Signal Processing and Renewable Energy
September 2023, (pp. 31-51)
ISSN: 2588-7327
eISSN: 2588-7335

Coordination Between the Automatic Voltage Regulator and Output of the Power System Stabilizer to Increase the Stability Improvement

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Received: 12-Mar-2023, Revised: 20-May-2023, Accepted: 27-May-2023.

Abstract

By combining particle swarm optimization (PSO) and fuzzy logic controller (FLC), the ability of these methods to solve complex and nonlinear problems effectively improves power system stability. Setting the power system stabilizer parameters using the PSO method is presented in this paper. Fuzzy logic controller has been used for simultaneous weighting of the automatic voltage regulator and power system stabilizer output. First, the simulation has been carried out in a single-machine power system, where the optimal PSS parameters have been obtained using the PSO algorithm. Then, by simultaneously adjusting the voltage and damping by the fuzzy logic controller, the effectiveness of the proposed method is verified compared to the PSS based on the linear optimization controller. In the following, the simulation results of a multi-machine system are shown. The efficiency of the method has been shown in response to a variety of disorders.

Keywords: Automatic voltage regulator, Fuzzy logic controller, Power system stabilizer.

1. INTRODUCTION

Automatic voltage regulators affect the damping of low-frequency fluctuations and the stability of power systems [1,2]. The above oscillations with low amplitude and low frequency remain in the system without proper control and are increasing [3,4]. To damp the low-frequency oscillations, the complementary control signal is used in the excitation system by means of the PSS [5,6].

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In general, the stabilizer of the power system should provide the appropriate electric torque component with the phase of the rotor speed deviations [7,8]. Conventional PSS includes phase compensation block, steady state signal effect removal block, and gain block [9,10]. Therefore, the required damping occurs, and the delay between the excitation input and the torque of the electric generator is compensated, and the signal of speed deviations is allowed to pass only with the help of a wash filter [11,12]. The effective response of the time-disturbance power system depends on the appropriate parameters selection for PSS [13,14].

A combination of proportional, integral, and derivative controllers are among the most widely used controllers, which can be used as power system stabilizers, and each of them helps to increase power system stability by reducing steady-state error, increasing damping, and reducing oscillations [15,16].

Nowadays, intelligent optimization techniques to obtain and choose the optimum PSS parameters, under different operating points, are most welcomed by scholars. Intelligent simulation methods for simulated annealing [17], ant colony optimization [18,19], harmony search [20,21], Tabu search [22], bacterial foraging optimization [23], genetic algorithm [24], and artificial neural networks [25] 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.

To solve the optimization problems, PSO is a widely used iteration-based method. In this algorithm, each parameter can be considered as a particle which is optimized as a candidate solution [26,27]. 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. PSO is utilized in the design of PSS, due to simple mathematical calculations and its high effectiveness in optimizing the PSS parameters [28]. A multi-objective design of the multi-machine PSS using ant colony optimization is proposed in [29], which the fine-tuning of the parameters problem is converted to an optimization problem.

Fuzzy logic controllers, without the need for an accurate mathematical model of the system, convert the control inputs into fuzzy input values [30,31]. Then, they make fuzzy controlling outputs by the fuzzy inference and based on a set of fuzzy rules [32]. Finally, in the de-fuzzification unit, fuzzy controlling outputs are converted into the applicable controlling outputs [33,34].

The works done on fuzzy logic control reveals its effectiveness, simplicity, and its ability to solve complex and nonlinear problems [35,36]. In [37] and [38], the type-2 fuzzy methods have been used to design PSS. Fuzzy logic can be utilized in combination with other methods. In some papers, a combination of fuzzy logic with neural networks and genetic algorithm is used to improve the results obtained from the PSS in increasing the stability and reducing oscillations [39]. In [40], a fuzzy power system stabilizer (FPSS) is designed and is effectively located in a multi-machine power system.

FPSS design using an adaptive evolutionary algorithm consisting of genetic algorithm for global search capability and evolution strategy for local search is proposed in [41], which is used to optimize membership functions and scaling factors of FPSS. The simulation results show the superiority of FPSS control performance over conventional power system stabilizers (CPSS) for three-phase fault in heavy loads.

In [42] fuzzy logic-based adaptive PSS, parameters are adjusted online by neural networks, where the system is divided into two subsystems, (a) a recursive least-squares identifier with a variable forgetting factor for the generator and (b) an adaptive controller based on fuzzy logic for damped oscillations.

Particle swarm optimization is a global optimization method. PSO is a collective search algorithm modeled on the social behavior of flocks of birds [43,44]. In PSO, particles flow through the search space, and at each instant, each particle adjusts its location in the search space according to the best location it has been in so far, and the best location in its entire neighborhood [45,46]. The general steps of the method are shown in Fig. 1 [47,48].

PSO algorithm has been used in solving various engineering problems [49,50]. The PSO method for the design of PSS parameters has been proposed in various studies and each of them tries to improve the design parameters [51]. The flexibility to achieve a compromise between conflicting design objectives, overshoot, and control limitation is one of the advantages of using this algorithm in PSS design [52,53].

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 [54] is clearly visible at the disturbance time. Then, a stabilizer, based on fuzzy logic (FLPSS) and the effective placement in a multi-machine system will be designed. Afterwards, with proper weighting of PSS and AVR outputs with FLC, a FL-FLC excitation controller will be made. In FL-FLC, the effectively 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 [55] in reducing the oscillations and increasing damping will be presented.

In this paper, the PD controller is used as a stabilizer of the power system, and the optimal design of its parameters is done using the PSO algorithm.

Then the output of the PSOPSS controller along with the AVR output is weighted by a fuzzy controller, according to the working conditions of the system. Finally, the PSOFLC controller is designed by combining PSOPSS and FLC, and its output is applied to the excitation system.

The highlights of this paper are:

1. PSO algorithm to optimize the parameters of PSOPSS.
2. Increasing the stability and oscillations damping of the power system.
3. The effect of this method is compared with a linear optimization controller.

This paper is organized as follows. After the introduction presented in the first section, in section 2, 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 section 3, the structure of the proposed excitation controller is presented. In section 4, 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 section 5.

2. AVR AND PSOPSS STRUCTURE

2.1. AVR Structure

In this paper, the conventional PID controller structure, according to [56], 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.

2.2. 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

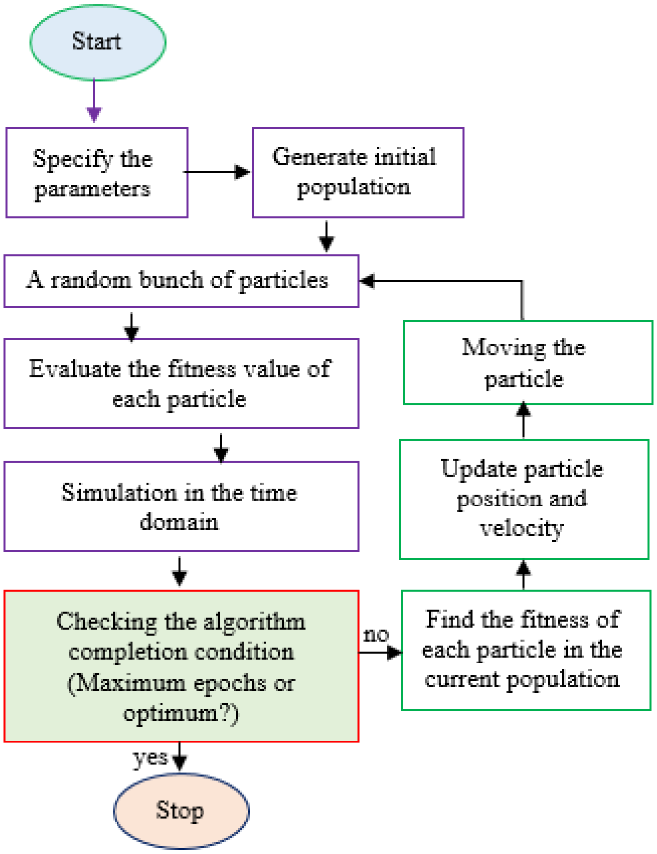


Fig. 1. Flowchart of the PSO algorithm.

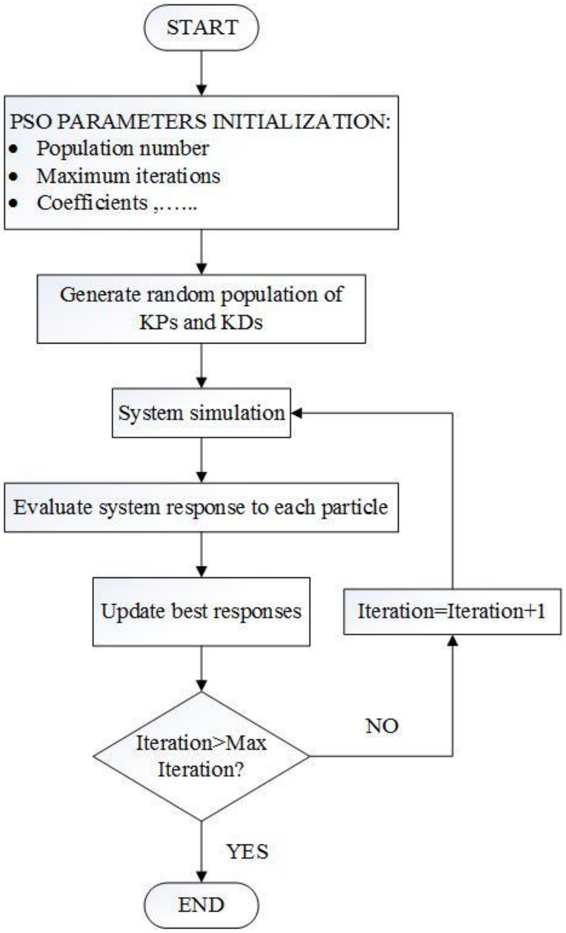


Fig. 2. Flowchart of PSO algorithm to determine the PSOPSS optimal parameters.

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 [57,58]. Maximization of the damping ratio has been considered as an objective function regarding to improvement of oscillations damping. In this algorithm, the optimal solution is determined by the following equations [59]:

$$\begin{aligned} V_i^{t+1} &= \omega v_i^t + c_1 \times \mathrm{rand}_1 \times (p_i^{BEST} - X_i^t) \\ &\quad + c_2 \times \mathrm{rand}_2 \times (g^{BEST} - X_i^t) \end{aligned} \tag{1}$$

$$X_i^{t+1} = X_i^t + v_i^{t+1} \tag{2}$$

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 particle i, and g^{BEST} is the best global position of the particles. In Fig. 2, the flowchart of PSO algorithm steps to find the optimal particles is shown. In this paper, according to Fig. 3, 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.

3. PROPOSED EXCİTATİON CONTROLLER STRUCTURE

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. 4, a block diagram of this controller is displayed. In the steady state of the power system, the excitation control adjusts and regulates 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.

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 that oscillations in the rotor angle of the system happen due to a minor disturbance. Or there are moments after a larger disturbance 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.

4. SIMULATION RESULTS AND DISCUSSION

The simulation was carried out in two parts. In the first part, the simulations were done on a single machine connected to an infinite bus system (SMIB). The schematic presentation of this system is depicted in Fig. 5. In the second part, simulations were carried out on

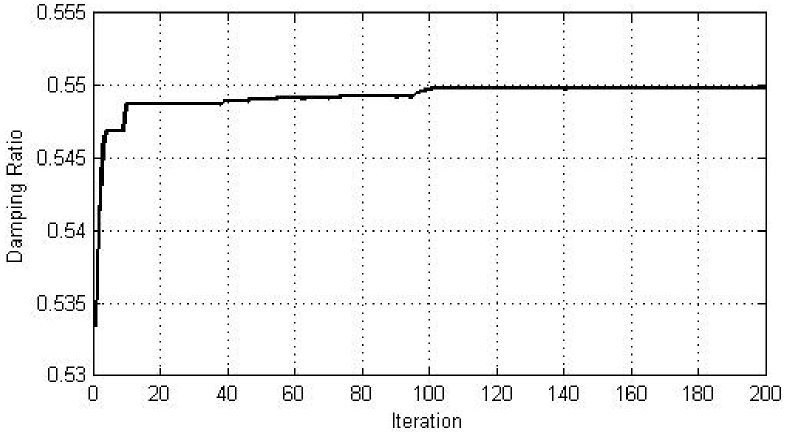


Fig. 3. Damping ratio and the number of iterations in PSO algorithm.

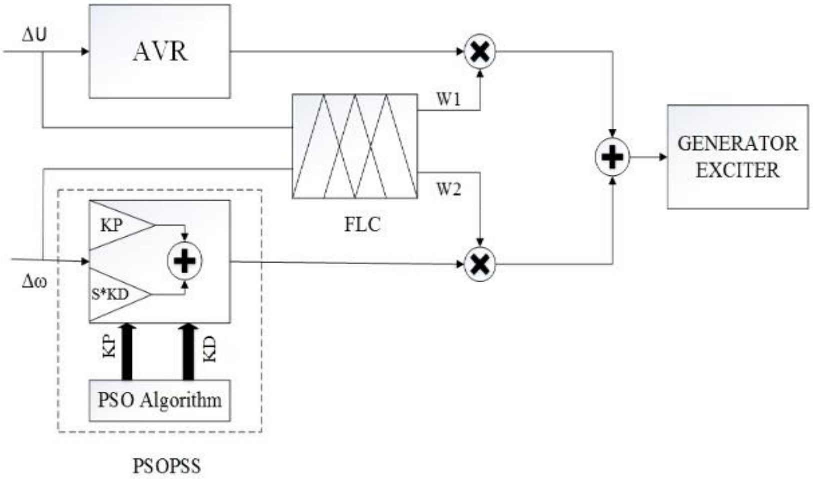


Fig. 4. Block diagram of the proposed excitation controller.

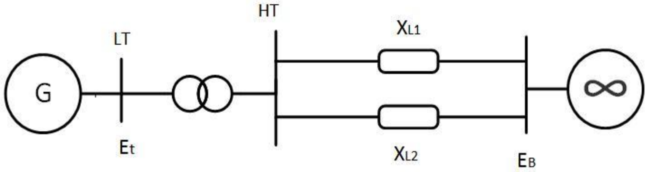


Fig. 5. A schematic design of a single machine system connected to an infinite bus (System 1).

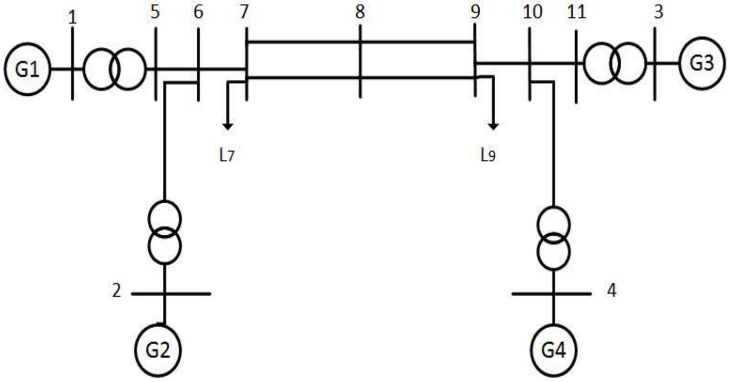


Fig. 6. A schematic design of a four-machine power system (System 2).

a four-machine two-area system. The schematic representation of this multi-machine system is shown in Fig. 6. The data and parameters of both above-mentioned systems are available in [60].

4.1. Single-Machine Power System

Simulation on a SMIB system is carried out under the operating point (U_t=1p.u, $\delta_\circ$=65°) when the system has 10% over-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 be damped and balanced with the help of PSS. The simulation is carried out and compared in three states, namely LOCPSS, PSOPSS, and PSOFLC. The implemented model of the power system along with PDPSO stabilizer and FLC fuzzy controller is given in Fig 7. Responses of rotor speed deviations and rotor angle deviations to above mentioned disturbance are respectively presented in Figs. 8 and 9. The results show that low-frequency oscillation damping in PSOPSS has increased more, compared with LOCPSS in [40] and the system stability has considerably improved

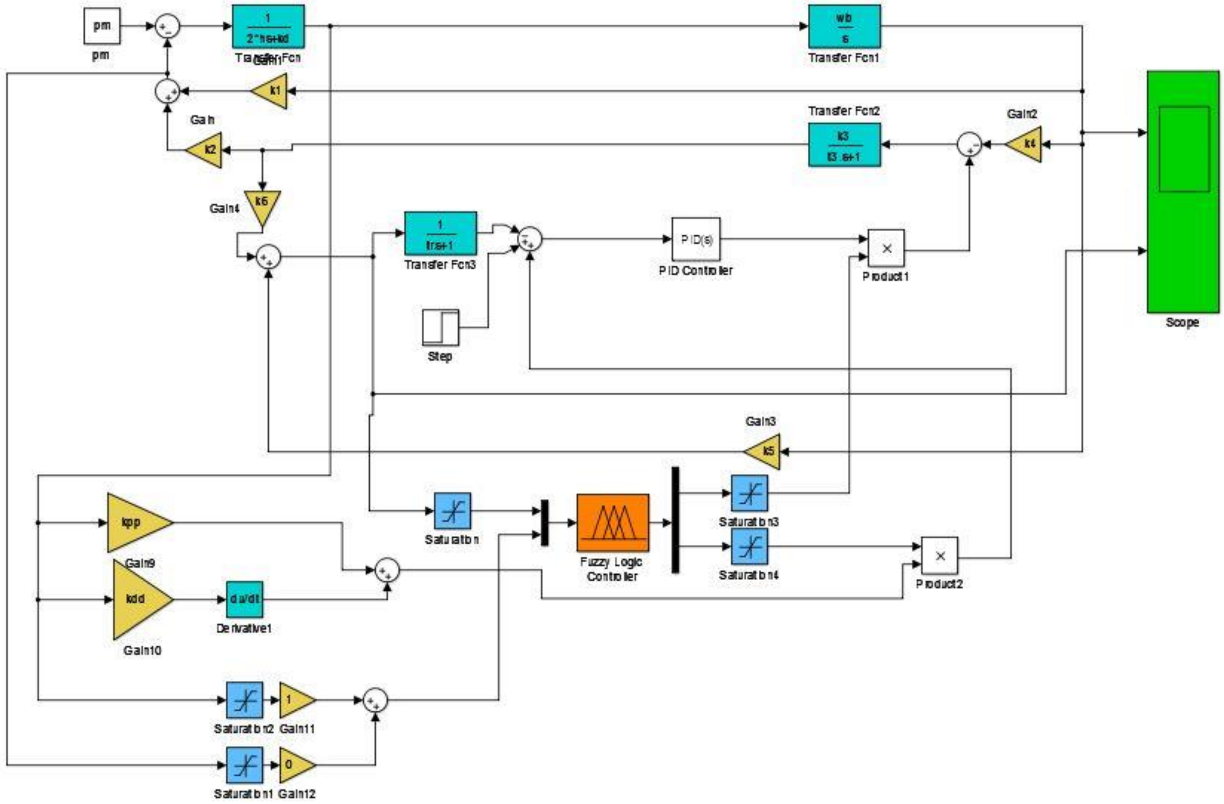


Fig. 7. The implemented model of the power system in Simulink MATLAB.

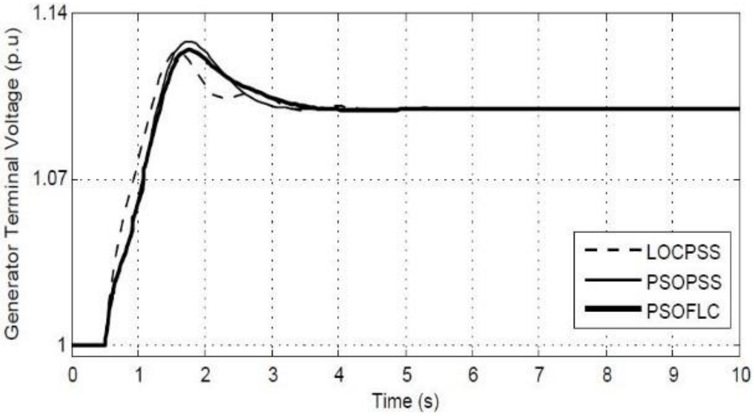


Fig. 8. Generator's terminal response to disturbance.

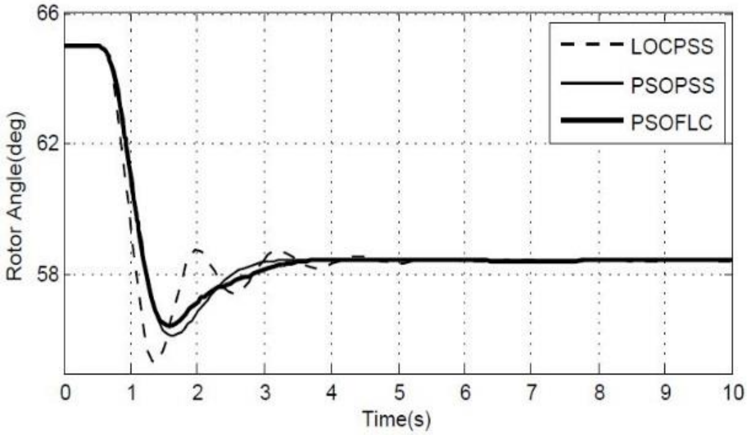
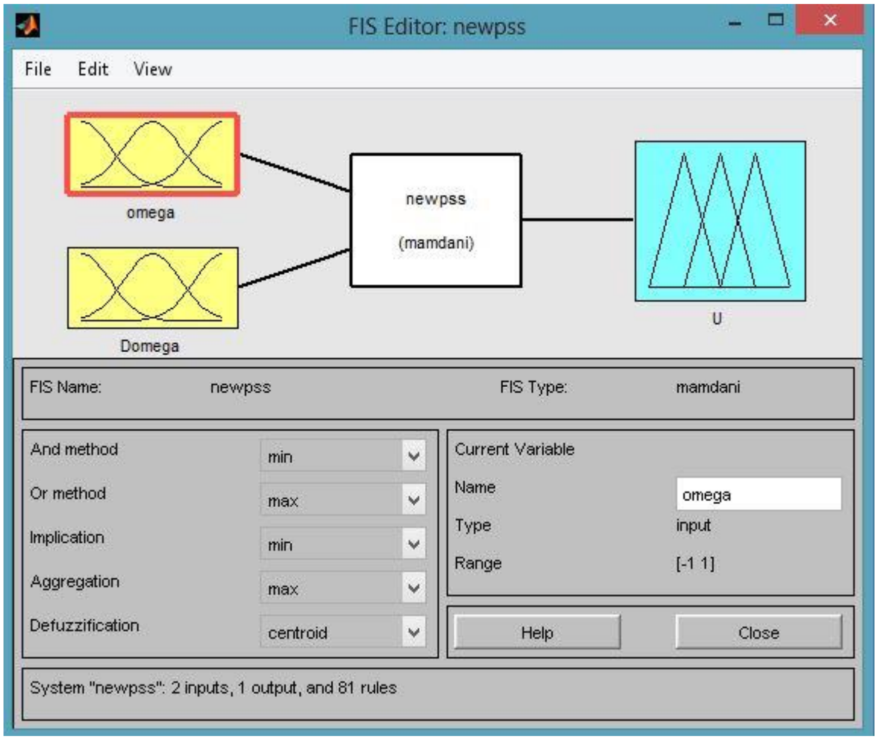


Fig. 9. Generator's rotor angle response to disturbance.



FIS Name: newpss

FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Defuzzification: centroid

Current Variable

Name: omega

Type: input

Range: [-1 1]

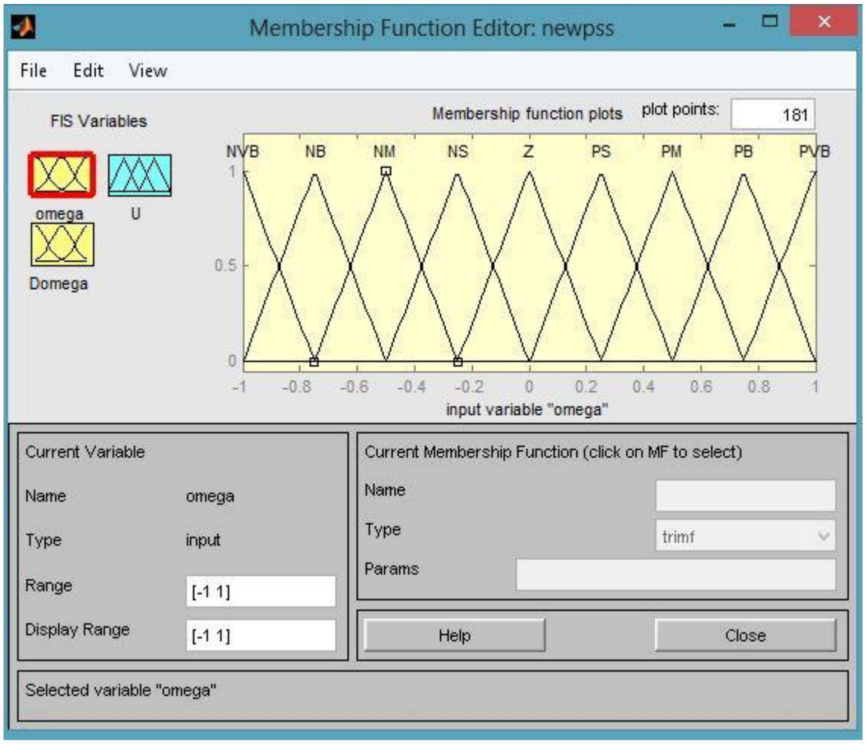
System "newpss": 2 inputs, 1 output, and 81 rules

Fig. 10. Implemented fuzzy stabilizer structure.

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 be better set on the reference value.

4.2. Multi-Machine Power System

Fuzzy FLPSS controller as a power system stabilizer is implemented in a two-zone four-machine power system using the MATLAB fuzzy toolbox. Figs. 10, 11, and 12 show the implemented controller structure, fuzzy membership functions of input and output variables, and distribution levels of fuzzy variables, respectively. For multi-machine system simulation, a four-machine two-area test system is used. For the optimal location of FLPSS, according to the results obtained from [40] presented in Table 1, 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 Δω 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.


Membership Function Editor: newpss

plot points: 181

Current Variable
Name omega
Type input
Range [-1 1]
Display Range [-1 1]

Current Membership Function (click on MF to select)
Type trimf

Selected variable "omega"

Fig. 11. Fuzzy membership functions of input and output variables.

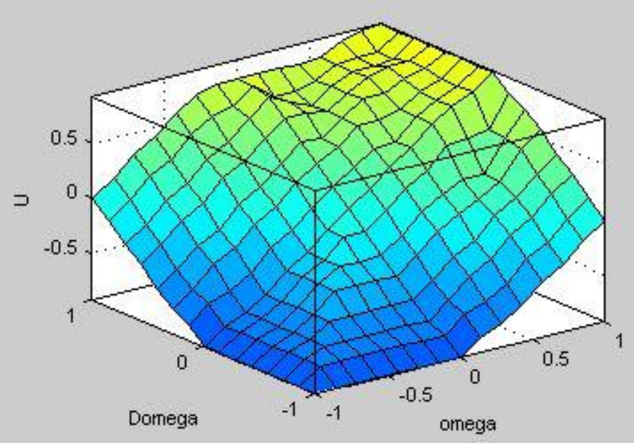


Fig. 12. Levels of distribution of fuzzy variables.

Table 1. ***Residue associated with swing mode 2 [40].***

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

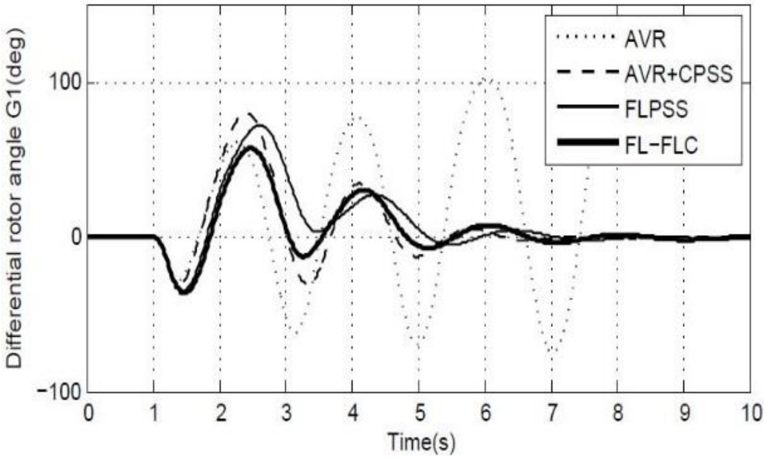


Fig. 13. Rotor angle difference response of the generator 1 to disturbance 1.

4.2.1. Disturbance one: short circuit on bus number nine

Disturbance one: The system experiences an instantaneous short circuit on bus number nine. This fault goes up to 200 milliseconds and is then removed. The simulation process is such that initially, the system will be exposed to fault only with AVR and without PSS. If it was the case, the system would lose its stability and be unable to restore its equilibrium. Then, the simulation is performed with the conventional PSS (CPSS). In this case, the system maintains stable facing the fault. In the third case, the results show that the system stability and volatility are 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, i.e. without PSS and CPSS in [39] and FLPSS in [40]. In this case, by combining FLPSS and FLC and using FL-FLC controller, the system shows a better performance than 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 from 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. 12 to 19.

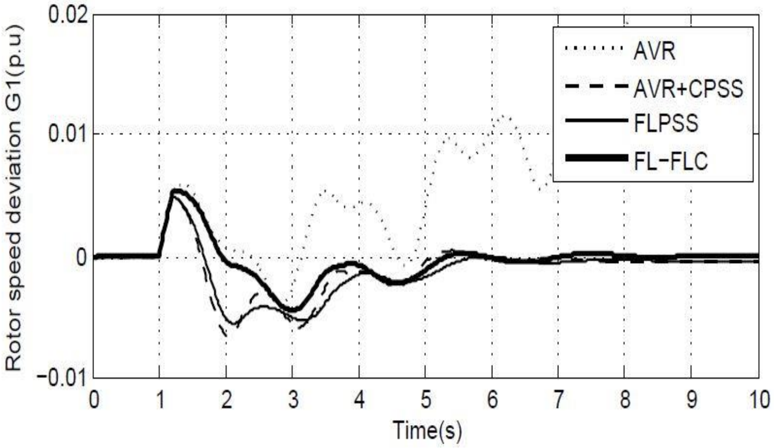


Fig. 14. Rotor speed deviation response of the generator 1 to disturbance 1.

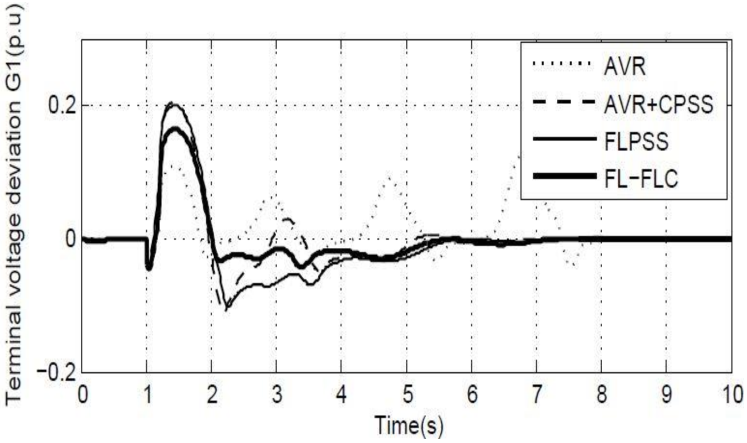


Fig. 15. Terminal voltage deviation response of generator 1 to disturbance 1.

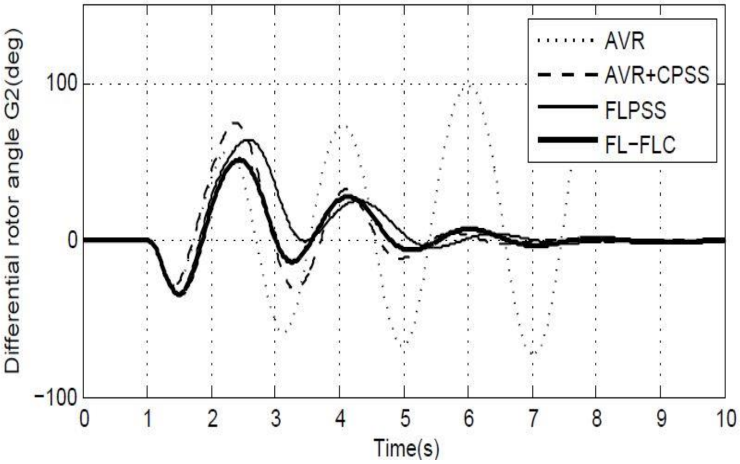


Fig. 16. Rotor angle difference response of the generator 2 to disturbance 1.

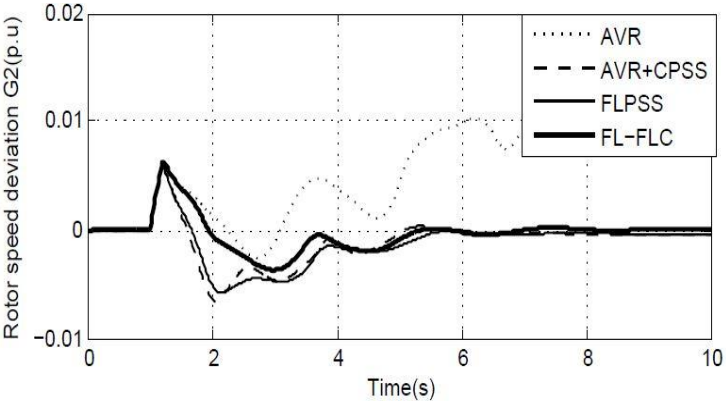


Fig. 17. Rotor speed deviation response of generator 2 to disturbance 1.

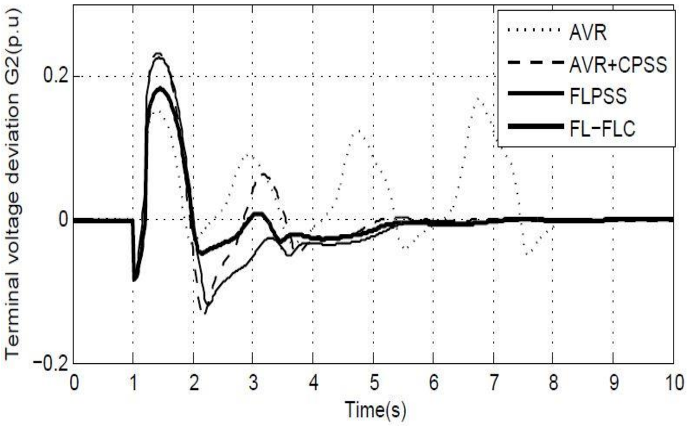


Fig. 18. Terminal voltage deviation response of generator 2 to disturbance 1.

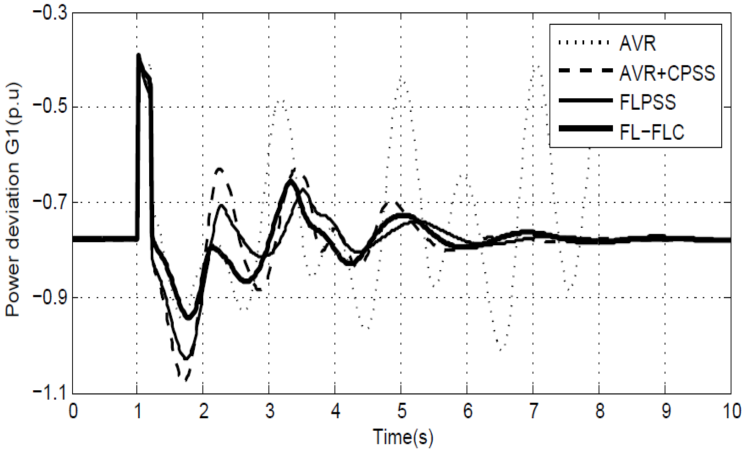


Fig. 19. Power deviation response of generator 1 to disturbance 1.

4.2.2. Disturbance two: A three-phase short-circuit on bus number eight

The system has experienced a three-phase short-circuit on bus number eight. This fault is cleared by disconnecting the line between buses seven and nine. The simulation process is similar to the 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, i.e. CPSS and individual FLPSS, works better in reducing oscillations, increasing damping, and maintaining the stability of the power system. The efficacy of the proposed approach is presented in Figs. 20 to 25. The figures are related to the responses of the machine rotor angle deviation from rotor angel of the reference machine, speed deviation of the generator shaft, and active power deviation in machines one and two.

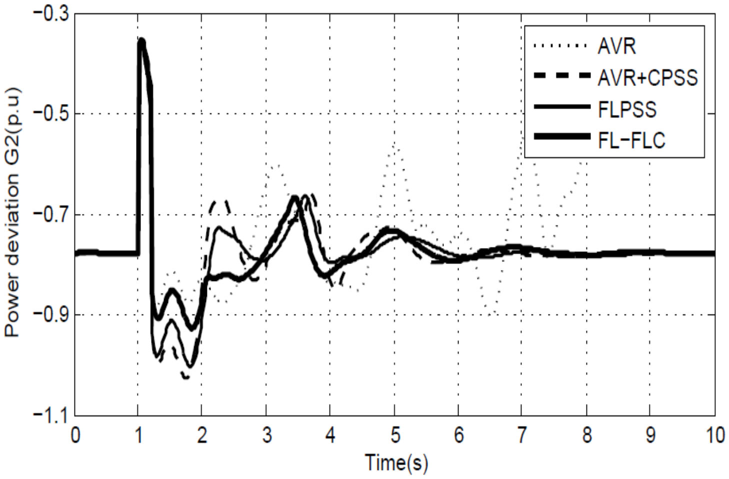


Fig. 20. Power deviation response of generator 2 to disturbance 1.

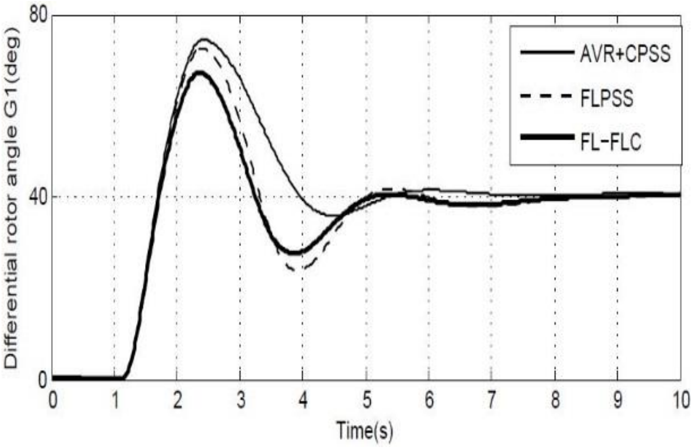


Fig. 21. Rotor angle difference response of the generator 1 to disturbance 2.

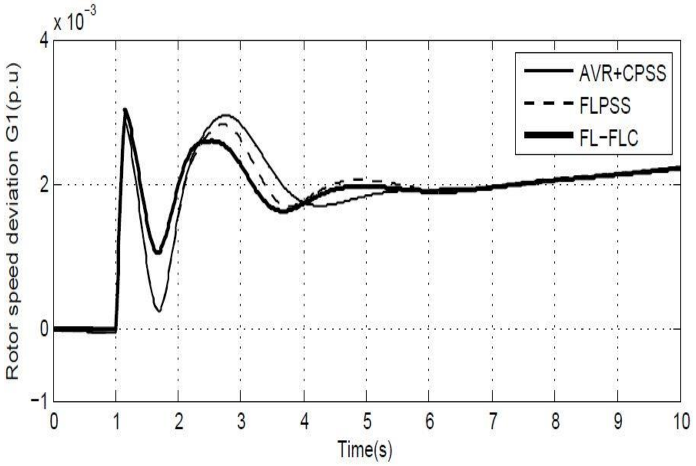


Fig. 22. Rotor speed deviation response of generator 1 to disturbance 2.

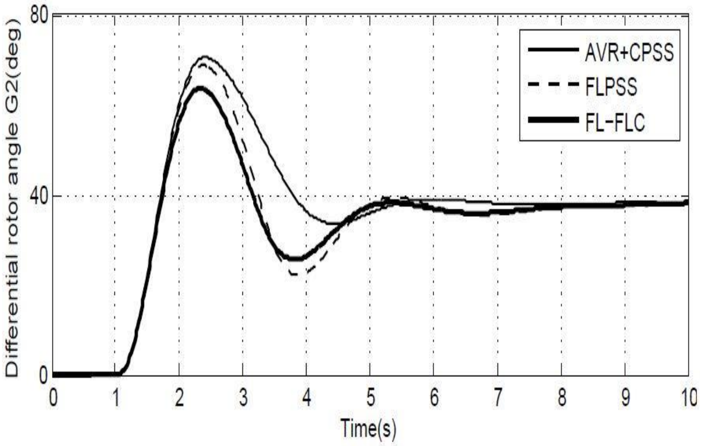


Fig. 23. Rotor angle difference response of the generator 2 to disturbance 2.

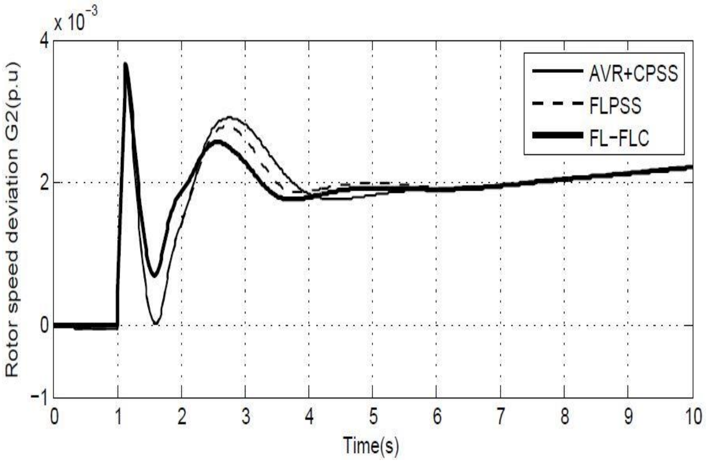


Fig. 24. Rotor speed deviation response of generator 2 to disturbance 2.

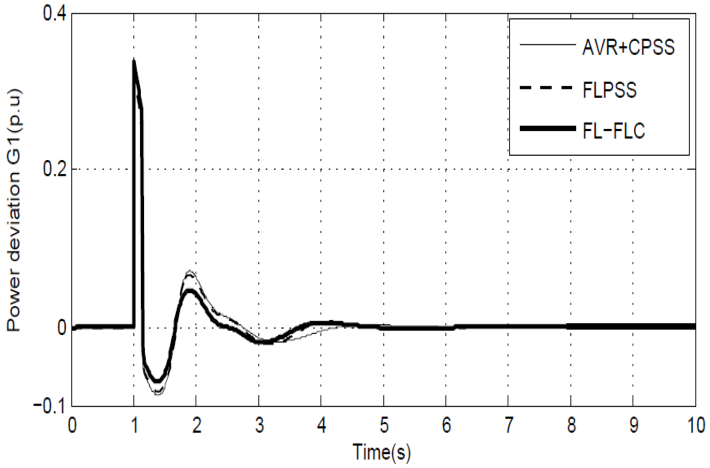


Fig. 25. Power deviation response of generator 1 to disturbance 2.

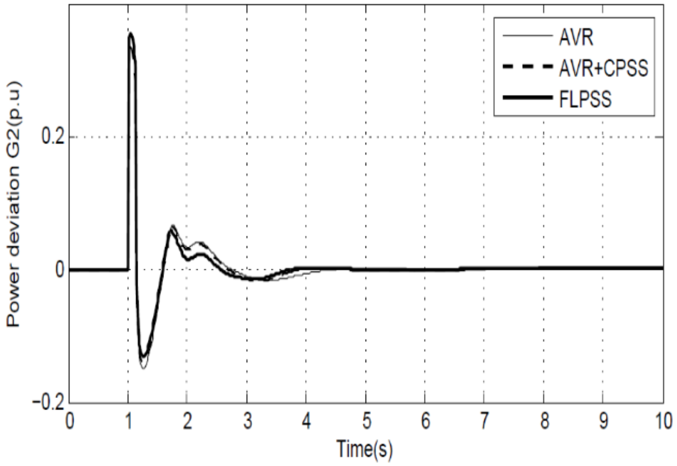


Fig. 26. Power deviation response of generator 2 to disturbance 2.

5. CONCLUTION

By combining PSOPSS, based on the PSO algorithm, with FLC fuzzy logic controller, a PSOFLC excitation controller for the power system is presented in this paper. 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, and performs well in improving the power system stability and increasing its damping along with 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 facing disturbances is presented. The simulation results on a multi-machine system indicate the optimal performance in reducing volatility and increasing damping.

Moreover, the efficiency of the proposed FL-FLC method in increasing the stability of the power system, reducing low-frequency oscillations increases system damping, compared with the conventional method.

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