuzzy PSS. The two inputs can also be generator rotor speed deviation and accelerating power deviation since accelerating power is proportional to speed deviation. In this project speed deviation and acceleration is taken as input as it depicts the system more accurately. The process will become much simplified with cost effective and less computational time.

2. Choosing of linguistic variables

Choosing of linguistic variables have a higher deciding factor in fuzzy logic performance, these values transform input numerical values to fuzzy quantities and the process is called fuzzification. With the increase in linguistic variables the quality of control increases, however as the variables increases required memory and computational time increases. In this work for the first input five linguistic variable and for the second input three variables are chosen. They are NB (negative big), NS (negative small), Z (zero), PS (positive small), PB (positive big). Triangular membership functions are used to define the degree of membership.

3. Designing the rule

Rules explains the relation between input and output variables and these rules are defined using linguistic variables. The two inputs to the FPSS i.e. Speed deviation and acceleration results in fifteen rules. Anticipates that the desired operating point will be reached soon and stabilization control is no longer needed is set by the rules. Rule table is shown in table 1. Structure of a typical rule is shown below.

Table 1. Fuzzy rule table

	Acceleration		
Speed Deviation	NB	Z	PB
NB	NB	NB	NS
NS	NS	NS	Z
Z	Z	Z	PS
PS	PS	PS	PB
PB	PB	PB	PB

4. Defuzzification

Defuzzification is the process of producing a quantifiable result in fuzzy logic, given fuzzy sets and corresponding membership degrees. In this paper, the Centroid Method is used.

5. Membership function

A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value. The input space is called as the universe of discourse. Figure 3, 4 and 5 shows the membership plot of inputs and output respectively.

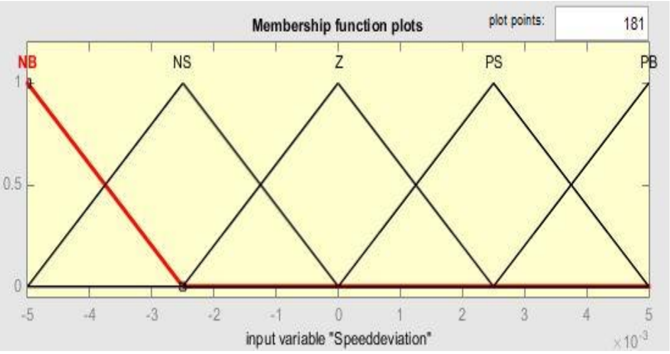

Figure 3.. Membership function plot of Speed deviation

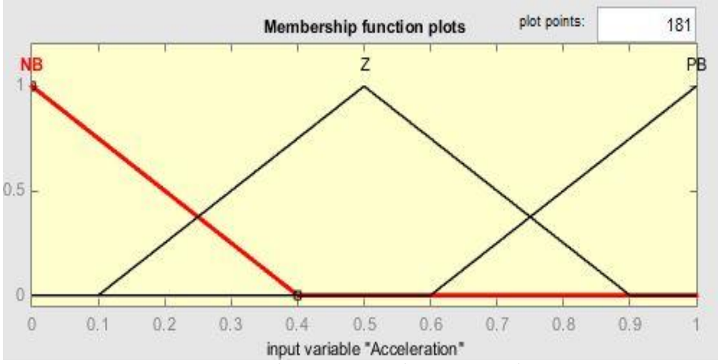

Figure 4.. Membership function plot of derivative of speed deviation

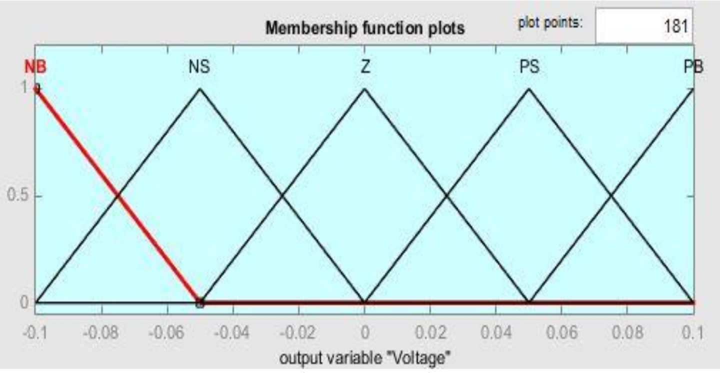

Figure 5.. Membership function plot of output (Voltage)

B. TCSC based POD controller

TCSC installation with POD controller in series with the transmission line is mainly to damp inter-area oscillations and to control the active power flow. TCSC is installed in the tie line between two areas.

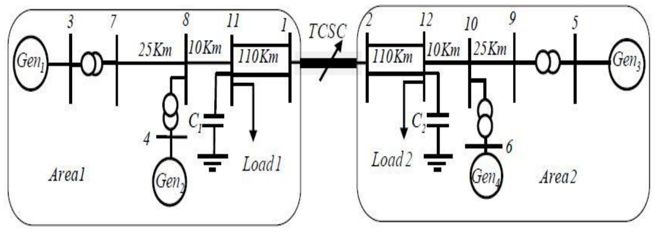

Figure 6.. Two area four machine system with TCSC

Figure 7 shows the conventional block diagram of TSCS based POD controller with lead lag compensator where T_m is the measurement transducer time constant, T_w is washout time constant, K_{pe} is POD gain.T_1 to T_4 provide required phase compensation.

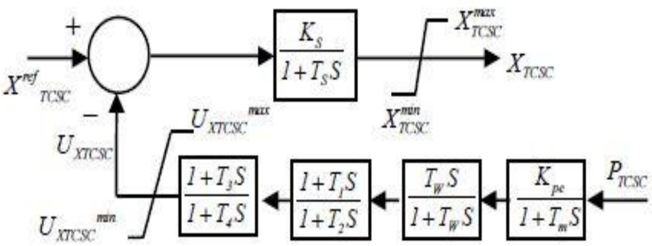

Figure 7.. TCSC based lead–lag POD controller

In small signal studies power oscillation damping controller is expressed by first order differential equation as shown below

$$\dot{X}_{TCSC} = \frac{1}{T_s}(K_S(X_{TCSC}^{ref} - U_{XTCSC}) - X_{TCSC}) \qquad (5)$$

Where K_S and T_S are gain and inherent time constant of the TCSC. U_{xtcsc} is the damping signal provided from the POD controller.

C. Particle Swarm Optimization technique

Particle swarm optimization (PSO) is one of the intelligence method proposed by Kennedy and Eberhart in 1995. The PSO is a population-based optimization algorithm and has now acquired wide applications in optimizing design problems due to its simplicity and ability to optimize complex constrained objective functions in multimodal search spaces.

In order to tune the proposed controller a most suitable algorithm need to be chosen, since PSO has gained wide application in power engineering and other fields due to its fast convergence and simplicity it is used as the technique used for optimization. In this technique, solution is called a ‘particle’ and set of particle makes ‘population’. Each particle has its own global best and personal best, they communicate with each other and the global best and local best is found. The position associated with the best value obtained so far by any particle is called global best or gbest.

$$v_i^{t+1} = w.v_i^t + c_1 r_1.(pbest_i - x_i^t) + c_2 r_2.(gbest - x_i^t), \qquad (6)$$
$$x_i^{t+1} = x_i^t + v_i^{t+1}, i = 1,2,....n.$$

where v is the particle velocity, x is the particle position, n is the number of particles, t is the number of iterations, w is the inertia weight factor, c_1 and c_2 are the cognitive and social acceleration factors, respectively and r_1 and r_2 are the uniformly distributed random numbers in the range (0, 1).

Figure 8 presents the flow chart of the PSO algorithm for the coordinated design of the PSS and TCSC problem.

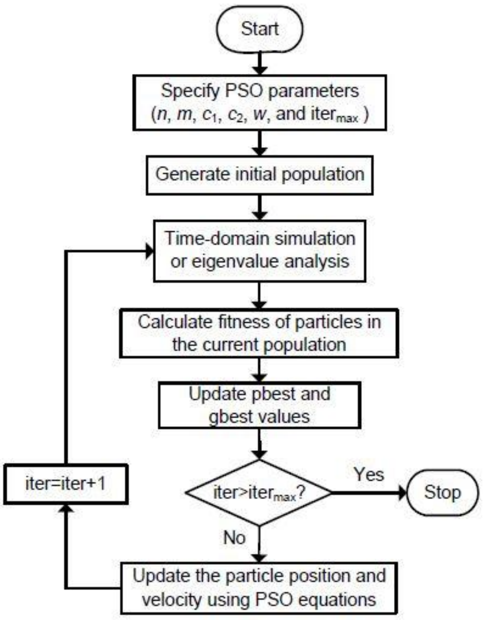

Figure 8. Flow chart of PSO algorithm

For the effective performance of the PSO appropriate selection of c_1, c_2, and w plays an important role. In this work, the PSO parameters are chosen as: n=30; w_{min}=0.4; w_{max}=0.9; c_1=c_2=2; γ=0.1; and t_{max} =30 where t_{max} is maximum number of iterations; w_{max} and w_{max} are the initial and final weights, respectively.

D. Adjustable parameters of controller

The given values of the controllers are T_m=0.05sec; T_{d1}=T_{d2}=T_{d3}=0.02sec; T_w=5sec; T_2=T_4=0.1sec; $\Delta UPSS_{max}$=-$\Delta UPSS_{min}$=0.3 p.u. The parameters that are optimized by PSO algorithm are $K_{pe,}$ T_1 and T_3 the POD controller

E. Objective function.

To obtain relatively robust coordinated controllers, the tunable parameters should be adjusted under different operating conditions concurrently. In this paper, Eigen value based multi-objective function is employed as

$$J = 10\sum_{j=1}^{N} \sum_{\zeta_{i,j}<=\zeta_0} (\zeta_0 - \zeta_{i,j})^2 + \sum_{j=1}^{N} \sum_{\sigma_{i,j}<=\sigma_0} (\sigma_0 - \sigma_{i,j})^2 \qquad (7)$$

Where $\sigma_{i,j}$ and $\zeta_{i,j}$ denote the real part and damping ratio of ith eigenvalue of jth operating point. σ_0 and ζ_0 are chosen thresholds that depict the desirable degree of system damping performance. In this work, σ_0 and ζ_0 are selected to be -2.0 and 0.4, respectively. N is total number of operating points considered in the design process simultaneously. According to the objective function, it is tried to put the relocated eigenvalues restrictedly within a D-shaped area for which, $\sigma i,j \leq \sigma 0$ and $\zeta i,j \geq \zeta 0$ [18]. It is invaluable to mention that just unstable or lightly damped local oscillation modes are adjusted here. The design problem is to minimize J subject to constraints pertain to adjustable gains and time constants limits. Also the gains are tuned in range of (0.1, 10).

F. Eigen value analysis

To evaluate the dynamic stability of power system the eigenvalue analysis can be a useful method in figure of damping ratio and damping coefficient measurement indices. Thus, a perturbation in system condition may result in heavy oscillations that can go on for a few seconds or even minute to be damped or may bring about instability due to the unstable mode. It can be observed that Fuzzy PSS POD coordinated controllers are more capable than CPSS-POD to move the EM modes toward the desired D-shaped area specified by $\sigma i,j \leq -2$ and $\zeta i,j \geq 0.4$. It means that damping ratios and coefficients at different loading conditions are improved remarkably by designed controllers.

Table 2. Eigen value analysis without PSO

Oscillation Frequency	Damping Ratio	Eigen Value
1.921097	0.376485	-5.088802±7.0459i
1.885041	0.369837	-4.887941±6.8807i
1.319485	0.570958	-6.168000±6.0159i
1.242489	0.619513	-6.684144±5.9826i

0.473550	0.280963	-0.897006±3.8725i
0.442951	0.499023	-1.689119±3.5387i
0.438245	0.503400	-1.692055±3.4756i
0.293029	0.526937	-1.209264±3.1491

Table 3. Eigen value anaysis with PSO

Oscillation Frequency	Damping Ratio	Eigen Value
1.921097	0.409223	-5.413619± 8.3943i
1.885041	0.401997	-5.199937± 6.9427i
1.319485	0.620606	-6.561702± 6.1249i
1.242489	0.673383	-7.110791± 6.4129i
0.473550	0.305395	-0.954262± 3.4359i
0.442951	0.542416	-1.796935±3.1457i
0.438245	0.547174	-1.800059± 3.671i
0.293029	0.572758	-1.286451± 3.4501i

The above table shows the Eigen value analysis of the system with and without PSO. In a system if the real part of Eigen value is more left to the vertical axis the system is said to be more stable. It is clear from the data that the system becomes more stable as the Eigen value is been shifted more left by the designed PSO algorithm.

Table 3. Optimized value of POD parameters

K_{Pe}	T_1	T_3
0.21	0.11	0.34

G. Time domain simulation

Since the designed controller should perform satisfactorily under small signal disturbances, the effectiveness of the coordinated controller is evaluated in a small disturbance. Small disturbance is given to the system as a step increase of 5% in the reference voltage ΔV_{ref} of generators 1 and 4 at instant of 1.2 sec. The speed deviation, terminal voltage and acceleration power is considered as output and compared with fuzzy PSS POD and conventional PSS POD controller. M1, M2, M3, M4 denotes all four machines respectively.

From the figure 7.a it is clear that the system loses its synchronism at 6.2 seconds, hence the simulation is made to stop when the system loses sysnchronism.

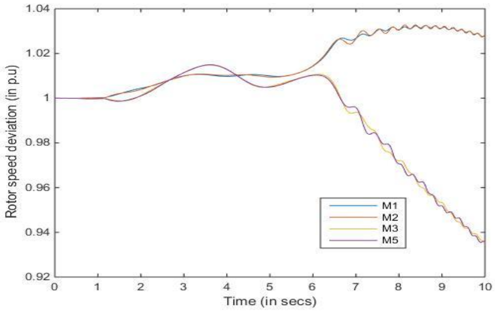

Figure 9.. Speed deviation of all machines with No PSS

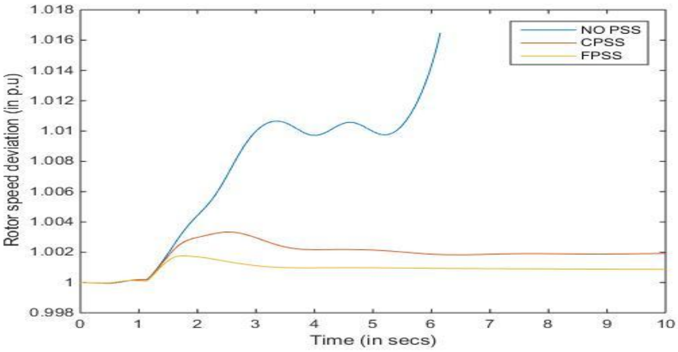

Figure 10.. Speed deviation of machine1 no PSS, CPSS, FPSS

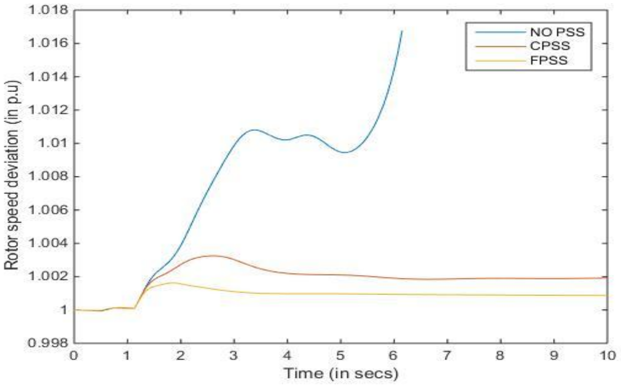

Figure 11.. Speed deviation of machine 2 no PSS, CPSS, FPSS

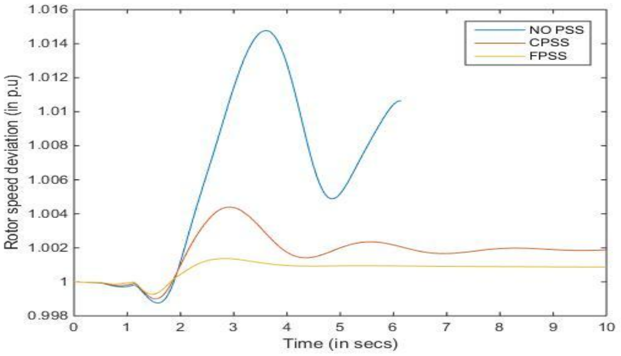

Figure 12..Speed deviation of machine 3 with no PSS, CPSS, FPSS

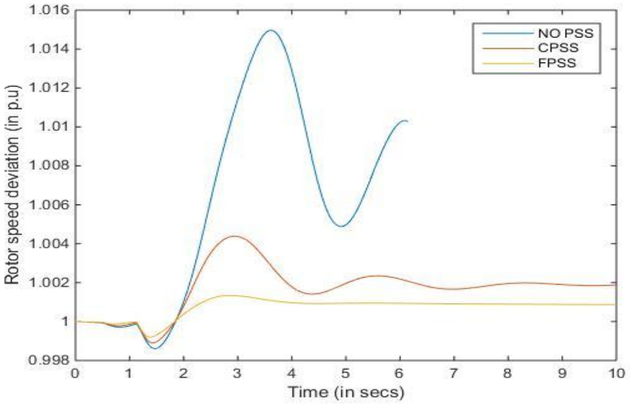

Figure 13. Speed deviation of machine 4 with no PSS, CPSS, FPSS

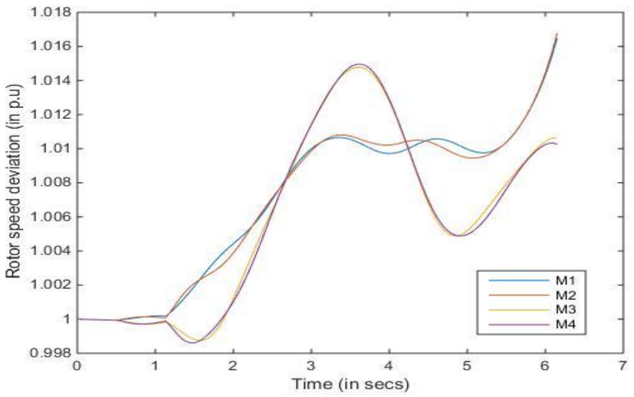

Figure 14.. Rotor speed deviation of all machines with no PSS

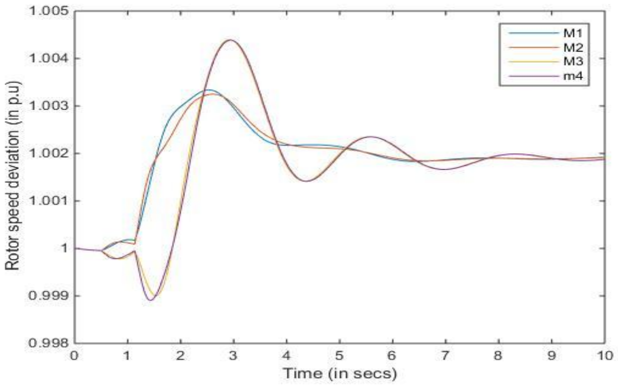

Figure 15.. Rotor speed deviation of all machines with CPSS

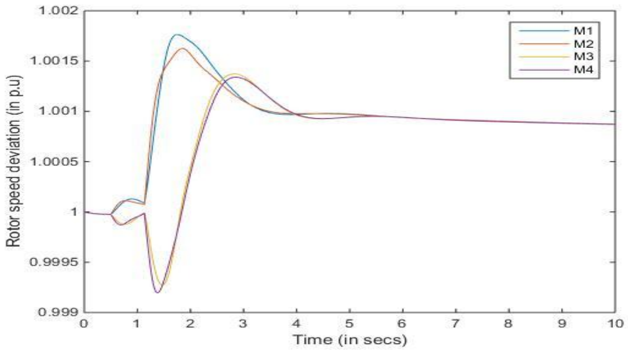

Figure 16.. Rotor speed deviation of all machines with FPSS

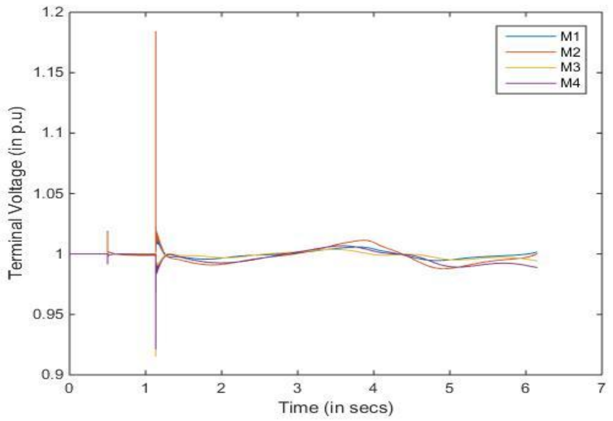

Figure 17.. Terminal voltage waveform without PSS of all machines

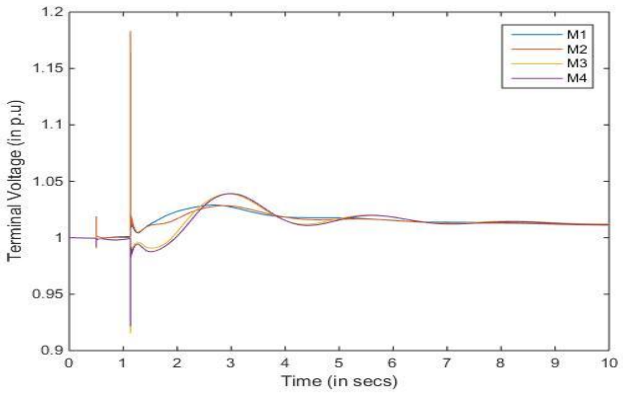

Figure 18.. Terminal voltage waveform with CPSS of all machines

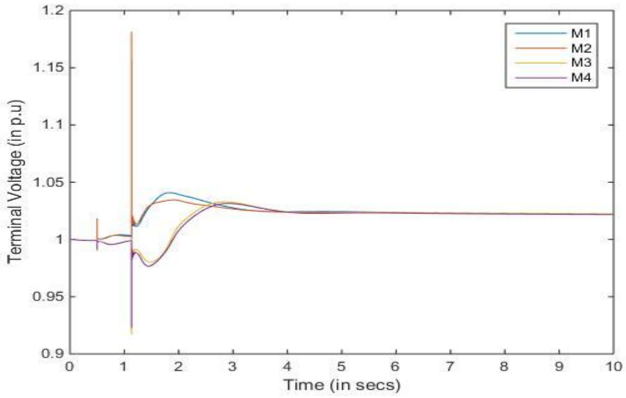

Figure 19.. Terminal voltage with FPSS of all machines

Figure 12 to 14 shows the graph of machine one to four in all three cases, i.e. without PSS, conventional PSS and Fuzzy PSS. From the graph it is clear that the settling time and oscillation magnitude is been reduced by using the fuzzy PSS designed. Figures from 15 to 19 gives the performance of each machine for the above stated three conditions when a fault is given in the system. The designed Fuzzy PSS seems more superior to the conventional PSS as it mitigates the oscillation time and amplitude and brings the system back into stable operation within a short span.

IV CONCLUSION

In this paper, coordinated design of the Fuzzy PSS-POD controllers using PSO algorithm has been performed to enhance small signal stability of 2A4M power system in comparison with the CPSS-POD coordination. The eigenvalue analysis of power system has shown that our designed coordinated controllers are more capable than CPSS-POD to move EM modes into the desired *D*-shape area to increase the damping coefficient and damping ratio of the modes. Also, the results of time domain simulations on the multi-machine system have revealed that with Fuzzy PSS-POD coordinated controllers, EM oscillations have been damped quickly with minimum undershoot and overshoot. Thus it can be concluded that by employing our controllers superior enhancement has been achieved in small-signal stability of power system.

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