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Original Article

Fuzzy Based Controller to Enhance Transient and Steady State Stability for Multimachine Power System

Madhusudhan M[1], H. Pradeepa[2]

[1] *Research Scholar, Department of Electrical and Electronics Engineering, The National Institute of Engineering, Karnataka, India*

[2]*Associate Professor, Department of Electrical and Electronics Engineering, The National Institute of Engineering, Karnataka, India*

[1]Madhusudhanm2015@gmail.com [2]Pradeep3080@nie.ac.in

Abstract *- The dynamic action of a large power system network is nonlinear in nature. System stability cannot be maintained due to disturbances, resulting in outages of electric power components in the power system network. To restore the system parameter to its operating points, proper damping control is necessary. PSS tuning is critical in dampening power system oscillations, improper tuning will not offer adequate damping of oscillation, and these undamped oscillations are responsible for power system instability under a perturbance. A fuzzy logic controller is proposed in this work to damp out power system oscillation and minimize the error indices, i.e., IAE, ISE and ITAE with respect to speed deviation, and the results are compared with different types of PSS controllers. The proposed controller is employed in 2 areas, 4 machines and 11 bus test systems, which is simulated in MATLAB 2018a.*

Keywords — *Automatic Voltage Regulator (AVR), Integral Square Error (ISE), Static Synchronous compensator (STATCOM), Power system stabilizer (PSS).*

I. INTRODUCTION

The ability of a power system to re-establish its operational point after being perturbed is referred to as stability. When a generator fails to meet the connected load due to a perturbation, power system stability becomes critical [1]. Electricity demand is rising as a result of new industries and a rapidly growing metropolis. Such power systems are operated at or near full capacity to meet escalating demands [2]. As a result, a range of small and large power network disturbances are introduced. Thus, ensuring the reliable functioning of power grids is a huge challenge [3]. If the power system oscillation is not completely damped out after the disturbance is cleared, the system cannot regain its equilibrium point, posing a significant risk to the power system network. This causes power equipment to heat up, fail to function properly and have its operating life cycle reduced, among other things [4-5]. Transients, machine speed deviation, and load angle deviation are the end outcomes of power system instability, which leads to inappropriate power transfer in the provided network. As a result, resolving power system oscillations has become a global priority [6-9]. For multi-machine power systems, controlling nonlinear oscillation in an operating network needs an efficient controller design [10-12]. The power system stabiliser (PSS) is a fundamental damping control in a power system; PSS is typically installed in the excitation system of generators [13]. Local and inter-area oscillation modes are typical in multimachine systems. These oscillation modes will lead to deviations in power level, frequency, rotor angle and the terminal voltage of the generators [14]. Local area mode oscillations are small cycles with a higher frequency range of 0.7-3.0 Hz. In comparison, inter-area mode oscillation is large cycles with a low-frequency range of 0.1-0.7Hz [15-17].

Large power systems with synchronous machines suffered voltage regulator stability. The power transfer capabilities of these big systems were limited by persistent low-frequency oscillations of small amplitude [18]. The capability of energy transfer was limited by insufficient dampening of these oscillations [19]. To resolve this problem, the Power System Stabilizer (PSS) was implemented to dampen these oscillations and improve the power system's energy transfer capacity [20]. PSS has been frequently employed since then. Even if the PSS construction has upgraded over the years, the basic fundamental is damping by modulation of the synchronous generator's excitation system [21]. PSS is also used to dampen other types of oscillations, such as torque oscillations caused by turbines [22]. The optimality of PSS is described in different ways based on its application, such as providing damping torque and synchronizing torque [23-24]. Fast, automatic voltage regulators (AVR) can boost generator terminal voltage (i.e., excitation voltage) to ceiling voltage limits in a short amount of Time, parallelly affecting the damping component of the synchronous generator electromagnetic torque, which is one of the significant aspects of power systems. Installing a power system stabilizer (PSS) in the synchronous generator's excitation

circuit is a cost-effective technique to boost damping in the power system [25].
In the proposed work, a fuzzy-based PSS tuning for multimachine machine systems is adapted for effective damping of power oscillations to minimize the error indices and maintain synchronism. The results obtained from the proposed work are compared with traditional PSS.

A. Generator Excitation System with PSS

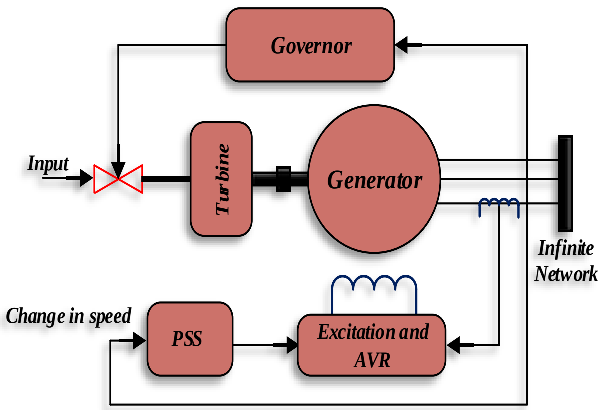

Fig.1 Basic Structure of Generator Excitation with PSS

An excitation system is a mechanism that supplies field current to a generator's rotor winding. Generator Excitation with PSS basic structure shown in Figure 1 Well-designed excitation systems provides a reliable and consistent operation, stability, and rapid transient response. An automatic voltage regulator (AVR) is a solid-state electronic system that regulates the voltage at the generator output terminals, and it is also part of generator excitation. The governor of steam turbine is a unit of turbine control system that adjusts rotational speed depending on varying load conditions. The governor output signal regulates the flow of steam to the turbine by adjusting the position of a steam inlet valve or nozzles.

II. MODELLING OF GENERATOR

A. Generator differential-algebraic modelling

The excitation system can be expressed as:

$$T_{Ei}\frac{dE_{fdi}}{dt} = -(K_{Ei} + S_{Ei}(E_{fdi}))E_{fdi} + V_{Ri} \qquad (1)$$

$$T_{Fi}\frac{dR_{fi}}{dt} = -R_{fi} + \frac{K_{fi}}{T_{fi}}E_{fdi} \qquad (2)$$

$$T_{Ai}\frac{dV_{Ri}}{dt} = -V_{Ri} + K_{Ai}R_{fi} - \frac{K_{Ai}K_{fi}}{T_{fi}}E_{fdi} + K_{Ai}(V_{refi} - V_i) \qquad (3)$$

Generator Dynamics are from [26]

$$T'_{doi}\frac{dE'_{qi}}{dt} = E_{fdi} - (X_{di} - X'_{di})\{i_{di} - \frac{(X'_{di} - X''_{di})}{(X'_{di} - X_{ls})^2}(\Psi_{1di} + (X'_{di} - X_{ls}) - E'_{qi}\} \qquad (4)$$

$$T''_{doi}\frac{d\Psi_{1di}}{dt} = -\Psi_{1di} + E'_{qi} - (X'_{di} - X_{ls})i_{di} \qquad (5)$$

$$T'_{qoi}\frac{dE'_{di}}{dt} = -E'_{di} + (X_{qi} - X'_{qi})\{i_{qi} - \frac{(X'_{qi} - X''_{qi})}{(X'_{qi} - X_{ls})^2}\left(\Psi_{2di} + (X'_{qi} - X_{ls}\right)i_{qi} - E'_{di}\} \qquad (6)$$

$$T''_{qoi}\frac{d\Psi_{2di}}{dt} = -\Psi_{2di} - E'_{di} - (X'_{qi} - X_{ls})i_{qi} \qquad (7)$$

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s \qquad (8)$$

$$\frac{2H_i}{\omega_s}\frac{d\omega_i}{dt} = T_{Mi} - \frac{(X''_{di} - X_{ls})}{(X'_{di} - X_{ls})}E'_{qi}i_{qi} - \frac{(X'_{di} - X''_{di})}{(X'_{di} - X_{ls})}\Psi_{1di}i_{qi} - \frac{(X''_{qi} - X_{ls})}{(X'_{qi} - X_{ls})}E'_{di}i_{di} + \frac{(X'_{qi} - X''_{qi})}{(X'_{qi} - X_{ls})}\Psi_{2qi}i_{di} - (X''_{qi} - X''_{di})\,i_{di}i_{qi} - T_{FW} \qquad (9)$$

Generator electric output power can be expressed in terms of d-q frame terminal voltage and armature as:

$$P_e = V_{td}I_d + V_{tq}I_q \qquad (10)$$

III. ERROR INDICES

In the proposed IAE, ISE and ITAE are measured for the machine speed deviation as expressed in Eqn. (11), Eqn. (12) and Eqn. (13), respectively.

A. Absolute Integral error of generator

Absolute Integral error is defined as the measure of system performance by integrating the absolute error over a fixed interval of time.

$$J_i = \int_0^{\infty} |\Delta\omega_i|\, dt \qquad (11)$$

B. An integral square error of generator

Integral square error is defined as the measure of system performance by integrating the square of error over a fixed interval of time.

$$k_i = \int_0^{\infty} |\Delta\omega_i|^2 \, dt \quad (12)$$

C. Integral Time Absolute error of generator

Integral square error is defined as the measure of system performance by integrating the product of Time and absolute error over a fixed interval of time.

$$l_i = \int_0^{\infty} t * |\Delta\omega_i| \, dt \quad (13)$$

Where,
'*i*' is the no. of generators, *i* can take values 1, 2, 3 and 4.
$\Delta\omega_i$ is the i^{th} generator machine speed deviation per unit?

IV. POWER SYSTEM STABILIZER

A power system stabilizer is used to damp out the electromechanical mode of oscillation. Block diagram of power system stabilizer is shown in figure 2

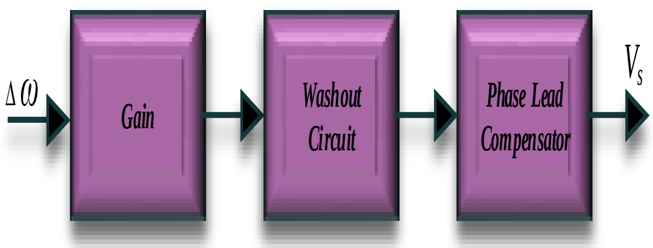

Fig. 2 Structure of PSS

The name assigned to the power system stabilizer is delta omega PSS, as the given input signal is 'Δω'. The input signal is extracted from the rotor speed derivative. PSS mainly consists of a gain block, washout circuit, and phase compensator. PSS is used to fix phase lag between the exciter input and the air gap torque. To produce torque in phase with the speed deviation, the PSS is modelled to compensate for the phase lag.

A. Washout Circuit

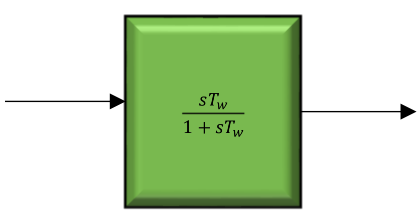

Fig. 3 Washout Block

Figure 3 represents a wash out Circuit is provided to allow the high-frequency signal and block the steady-state deviation. Washout Circuit is also known as a high pass filter. T_w is the Time constant of the washout circuit.

B. Phase compensator

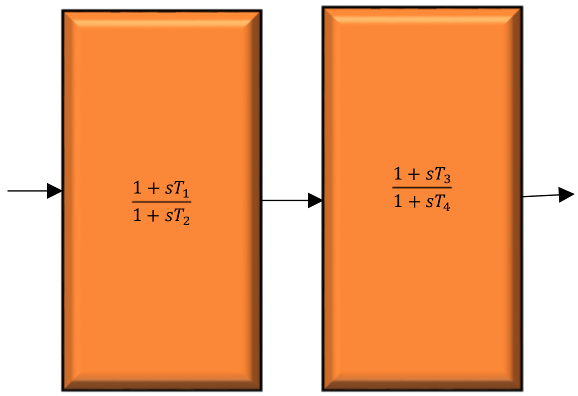

Fig. 4 Two-stage Phase compensator block

Figure 4 shows the block diagram of the compensator, and its basic function is to provide the phase lead, i.e., $T_1 > T_2$ and $T_3 > T_4$, where T_1, T_2, T_3 and T_4 are the Time constant of the Phase compensator. Suppose $T_2 > T_1$ and $T_4 > T_3$, Then the lag type compensation is obtained. Phase compensation is physically realised by using an operational amplifier.
Phase lead compensator must be carefully designed to damp the oscillations, which are local (0.7- 3.0Hz) and interarea (0.1-0.7Hz) oscillations. Hence, the frequency range from 0.1 Hz to 3 Hz is damped out.

C. The objective of the Proposed work

- To damp out rotor oscillation.
- To maintain a terminal voltage of the generator within the acceptable limit.
- To maintain the synchronism of machines.
- To minimize IAE, ISE and ITAE, i.e., min J_i, k_i & l_i

V. ANALYSIS OF FUZZY LOGIC

The most commonly used fuzzy inference control is Mamdani base fuzzy inference, and it is the first control system built using fuzzy set theory. Mamdani fuzzy inferences are intuitive, have widespread acceptance and are well suited to human input. Fuzzy controllers perform three basic process steps fuzzification, interference and defuzzification mechanisms. In the Fuzzification system, variables are translated into linguistic rules. In the proposed work, the membership function considered are speed deviation and change in speed deviation to control excitation.

A. Proposed Fuzzy Logic Control Strategy for PSS

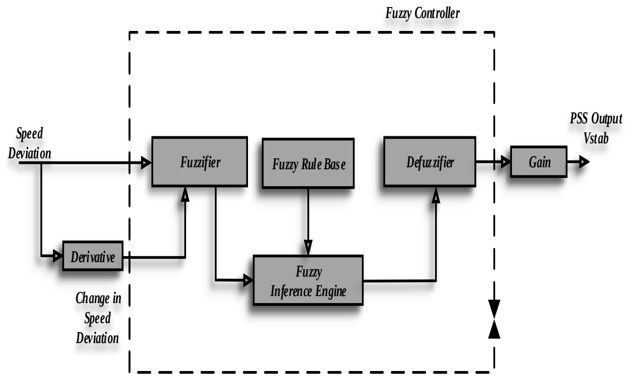

Fig. 5 Proposed Fuzzy Controller based PSS

Figure 5 shows the proposed fuzzy-based PSS controller for power oscillation damping. Assigning the ranges for each linguistic variable, i.e., speed deviation and change in speed deviation is mapped into fuzzy controlled output with the fuzzy rules shown in table 1. The 5 Linguistics variables considered are Very Small (VS), Small(S), Medium (M), High (H), Very High (VH). The output variable is obtained based on linguistic rules, i.e., defuzzification.

Table 1. FUZZY RULES

Change in Speed Deviation \ Speed Deviation	PSS Output Voltage (V_{stab})				
	VS	***S***	***M***	***H***	***VH***
VS	*VS*	*VS*	*VS*	*S*	*S*
S	*VS*	*VS*	*S*	*S*	*M*
M	*VS*	*S*	*S*	*M*	*M*
H	*S*	*S*	*M*	*M*	*H*
VH	*M*	*M*	*H*	*H*	*VH*

In this proposed work, the input1 is the speed deviation of the generator, and input2 is the variation in speed deviation as shown in Fig. 6-7 respectively, and the output 1 is the 'V_{stab}' shown in figure 8, and the corresponding surf view is shown in figure 9.

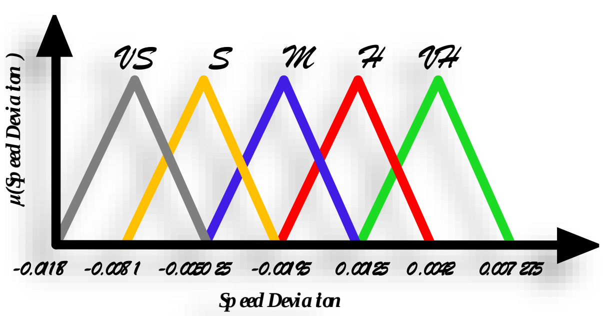

Fig. 6 Triangular membership function change in speed as a variable

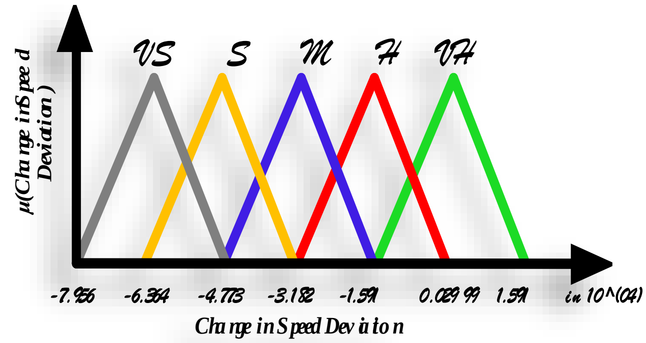

Fig. 7 Triangular membership function speed as a variable

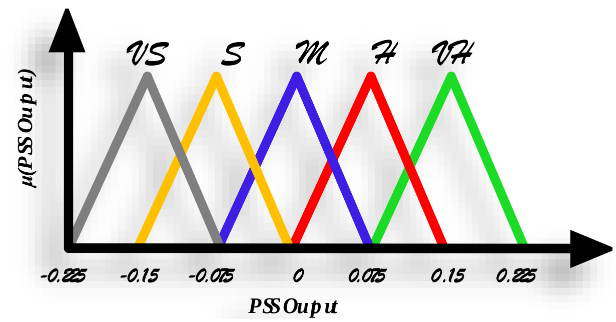

Fig. 8 Triangular membership function control output

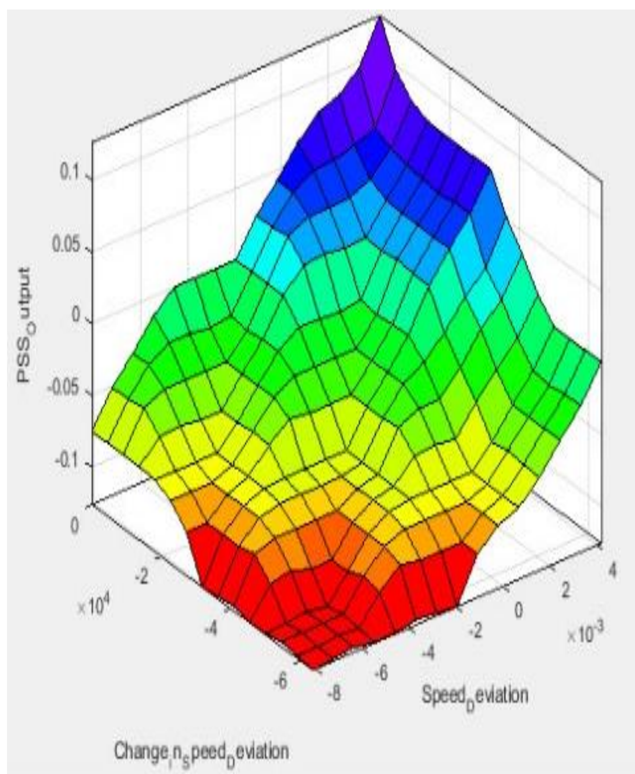

Fig. 9 Surf view of inputs and output

VI. BENCHMARK (TEST SYSTEM)

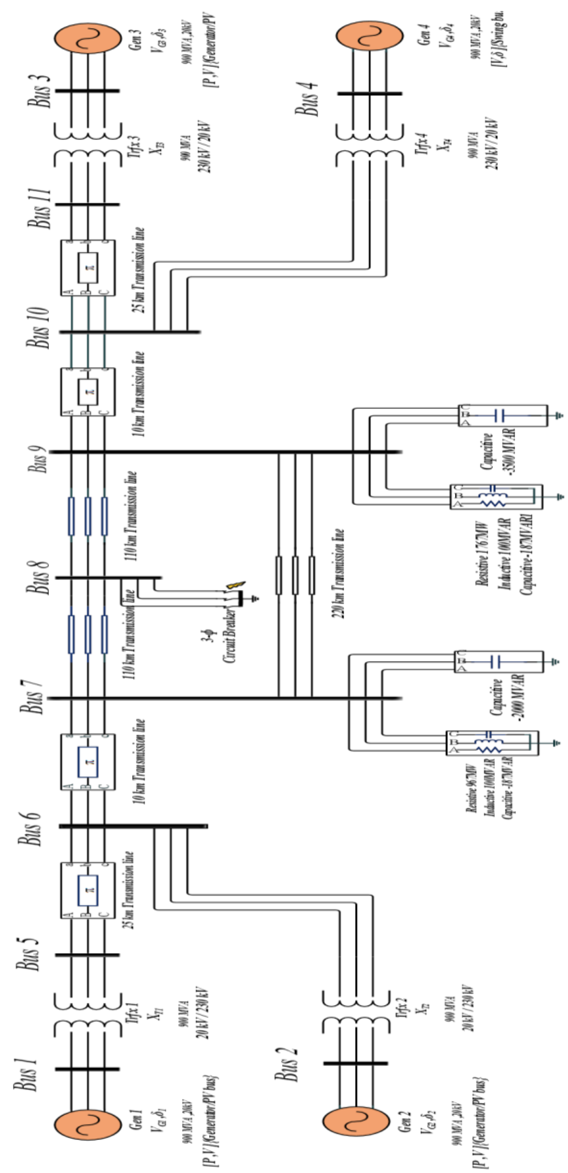

Fig. 10 Simulink Model of 4-Machine 11-Bus Test System

The Benchmark system shown in Figure 10 consists of four generators, namely Gen1, Gen2, Gen3 and Gen 4, which are connected at bus 1, bus 2, bus 3 and bus 4, respectively. Each generator voltage level and MVA rating are 20kV and 900MVA, respectively. The generated voltage is step up to 230kV at bus 5, bus 6, bus10 and bus 11 using Power transformers Trfx1, Trfx2, Trfx3 and Trfx4, each MVA rating of 900MVA. Two transmission lines of 25km each are Connected. Integration of various PSS Controllers along with the excitation system and detail generator modelling is as shown in Figure 11. Based on the PSS controller, the output of excitation is regulated to damp out the power system oscillation. Using standard indices, the controller performance is analysed. Modelling of error indices is shown in figure 12.

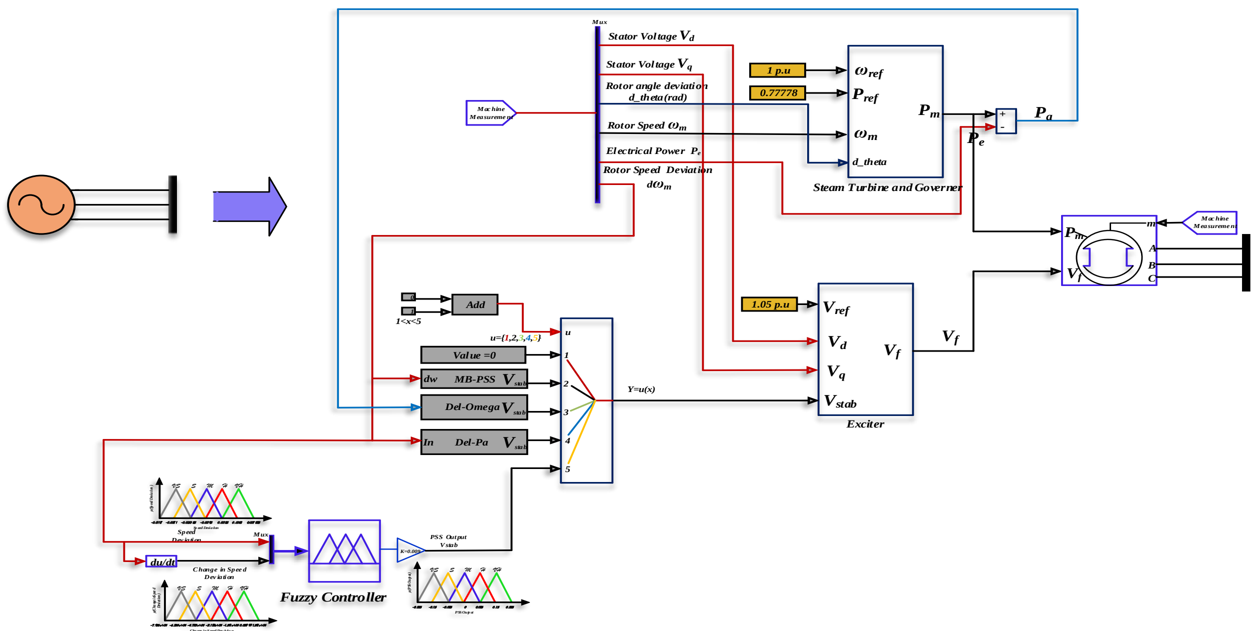

Fig. 11 PSS Coordination with Excitation system

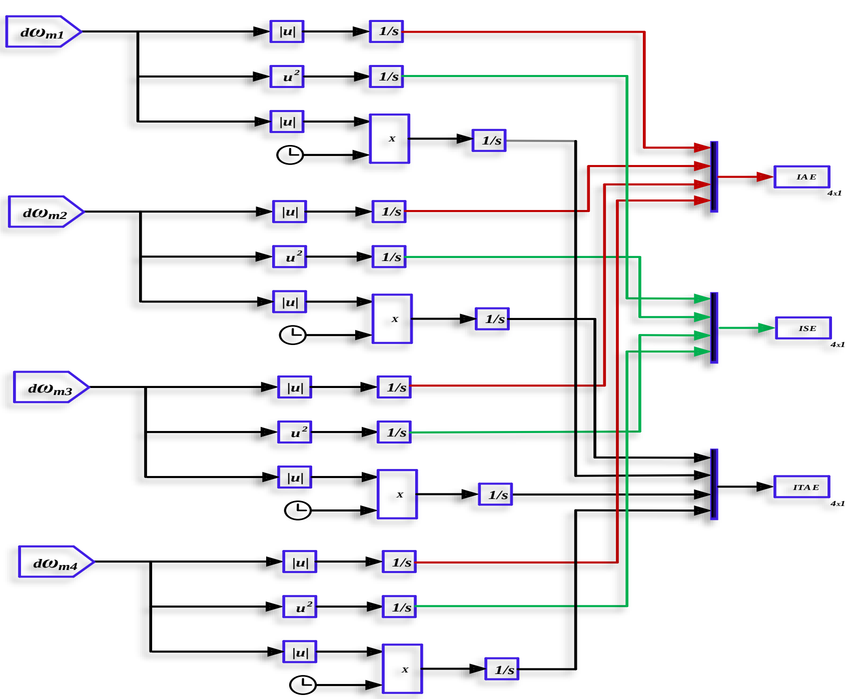

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Fig. 12 Modelling of Error Indices

VII. CASE STUDY

The various cases studies considered to analyse the capability of Fuzzy based PSS controllers to damp power oscillations are tabulated in table 2.

TABLE 2: STATE OF POWER CIRCUIT FOR DIFFERENT CASES

Cases	Type of Fault	PSS	Type of PSS
1.	LLL-G	Absent	No
2.	LLL-G	Present	MB-PSS
3.	LLL-G	Present	Del-Omega-PSS
4.	LLL-G	Present	Del-Pa-PSS
5.	LLL-G	Present	Fuzzy-PSS

Figure 13 shows the Principle of Control logic for the excitation system, and the control signal is denoted as 'u' that decides which kind of PSS has to be connected to the generator excitation system. If u=1 is linked to a NO PSS with a gain of zero, that is, no control circuit is connected to the excitation system. This is the base case, or case 1. Similarly, referring to Table 3 for u=2, 3, 4 and 5, different types of PSS is used to regulate the excitation system.

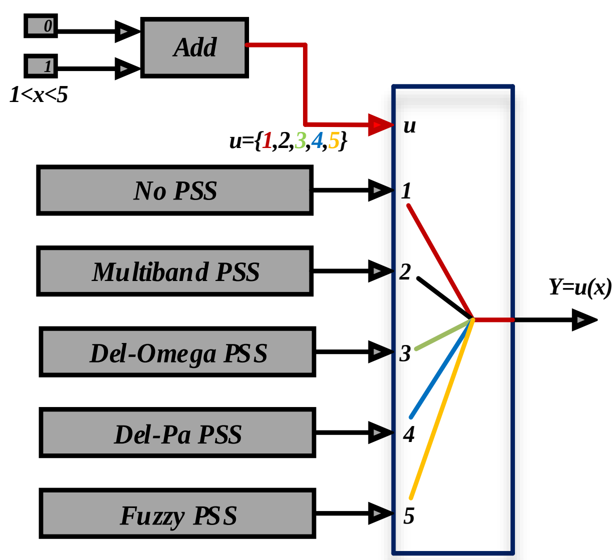

Fig:13 Control logic for Excitation System

TABLE 3: TYPE OF PSS USED FOR CASE STUDIES

Cases	Control Signal 'u'	PSS	Type of PSS
1	1	Absent	No
2	2	Present	MB-PSS
3	3	Present	Del-Omega-PSS
4	4	Present	Del-Pa-PSS
5	5	Present	Fuzzy-PSS

In our case studies, the power oscillations of system parameters considered are rotor angle deviation($\Delta\delta$), terminal voltage (Vg) and rotor speed(ω) for each generator is considered. In all cases, we initiated the 3-ϕ to ground fault at 0.5 sec and cleared at [0.5+ (12cycles/frequency)]sec, here power frequency is 60Hz. Hence, the fault is cleared at 0.7sec. Thus the fault duration is 0.7-0.5=0.2 sec is given to the system.

Case 1: In this case power system is operated in normal condition. Under pre-fault conditions, the load angles of Machine 1, Machine 2 and Machine 3 are 36.34150799°, 24.95113671° and 11.41908353°, respectively. As soon as a fault is initiated at bus 8, the load angle of the system starts oscillating, as shown in figure14.

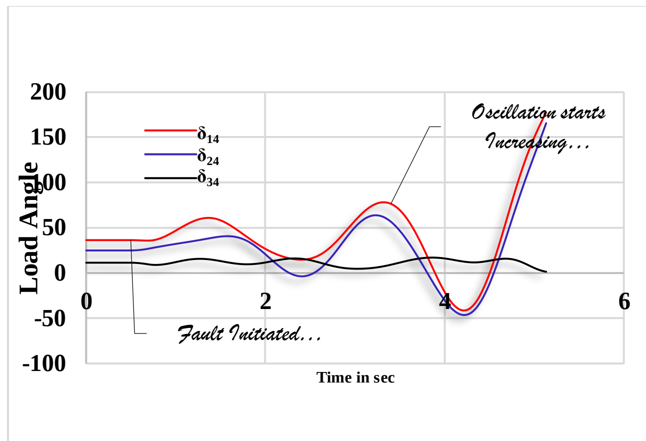

Fig. 14 load angle in degree Without PSS

At t=5.17 sec the load angle $\boldsymbol{\delta_{14}}$ tends to be 180 degrees. If it increases beyond 180 degrees, then reverse power occurs in the system. In order to avoid the reverse power, the control signal has been initiated with reference to load angle and terminate the simulation, i.e., stop the simulation.

The generators in the power system network are operated in synchronism in order to get the stabilised frequency. If the system is perturbed, the machine starts losing its synchronism. From figure 15, we can observe that before fault, the speed profile of machines overlaps each other, implying that all the machines are operated in synchronism. As soon as the fault is initiated, machine 1 and machine 2 in area 1 starts losing their synchronism, and in area 2, machine 3 and machine 4 starts losing their synchronism.

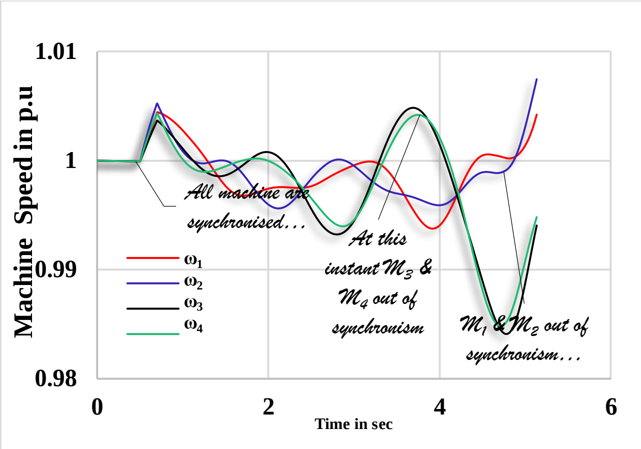

Fig. 15 Machines Speed without PSS

Figure 16 shows the terminal voltage of the generator. As the fault is initiated, the voltage of generator buses dipped below the minimum acceptable limits. As soon as a fault is cleared, the voltage rises and start oscillating, violating the system constraints. Hence the system voltage stability is not maintained once the fault has been cleared, which leads to overdamp in the terminal voltage of the generator.

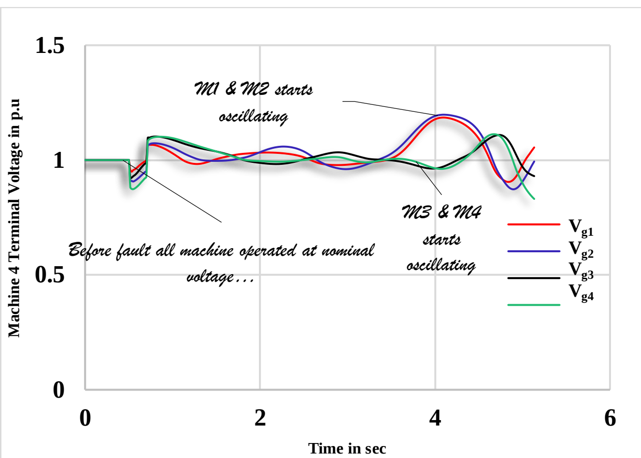

Fig. 16 Terminal voltages of Machines without PSS

From case2 – case 5, the plots of all 4 cases for each parameter is shown together so that a comparison of the performance of a different type of PSS is easily analyzed. Load angle δ_{14}, δ_{24} & δ_{34} are shown in figure(17-19), respectively. Each figure contains the results of all 4 cases. Similarly, for Machine speed ω_1,ω_2,ω_3 & ω_4 are shown in figure(20-23) and generator terminal voltage V_{g1}, V_{g2}, V_{g3} & V_{g4} are shown in figure(24-27).

Case 2: In this case, multiband PSS is activated for control signal u=2. As we can clearly observe that the transient stability of the system in the presence of PSS is improved; however, for each parameter (load angle, machine speed and generator terminal voltage), steady-state stability improvement requires more Time to reach a stable operating point as observed from Figure 17-27.

Case3: In this case, Delta-Omega PSS is activated for control signal u=3. As we can clearly observe from figure 17-27 that the transient and steady-state stability that reach the stable operating point is improved compared to that of multiband PSS.

Case4: In this case, Delta-Pa PSS is activated for control signal u=4. Pa is the accelerating power which is derived by subtracting mechanical power and generated electrical power, the derived signal feed to delta-Pa PSS. As observed from figure 17-27, the transient and steady-state stability is poor when compared with case1 case 2. The operating point requires more Time to reach near neighbourhood stable operating point

Case5: In this case, Fuzzy PSS is activated for control signal u=5. Here the input to the fuzzy controller is speed deviation and change in speed deviation, and the corresponding output is V_{stab}. It can be observed from figure 17-27 that with fuzzy based PSS, the oscillation is damped out, and steady-state error is minimized as compared to the previous 4 cases.

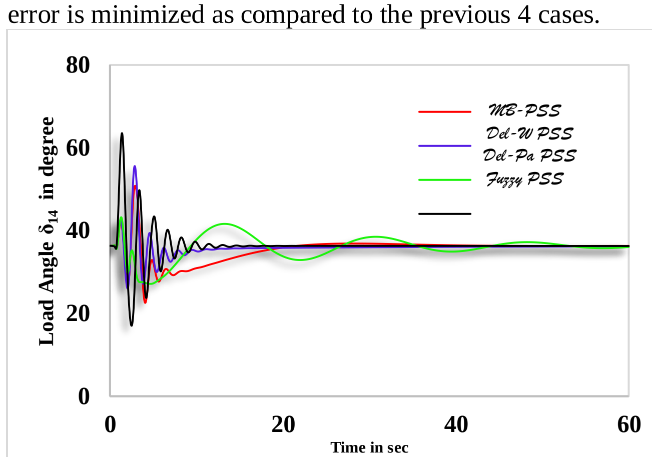

Fig. 17 Load angle between machine one and four (δ_{14}) in degree With PSS

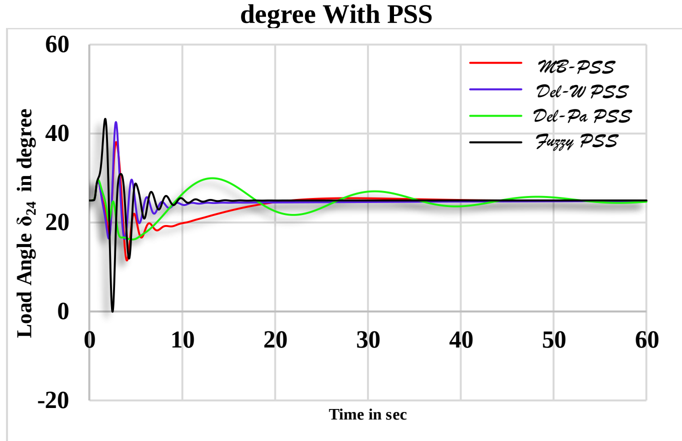

Fig. 18 Load angle between machine one and four (δ_{24}) in degree With PSS

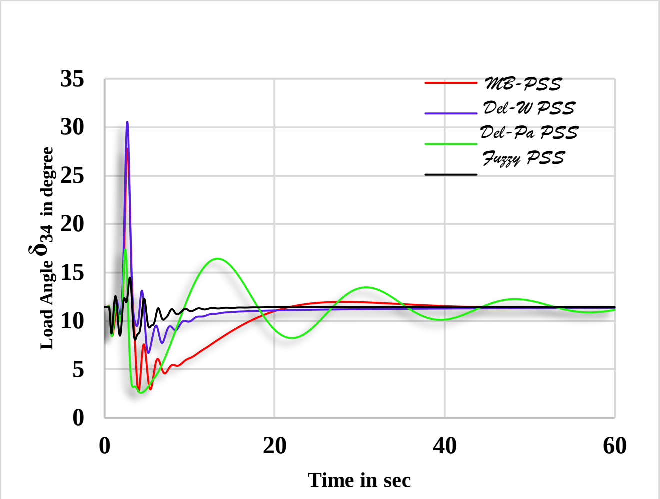

Fig. 19 Load angle between machine one and four (δ_{34}) in degree with PSS

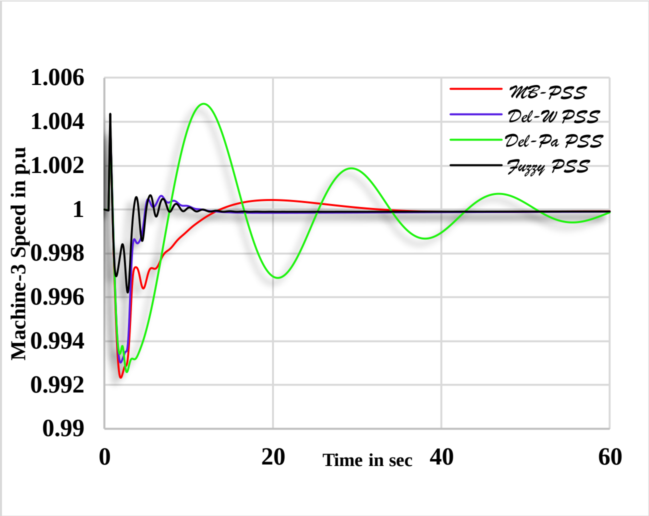

Fig. 22 Machine-3 Speed with PSS

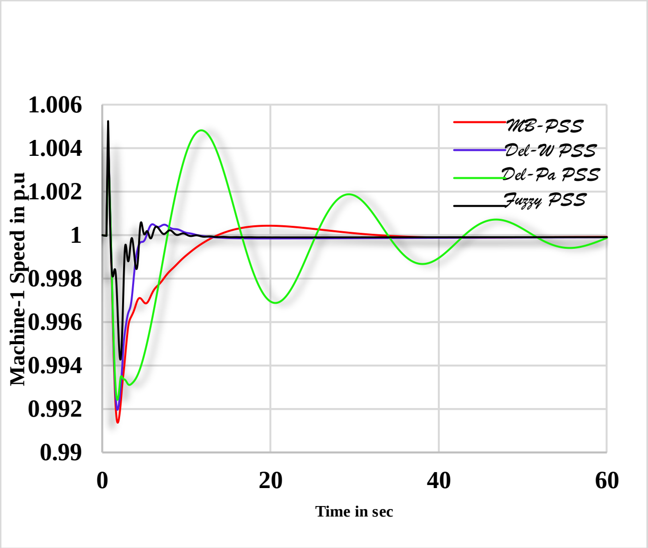

Fig. 20 Machines-1 Speed with PSS

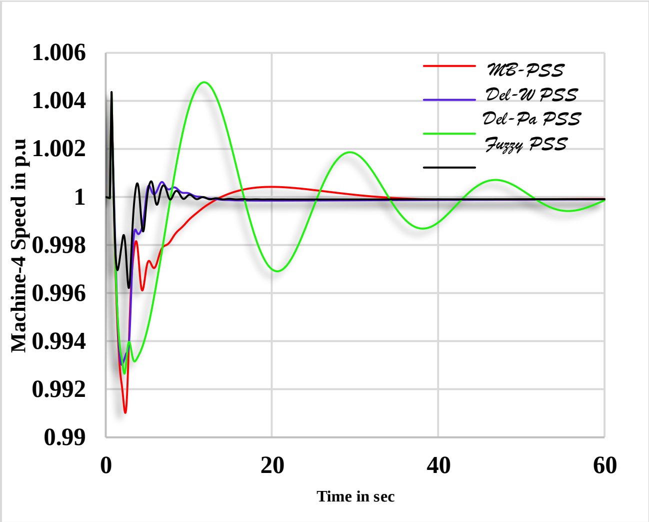

Fig. 23 Machine-4 Speed with PSS

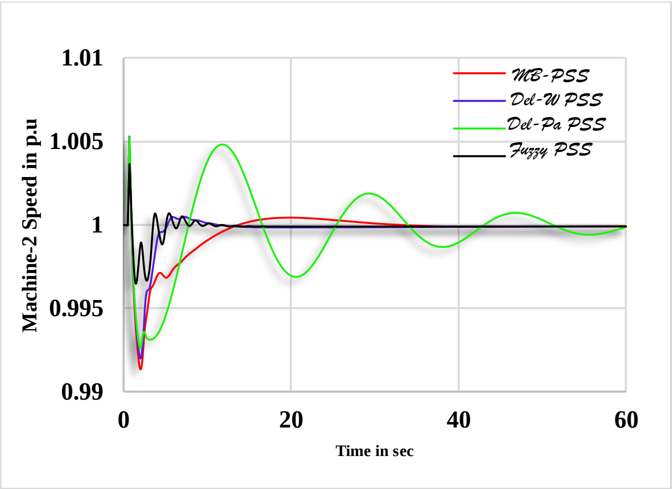

Fig. 21 Machine-2 Speed with PSS

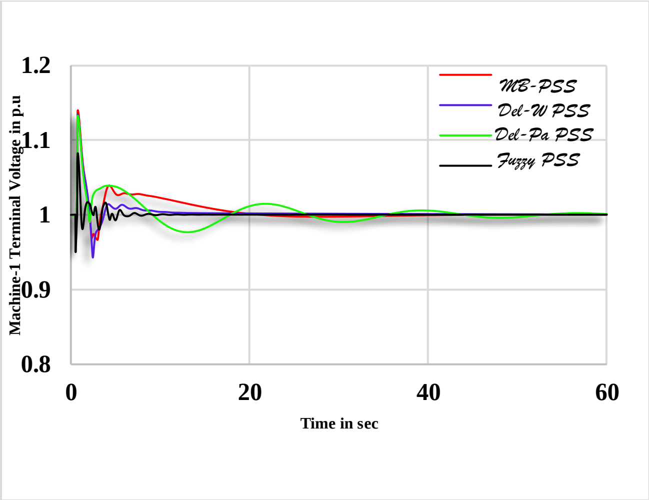

Fig. 24 Terminal voltages of Machine-1 with PSS

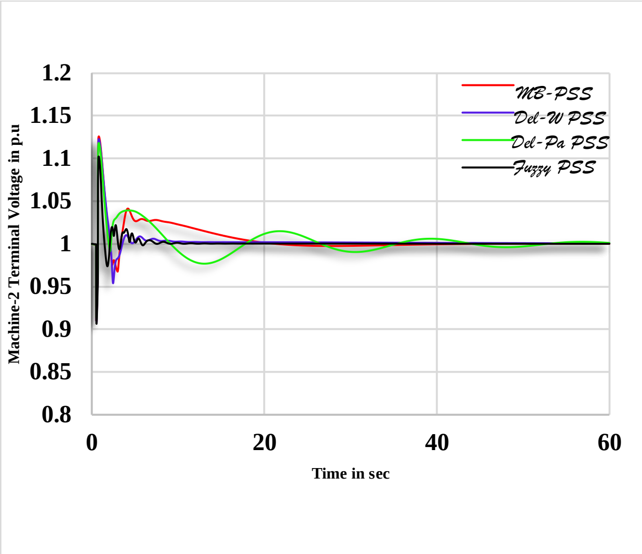

Fig. 25 Terminal voltages of Machine-2 with PSS

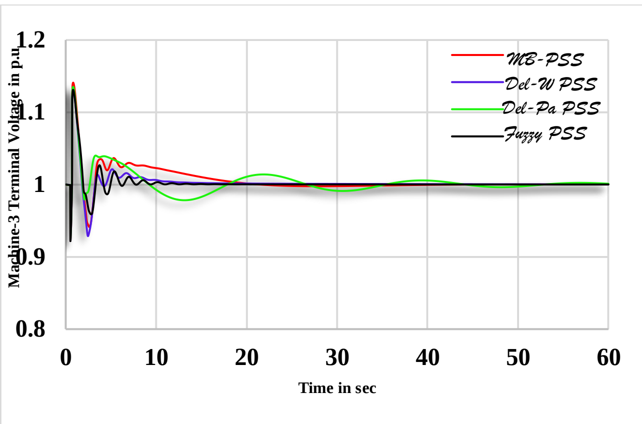

Fig. 26 Terminal voltages of Machine-3 without PSS

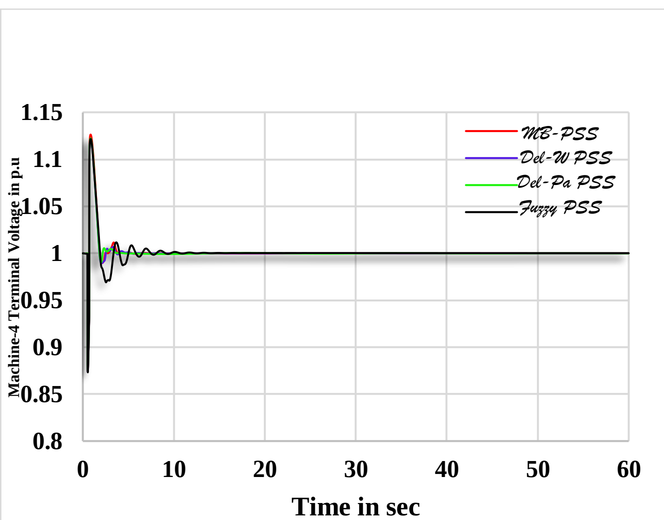

Fig. 27 Terminal voltages of Machine-4 without PSS

A. Error indices

The error indices IAE, ISE and ITAE for all the 5 cases considered are calculated and tabulated in Table4, Table 5 and Table 6, respectively. The same is represented with the help of a bar graph as shown in figure 28, figure 29 and figure 30. Referring to Table 4-6, it is clearly observed that implementation of Fuzzy based PSS has significantly enhanced the system performance and has effectively minimized the error indices.

TABLE 4 COMPARISON OF INTEGRAL ABSOLUTE ERROR OF GENERATOR FOR ALL FOUR CASES

IAE				
	Del-Pa-PSS	MB-PSS	Del-Omega-PSS	Fuzzy PSS
Gen-1	0.1034	0.03904	0.02319	0.01489
Gen-2	0.1035	0.0392	0.02323	0.01329
Gen-3	0.1022	0.03849	0.02298	0.01353
Gen-4	0.1028	0.03854	0.02285	0.01342

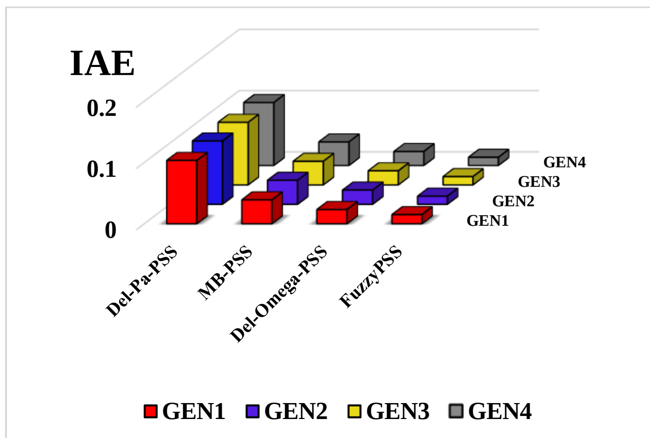

Fig. 28 IAE

TABLE 5 COMPARISON OF INTEGRAL SQUARE ERROR OF GENERATOR FOR ALL FOUR CASES

ISAE				
	Del-Pa-PSS	MB-PSS	Del-Omega-PSS	Fuzzy PSS
Gen-1	0.000366	0.000137	8.30E-05	3.13E-05
Gen-2	0.000366	0.000138	8.29E-05	2.61E-05
Gen-3	0.000355	0.000138	8.62E-05	1.98E-05
Gen-4	0.000361	0.000132	7.86E-05	1.94E-05

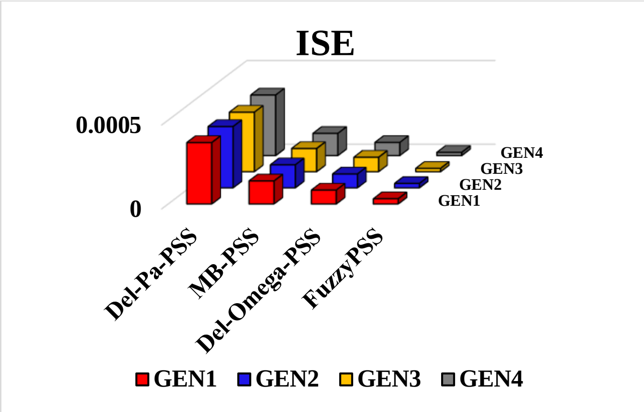

Fig. 29 ISE

TABLE 6 COMPARISON OF INTEGRAL TIME ABSOLUTE ERROR OF GENERATOR FOR ALL FOUR CASES

ITAE				
	Del-Pa-PSS	**MB-PSS**	**Del-Omega-PSS**	**Fuzzy PSS**
Gen-1	1.774	0.3604	0.258	0.1946
Gen-2	1.773	0.3602	0.2576	0.1894
Gen-3	1.761	0.3569	0.2586	0.193
Gen-4	1.773	0.3601	0.2587	0.1927

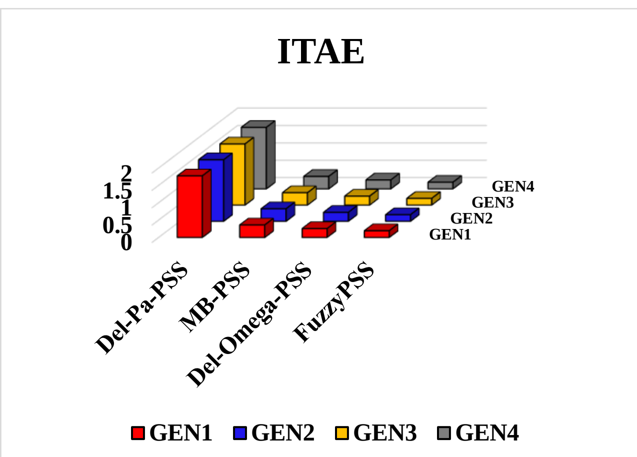

Fig. 30 ITAE

VIII. CONCLUSION

The main objective function is to minimize the error indices that define the performance of the power system operation point. To dampen the rotor oscillation in the power system network, a fuzzy-based controller is used so as to maintain synchronism between the machines and keep the terminal voltage and load angle within the acceptable limit. Various controlling methods for PSS are used. The capability of the different types of conventional PSS and Fuzzy controlled PSS are compared and the results obtained from Fuzzy controlled PSS are exceptional than that of conventional types of PSS. The error indices obtained with Fuzzy controlled PSS are significantly less compared to other types of PSS. Thus, intelligent tuning of PSS results in the enhancement of transient and steady-state stability in the multimachine power system network.

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APPENDIX A

Terminology

R_s Stator resistance $(\mathrm{p.u})$
X_q quadrature-axis reactance $(\mathrm{p.u})$
X'_q Transient q-axis reactance $(\mathrm{p.u})$
X''_q Sub-Transient quadrature-axis reactance$(\mathrm{p.u})$
X_d direct-axis reactance $(\mathrm{p.u})$
X'_d Transient d-axis reactance in p.u
X''_d Sub-Transient d-axis reactance $(\mathrm{p.u})$
H Shaft inertia constant (seconds)
E'_q q-axis transient internal voltage $(\mathrm{p.u})$
E'_d direct -axis transient internal voltages $(\mathrm{p.u})$
Ψ_{1d} Damper winding 1d flux linkages $(\mathrm{p.u})$
Ψ_{2d} Damper winding 2q flux linkages $(\mathrm{p.u})$
E_{fd} Field voltage $(\mathrm{p.u})$
R_F Rate feedback $(\mathrm{p.u})$
T_{Fw} Frictional windage torques
δ Rotor angle or load angle in rad
ω Angular speed of generator (rad/sec)
ω_s Generator synchronous speed (rad/sec)

T'_{qo} q-axis time constant associated with E'_d (seconds)

T''_{qo} q-axis time constant associated with Ψ_{2d} (seconds)

T'_{do} d-axis time constant associated with E'_q(seconds)

T''_{do} d-axis time constant associated with Ψ_{1d} (seconds)

T_A Amplifier time constant (seconds)

Authors:

Madhusudhan M, born in Mysore, India, on January 13, 1995, received, B.E., M. Tech from Electrical and Electronics Department, Visvesvaraya Technological University Belgaum in 2017 and 2019, respectively. Currently pursuing 3rd-year full-time Ph. D in Electrical and Electronics Department at The National Institute of Engineering, Mysore, Karnataka, India under Visvesvaraya Technological University Belgaum. Area of research in Power System Dynamics Control, application of FACTS devices and optimization in power systems.

Dr H. Pradeepa Received a Bachelor of Engineering degree from Bangalore University, M. Tech from National Institute of Technology Karnataka, Surathkal, and Ph. D from Visvesvaraya Technological university, Belagavi. Currently working as an Associate Professor in the Dept. of Electrical and Electronics Engineering at The National Institute of Engineering, Mysore, Karnataka, India. Research interest is in power systems which include distribution systems, renewable energy, and smart grid. Currently working on a project titled “Digital Protection Algorithms for Renewable Integrated Grid”, Sponsored by VGST and Govt. of Karnataka”. At present guiding 2 full-time PhD scholars (AICTE – NDF Scheme) in the area of Energy Management System.