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Simultaneous Adjustment of AVR and Optimized PSS Outputs Effect in Power Systems for Stability Improvement

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Abstract

Due to the problems related to low-frequency oscillations (LFOs) and power systems complexities, using intelligent methods and optimization techniques is essential for solving power system stabilizer (PSS) problems. In this paper, power system stabilizer, based on the PSOPSS, is designed to set the parameters of PSS. Then, the FLC is designed to simultaneously weighting the automated voltage regulator and power system stabilizer outputs, to adjust the excitation controller facing with disturbance. The ability to optimize particle swarm algorithm, in combination with FLC ability to solve complex and nonlinear problems, will effectively improve the stability of the power system. Initially, the simulation was performed on a single machine system in which the PSS optimal parameters were obtained using particle swarm optimization (PSO). Afterwards, with simultaneous regulation of the voltage and damping by the fuzzy logic controller, the effectiveness of the proposed approach, compared with the PSS based on the linear optimization controller, is confirmed. Next, more effective results can be obtained on a multi-machine system with effective placement of the FLPSS, compared with the conventional PSS and with simultaneous adjustment of the output weights of voltage and damping controllers using FLC. The efficiency of the proposed method in response to a variety of disturbances is determined.

Keyword: automatic voltage regulator, fuzzy logic controller, power system stabilizer

Introduction

Automatic voltage regulators influence on the damping of LFOs and their effect on the stability and power systems is vital. These oscillations with small amplitude and low frequency without proper control remain and increase in the system [1,2]. PSS is utilized as a supplementary control signal in the excitation system for LFO damping and improving the dynamic stability of the system [3,4].

Generally, the stabilizer should make the proper electrical torque component in phase with speed deviations in rotor [5,6]. The conventional PSS includes phase compensation, removing a steady state signal effect (washout) and gain blocks [7,8]. Therefore, the needed damping happens and the lag between the excitation input and the electric generator torque is compensated and the speed deviations signal are only allowed to pass with the help of a washout filter [9,10]. Effective system response, at the time of disturbance, depends on the proper determination of the PSS parameters. PI, PD and PID controllers are among the most commonly used controllers that can be utilized as a stabilizer and each of them help increase the power system stability and reduce its volatility by increasing stability and reducing steady-state error or by increasing damping and reducing overshoot or even a combination of both [11,12]. Nowadays, intelligent optimization techniques used to obtain and choose the optimum PSS parameters, under different operating points, are most welcomed by scholars. Intelligent simulation methods for simulated annealing (SA) [13], ant colony optimization (ACO) [14], harmony search (HS) [15], tabu search algorithm [16], bacterial foraging optimization (BFO) [17], genetic algorithm (GA) [18,19] and artificial neural networks (ANN) [20,21] are among the ways used in the design of the power system stabilizer due to the reduction of complex calculations and use of optimization techniques [22].

To solve the optimization problems, PSO is a widely used iteration-based method [23]. In this algorithm, each parameter can be considered as a particle which is optimized as a candidate solution. In PSO, each particle moves at a certain velocity and its velocity will be amended with regard to its own velocity and the velocity of the other particles at each iteration [24,25]. PSO is utilized in the design of PSS, due to simple mathematical calculations and its high effectiveness in optimizing the PSS parameters [26,27]. In [28] and [29], PSO is used for damping the power system oscillations and increasing its stability. A multi-objective design of the multi-machine PSS using ant colony optimization is proposed in [30], where the fine tuning of parameters problem is converted to an optimization problem.

Fuzzy logic controllers, without the need for accurate mathematical model of the system, convert the control inputs into fuzzy input values. Then, they make fuzzy controlling outputs by the fuzzy inference and based on a set of fuzzy rules. Finally, in the de-fuzzification unit, fuzzy controlling outputs are converted into the controlling outputs applicable to the system [31,32]. The work done on fuzzy logic control reveals its effectiveness, simplicity and its ability to solve complex and nonlinear problems. In [33] and [34], the type-2 fuzzy methods have been used to design PSS. Fuzzy logic can be utilized in combination with other methods. In some articles, a combination of fuzzy logic with neural networks [35] and genetic algorithm [36] is used to improve the results obtained from the PSS in increasing the stability and reducing oscillations. Fuzzy logic controller also is used to adjust the weights of AVR and PSS outputs which significantly improved the system damping and dynamic stability of the system [37]. In [38], a fuzzy power system stabilizer is designed and is effectively located in a multi-machine power system. The use of the non-dominated sorting genetic algorithm to achieve optimal PSS parameters using an eigenvalue-based multi-objective function for a given operating point with a renewable source of energy so as to increase the system damping and guarantee enough stability margin is show in [39].

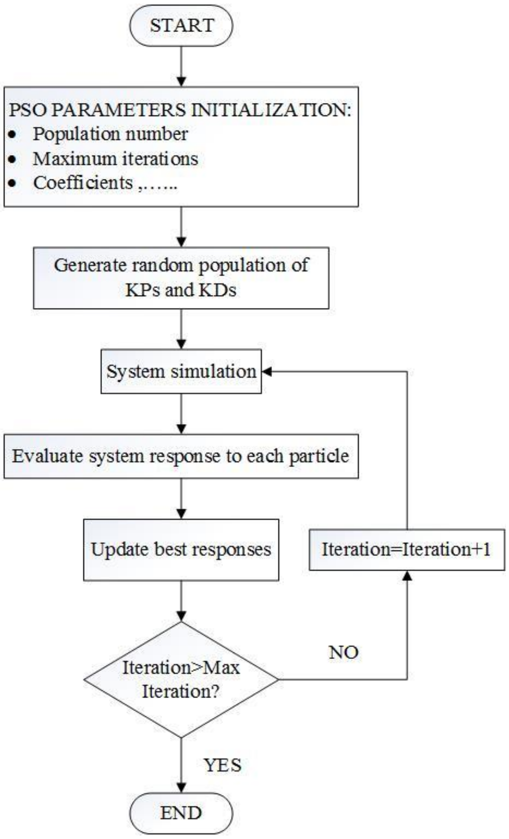

Figure 1: Flowchart of PSO algorithm to determine the PSOPSS optimal parameters

In this paper, the PD controller is used as PSS with its parameters being optimized by PSO algorithm. Afterwards, the output of PSOPSS controller will be weighted along with the AVR output by a FLC, according to the system working condition. Finally, the PSOFLC controller is made by combining PSOPSS and FLC and its output is applied to the excitation system. The proposed method is implemented on a single machine system and its effectiveness in reducing oscillations and increasing damping, compared with the linear optimization controller (LOC) in [40] is clearly visible at the disturbance time. Then, a stabilizer, based on fuzzy logic (FLPSS) and effective placement in a multi-machine system, will be designed. Afterwards, with proper weighting of PSS and AVR outputs with FLC, FL-FLC excitation controller will be made. In FL-FLC, the effective placed FLPSS will be used in addition to FLC. The effectiveness of the proposed method, compared with conventional PSS at the time of disturbance and compared with the results obtained in [31] in reducing the oscillations and increasing damping will be presented.

This paper is organized as follows. After the introduction presented in the first section, in the second section, the structure of the proposed AVR and PSOPSS is presented. In this section, the design of the particle swarm algorithm to obtain the optimal PSS parameters is shown. In the third section, the structure of the proposed excitation controller is presented. In the first part of the same section, the design procedure of simultaneous controller of AVR and PSS output, using fuzzy logic, which is called FLC is described and in the second part of the same section, the design of FLPSS for multi-machine power system is discussed. In the fourth section, a single-machine power system model, along with the corresponding equations, have been presented. Furthermore, linear optimization controller-based stabilizer, to compare with the proposed method, is described. In the fifth section, simulation results on single-machine and multi-machine power systems, to demonstrate the effectiveness and efficiency of the proposed method in a state of disturbance, is presented. Finally, conclusion is presented in the sixth section.

AVR and PSOPSS structure

AVR structure

In this paper, the conventional PID controller structure, according to reference [41], is used for automatic voltage regulator. These controllers increase the gain stability and reduce the steady-state error and the maximum overshoot of the output signal. Their structure is in the form of a proportional gain in combination with the integral and derivative gains. The job of this controller in the AVR structure is voltage regulation in proportionate to the setting values. If the system changes due to the voltage disturbance, this controller returns the voltage to the setting mode with a low error rate. The controller uses generator terminal voltage U_t as input and generates the proper output.

PSOPSS structure

In this paper, PD controller structure is used to stabilize the power system and its parameters are optimized by PSO algorithm. The controller provides a proper performance in reducing system oscillations and increasing the dynamic stability by increasing system damping which results in overshoot reduction. This controller is created by combining two proportional and derivative gains of K_P and K_D. K_P and K_D optimal parameters are obtained from the PSO algorithm. The deviations in the generator rotor speed are used as the input to PSS in this stabilizer. In the PSO algorithm, each parameter can be considered as a particle which is optimized as a candidate solution. In PSO, each particle moves at a certain velocity and its velocity will be amended with regard to its own speed and the speed of the particles at each iteration to be able to select the optimized solution considering the objective function. Maximization of the damping ratio is considered as an objective function regarding the improvement of oscillations damping. In this algorithm, the optimal solution is determined by the following equations [42]:

$$V_i^{t+1} = \omega v_i^t + c_1 \times rand_1 \times (p_i^{BEST} - X_i^t) + c_2 \times rand_2 \times (g^{BEST} - X_i^t) \quad (1)$$

$$X_i^{t+1} = X_i^t + v_i^{t+1} \quad (2)$$

1. where V_i^t is the velocity of the particle i at the iteration time t and X_i^t is the location of particle i at the iteration time t, i = 1, 2, ..., n where n is the total number of particles. ω, inertia factor, c_1, cognitive acceleration factor and c_2, social acceleration factor. $rand_1$ and $rand_2$ are random numbers with uniform distributions in the range

of zero to one. p_i^{BEST} is the best personal position of the particle i, and g^{BEST} is the best global position of the particles.

2. In Fig. 1, the flowchart of PSO algorithm steps to find the optimal particles is shown. In this paper, according to Fig. 2, after 200 iterations on 200 particles the optimal values are obtained. Optimal values of the gains of K_p=-12.07 and K_D=-19.62 for a single-machine system and by using the PSO algorithm are provided.

The structure of the proposed excitation controller

In the proposed excitation controller, the output of the AVR and PSOPSS controllers is weighted with fuzzy logic controller, according to the system working conditions and the type of disturbance and eventually applied to the generator excitation system. In Fig. 3, a block diagram of this controller is displayed. In the steady state of the power system, the excitation control is adjusting and regulating the generator's voltage. Therefore, the role of AVR should be highlighted, compared with the PSS. In conclusion, more weight is assigned to AVR in the excitation control.

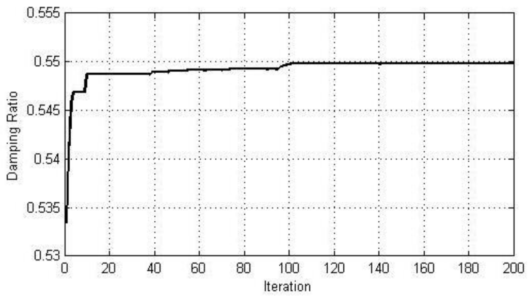

Figure 2: Damping ratio and the number of iterations in PSO algorithm

Also, if the system undergoes a disturbance with a large amplitude, initially there will be big changes in the voltage range and naturally, AVR assigns more weight to itself. However, there are cases where oscillations in the rotor angle of the system happen due to a minor disturbance. Or there are moments after larger disturbances when the system is still faced with oscillations in the generator rotor angle. It is obvious that in such cases, PSS plays a vital role and needs to allocate more weight to itself.

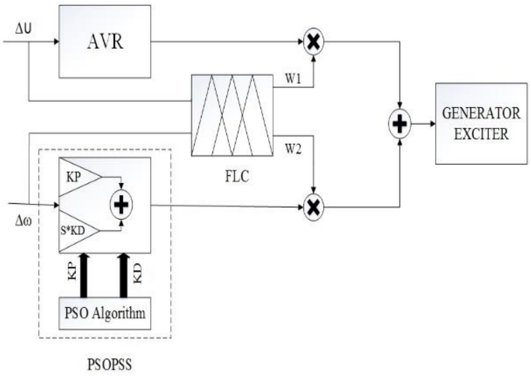

Figure 3: Block diagram of the proposed excitation controller

Fuzzy controller structure

Fuzzy controller uses the signals of speed and voltage deviations as the input and the weights W_1 and W_2 are used respectively for weighting the output signals of AVR and PSS. FLC is composed of fuzzification, fuzzy inference engine and defuzzification. Linguistic terms, fuzzy membership functions and fuzzy rules of the FLC controller will be determined as follows:

The linguistic terms of the input variables ΔU_t and $\Delta\omega$ are as follows:

- ZE (Zero),
- S (Small),
- M (Medium),
- B (Big)

The linguistic terms of the output variables W1 and W2 are as follows:

- ZE (Zero),
- VS (Very Small),
- S (Small),
- LM (Light Medium),
- M (Medium),
- MB (Medium Big),
- B (Big)

Input and output variables membership functions are presented in Figs. 4 and 5 respectively.

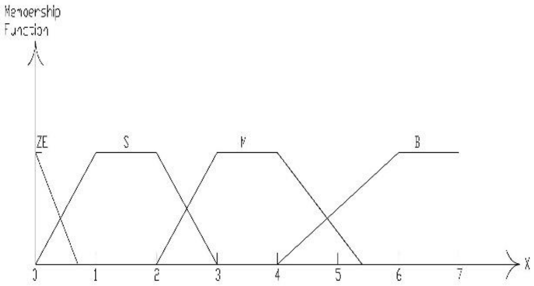

Figure 4: Membership function of input variables

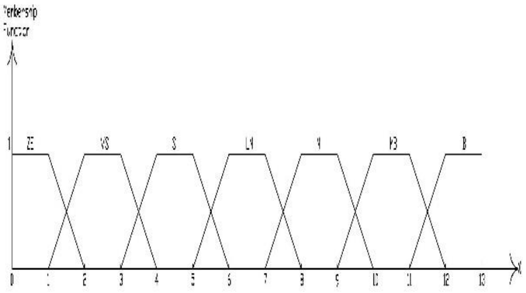

Figure 5: The membership function of output variables

Fuzzy rules are in the form of IF-THEN statements in the fuzzy inference engine. One statement is presented below as an example and for simplification and ease of access, the rest of the statements are presented in Table 1.

IF $\Delta\omega$ is ZE and ΔU_t is ZE THEN W1 is M and W2 is ZE.

FLPSS fuzzy stabilizer structure for a multi-machine system

A fuzzy stabilizer is used for a multi-machine power system whose proper placement in the system will positively influence the stability of the power system. The stabilizer uses the generator speed deviations and its derivation as input. FLPSS Output, after weighting by FLC, will be applied to the excitation system as a supplementary signal. Linguistic terms, fuzzy membership functions and the fuzzy rules of FLPSS controller will be determined as follows [40]:

The linguistic terms of input and output variables: NVB (Negative Very Big), NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big), PVB (Positive Very Big)

In Fig. 6, the membership function of the input and output variables is presented.

Fuzzy rules are in the form of IF-THEN statements in the fuzzy inference engine. One statement is presented below as an example and for simplification and ease of access, the rest of the statements are shown in Table 2.

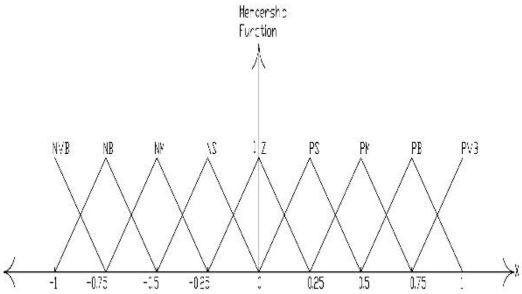

Figure 6: The membership function of FLPSS input and output variables

IF $\Delta\omega$ is NVB and $d(\Delta\omega)/dt$ is NVB THEN Output is NVB

FLPSS structure is shown in Fig. 7. Gain setting the input and output variables is $\alpha_1 = 4$, $\alpha_2 = 3$ and $\alpha_3 = 5$ respectively.

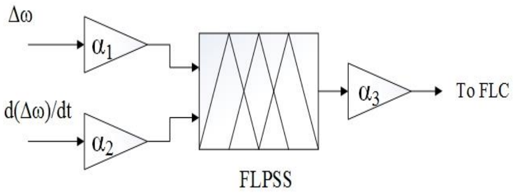

Figure 7: FLPSS's structure in the multi-machine power system

Single-machine power system model

Based on the reference [43], linearized third-order equations of single-machine system in equilibrium point, can be expressed as (3):

$$\dot{X} = AX + BU \tag{3}$$

where A is the system state matrix, B is the control matrix and U is the input vector and the system state vector is as (4):

$$X = [\,\Delta\delta \quad \Delta\omega \quad \Delta E'_q \quad \Delta P_e\,]^T \tag{4}$$

deviations of the rotor, $\Delta \acute{E}_q$, transient voltage deviations along the axis q and ΔP_e is the electric power deviations.

The system state matrix, the control matrix and the input vector are given by (5), (6) and (7), respectively:

$$A = \begin{bmatrix} 0 & \omega_b & 0 & 0 \\ -\dfrac{K_1}{2H} & 0 & -\dfrac{K_2}{2H} & 0 \\ -\dfrac{K_4}{T_3} & 0 & -\dfrac{1}{K_3 T_3} & 0 \\ -\dfrac{K_2 K_4}{T_3} & K_1\omega_b & -\dfrac{K_2}{K_3 T_3} & 0 \end{bmatrix} \tag{5}$$

$$B = \begin{bmatrix} 0 & 0 & \dfrac{1}{T_3} & \dfrac{K_2}{T_3} \end{bmatrix}^T \tag{6}$$

T`able 1: FLC fuzzy rules

		Δω			
		ZE	S	M	B
ΔU$_t$	ZE	W1:M	W1:S	W1:VS	
		W2:ZE	W2:M	W2:MB	
	S	W1:M	W1:M	W1:S	
		W2:S	*W2:MB*	W2:B	
	M	W1:MB	W1:M	W1:S	
		W2:ZE	W2:VS	W2:MB	
	B	W1:MB	W1:M	W1:B	
		W2:ZE	W2:VS	W2:B	

Table 2: FLPSS fuzzy rules

		Δω								
	Output	NVB	NB	NM	NS	Z	PS	PM	PB	PVB
d(Δω)/dt	NVB	NVB	NVB	NVB	NVB	NVB	NB	NM	NS	Z
	NB	NVB	NB	NB	NB	NB	NM	NS	Z	PS
	NM	NVB	NB	NM	NM	NM	NS	Z	PS	PB
	NS	NVB	NB	NM	NS	NS	Z	PS	PS	PB
	Z	NVB	NB	NM	NS	Z	PS	PM	PB	PVB
	PS	NB	NM	NS	Z	PS	PM	PM	PB	PVB
	PM	NM	NS	Z	PS	PM	PM	PVB	PVB	PVB
	PB	NS	Z	PS	PM	PB	PM	PB	PB	PVB
	PVB	Z	PS	PM	PB	PB	PB	PB	PVB	PVB

where Δδ is the rotor angle deviations, Δω, speed

$$U = [\,\Delta E_{fd}\,] \tag{7}$$

where H is inertia constant, T_3, transient time constant of the excitation winding, and the coefficients K_1, K_2, K_3 and K_4 are constants called K in [44]. A PSS, based on a linear optimization control theory of LOCPSS, has been brought from reference [36] for comparison with PSOPSS of the proposed excitation system. The results obtained from PSOPSS and simultaneous setting of the excitation system inputs by PSOFLC, - indicate a significant improvement in dynamic stability and damping of the system, compared with LOCPSS. LOCPSS objective function is as (8):

$$J = \frac{1}{2}\int_0^{\infty} (\,X^T Q X + U^T R U\,)dt = J_{min} \tag{8}$$

where Q is a diagonal matrix and R = 1. By considering feedback gain matrix as (9):

$$K = R^{-1}B^{T}P = [\,K_{pe} \quad K_{\omega} \quad K_{u}\,]^{T} \tag{9}$$

and by obtaining P from solving the Riccati equation, LOCPSS is implemented. Kpe is the gain of electrical power deviations and Kω is the gain of speed deviations. LOCPSS block diagram is shown in Fig. 8.

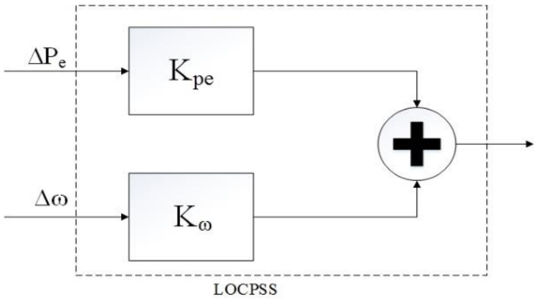

Figure 8: LOCPSS block diagram

Simulation results

The simulation was carried out in two parts. In the first part, the simulation was done on a single machine connected to an infinite bus system (SMIB). The schematic presentation of this system is depicted in Fig. 9. In the second part, simulations were carried out on a four-machine two-area system. The schematic representation of this multi-machine system is shown in Fig. 10. The data and parameters of both above mentioned systems are available in [41].

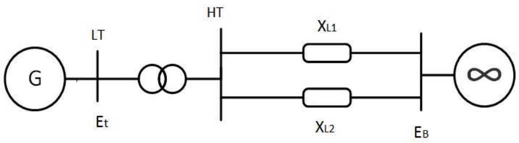

Figure 9: A schematic design of single machine system connected to an infinite bus (System 1)

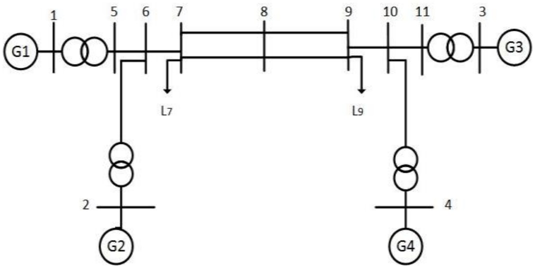

Figure 10: A schematic design of four-machine power system (System 2)

Single-machine power system

Simulation on a SMIB system was carried out under the operating point (U_t=1p.u, $\delta_{\circ}$=65°) when the system had 10% more voltage than the base voltage of the generator's terminal. In this disturbance, the system voltage will be set by AVR, along with some oscillations, in the new value. The oscillations of the rotor angle will damp and balance with the help of PSS. The simulation has been carried out and compared in three states, namely LOCPSS, PSOPSS and PSOFLC. Responses of rotor speed deviations and rotor angle deviations to the previously mentioned disturbance are respectively presented in Figs. 11 and 12. The results show that low-frequency oscillation damping in PSOPSS has increased more, compared with LOCPSS in [33] and the system stability has considerably improved. Finally, in PSOFLC state, the dynamic stability of the system improves with oscillations and overshoot reduction compared to the previous two states; furthermore, the voltage of the generator's terminal will better set on the reference value.

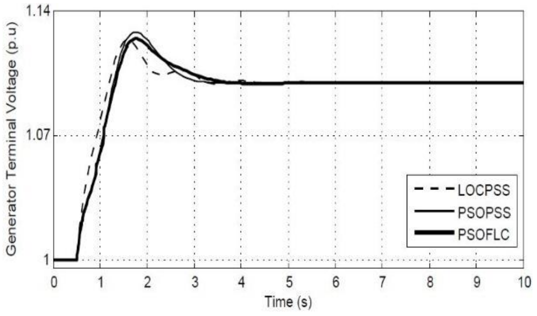

Figure 11: Generator's terminal response to disturbance

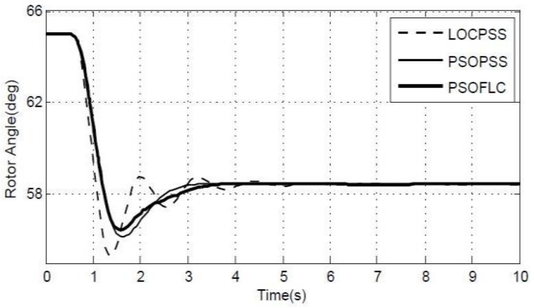

Figure 12: Generator's rotor angle response to disturbance

Multi-machine power system

For multi-machine system simulation, a four-machine two-area test system is used. For optimal location of FLPSS, according to the results obtained from reference [40] presented in Table III, machine four is selected. The guideline to this placement is obtained by computing residues (associated with swing mode) between measured values and control signals of $\Delta\omega$ and PSS output for each generator since the greatest difference in the measured values is in the fourth generator; therefore, machine four is selected for optimal placement of FLPSS. Simulations were carried out on a multi-machine power system in MATLAB Simulink software environment and in two different states of disturbance.

Table 3: Residue associated with swing mode#2

Generator No.	Residue magnitudes
Gen#1	0.016682
Gen#2	0.016877
Gen#3	0.014092
Gen#4	0.018701

Disturbance one: short circuit at bus number nine

Disturbance one: System experiences an instantaneous short circuit with bus number nine. This fault goes up to 200 milliseconds and is then removed. Simulation process is such that initially, the system will be exposed to fault only with AVR and without PSS. If it were the case, the system would lose its stability and is unable to restore its equilibrium.

Then, the simulation is performed with the conventional PSS (CPSS). In this case, the system maintains its stability in the face of fault. In the third case, the results show that the system stability and volatility is improved, compared with the two previous cases, due to the effective placement of FLPSS in the fourth machine. Finally, in the fourth case, with FL-FLC and appropriate weighting of the AVR and FLPSS outputs by FLC, system performance improves and is compared with the three previous states, that is without PSS and CPSS in [38] and FLPSS in [40].

In this case, by combining FLPSS and FLC and using FL-FLC controller, system shows a better performance than in the previous three cases with regard to damping increase and oscillations reduction and in general, the stability of the power system increases as a result. The fourth generator is considered as the reference.

Responses of rotor's angle differences with the rotor's angle of the reference machine, the speed deviation of the generator's shaft, the deviation of the generator's terminal voltage and active power deviation from the disturbance for generators one and two are presented in Figs. 13-20.

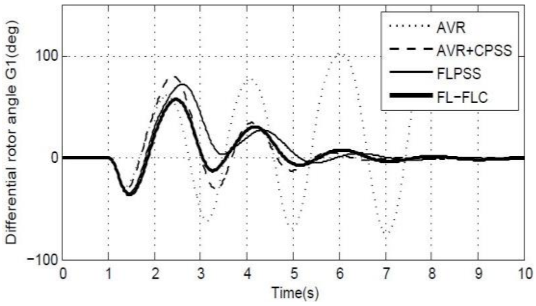

Figure 13: Rotor angle difference response of the generator 1 to disturbance 1

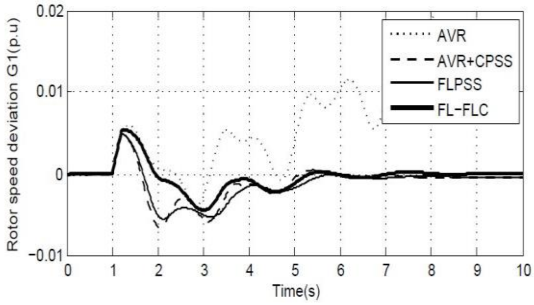

Figure 14: Rotor speed deviation response of the generator 1 to disturbance 1

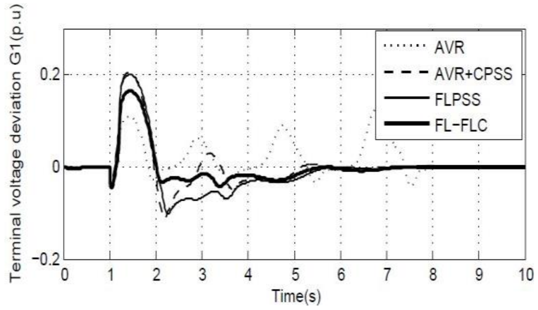

Figure 15: Terminal voltage deviation response of generator 1 to disturbance 1

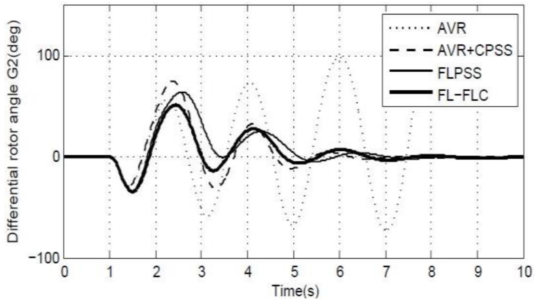

Figure 16: Rotor angle difference response of the generator 2 to disturbance 1

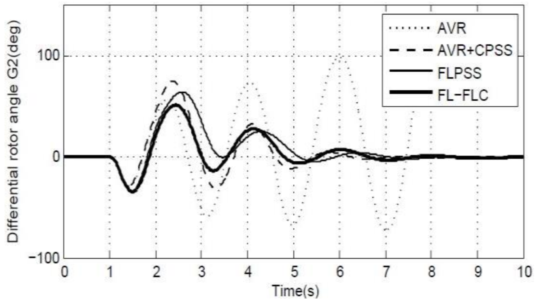

Figure 17: Rotor speed deviation response of generator 2 to disturbance 1

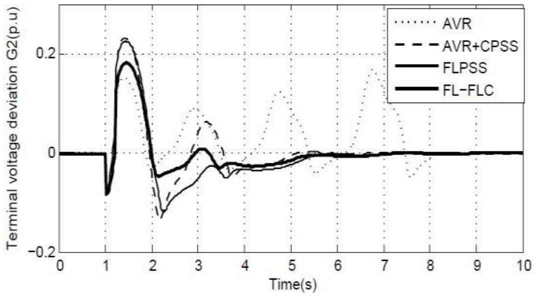

Figure 18: Terminal voltage deviation response of generator 2 to disturbance 1

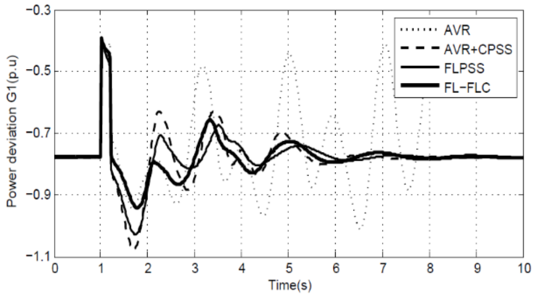

Figure 19: Power deviation response of generator 1 to disturbance 1

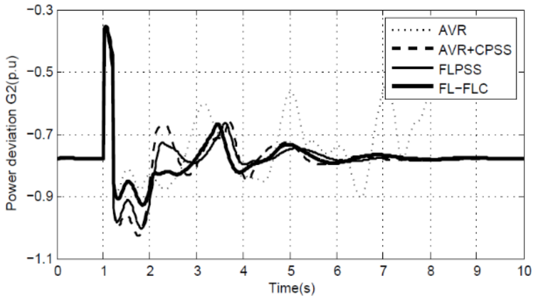

Figure 20: Power deviation response of generator 2 to disturbance 1

Disturbance two: a three-phase short-circuit in bus number eight

Disturbance two: the system experiences a three-phase short-circuit on bus number eight. This fault is resolved by separating the connecting line between buses seven and nine. The simulation process is similar to disturbance number one. The system performance, with an individual FLPSS, has been improved in terms of reducing oscillations, compared with the CPSS. However, in this type of disturbance it can be observed that the FL-FLC controller, compared with its previous cases, that is CPSS and individual FLPSS, works better in reducing oscillations, increasing damping and maintain the stability of the power system. The efficacy of the proposed approach is presented in Figs. 21 to 26. The figures are related to the responses of machine rotor angle difference from rotor angle of the reference machine, speed deviation of the generator shaft and active power deviation in machines one and two.

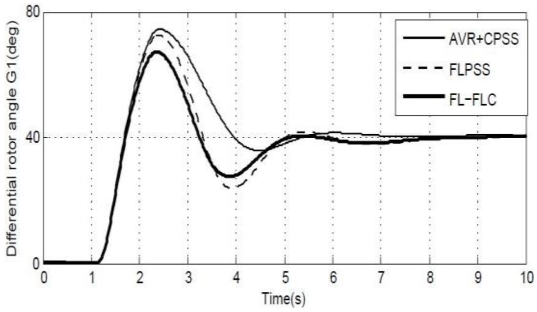

Figure 21: Rotor angle difference response of the generator 1 to disturbance 2

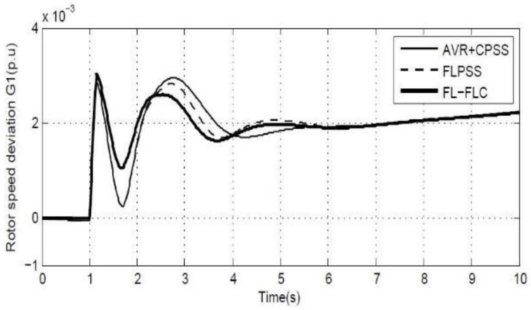

Figure 22: Rotor speed deviation response of generator 1 to disturbance 2

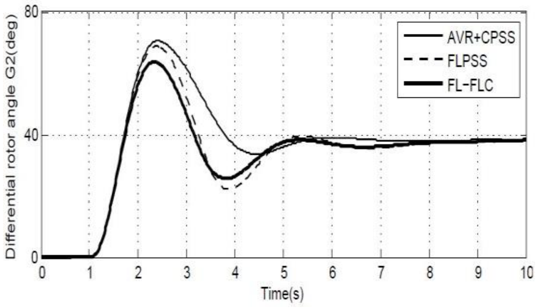

Figure 23: Rotor angle difference response of the generator 2 to disturbance 2

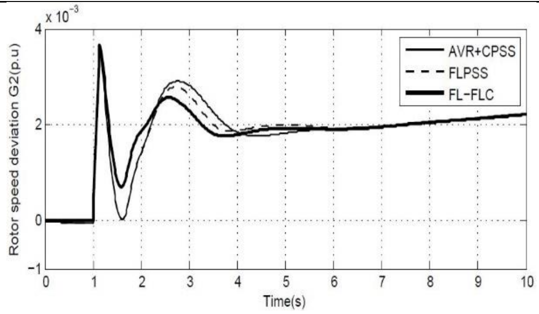

Figure 24: Rotor speed deviation response of generator 2 to disturbance 2

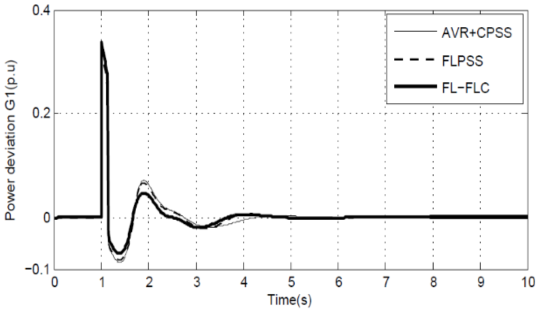

Figure 25: Power deviation response of generator 1 to disturbance 2

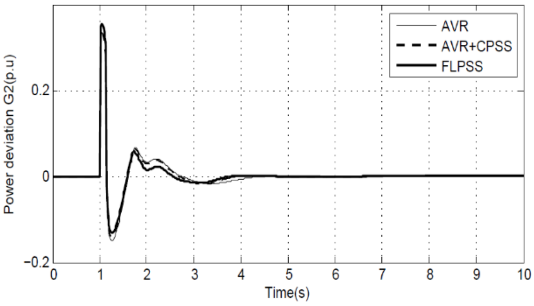

Figure 26: Power deviation response of generator 2 to disturbance 2

Conclusion

This paper presents advantages of PSOFLC excitation controller for the power system achieved by combining PSOPSS, based on the PSO algorithm, with FLC fuzzy logic controller. This excitation controller is designed with the optimized stabilizer, and the simultaneous adjustment of the AVR's and stabilizer's outputs. This design fits the disturbance state, performs well in improving the power system stability and increasing its damping along with achieving optimal voltage stability. The simulation results clearly confirm the impact of the proposed method, compared with the conventional methods and linear optimal control in a single-machine system. Moreover, the proposed method performs well with the power system stabilizer based on fuzzy logic (FLPSS). With its optimal placement on a multi-machine system and simultaneous adjustment of the voltage controllers and damping, the efficiency of this method in facing the disturbance is presented. The simulation results on a multi-machine system indicate the optimal performance in reducing volatility and increasing damping. Moreover, the results show the efficiency of the proposed FL-FLC method in increasing the stability of the power system, reducing LFOs and as a result, system damping increases, compared with the conventional method.

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