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Multi-stage Fuzzy Power System Stabilizer based on Modified Shuffled Frog Leaping Algorithm

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Abstract

This paper presents a new strategy based on Multi-stage Fuzzy (MSF) PID controller for damping Power System Stabilizer (PSS) in multi-machine environment using Modified Shuffled Frog Leaping (MSFL) algorithm. The proposed technique is a new meta-heuristic algorithm which is inspired by mating procedure of the honey bee. Actually, the mentioned algorithm is used recently in power systems which demonstrate the good reflex of this algorithm. Also, finding the parameters of PID controller in power system has direct effect for damping oscillation. Hence, to reduce the design effort and find a better fuzzy system control, the parameters of proposed controller is obtained by MSFL that leads to design controller with simple structure that is easy to implement. The effectiveness of the proposed technique is applied to Single machine connected to Infinite Bus (SMIB) and IEEE 3-9 bus power system. The proposed technique is compared with other techniques through ITAE and FD.

Keywords*: MSFL, Multi-stage PID, Power System Stabilizer*

1. Introduction

In the last few decades, considerable attention has been given to the excitation system and its role in improving power system stability. Because of the small effective time constants in the excitation control loop, it was assumed that a large control effort could be expanded through excitation control with a relatively small input of control energy. By the use of a voltage regulator in the excitation control system, the output of the exciter can be adjusted so that the generated voltage and reactive power change in a desired way [1]. In early systems, the voltage regulator was entirely manual. In modern control systems the voltage regulator is an automatic controller that senses the generator output voltage as a feedback signal then adjusts the generator excitation level in the desired direction. This kind of voltage regulator has been known as an Automatic Voltage Regulator (AVR) [2].

In the recent years, a large number of research papers have been appeared in the area of Power System Stabilizer (PSS). Also they directed towards obtaining such a PSS that can provide an optimal performance for a wide range of machine and system parameters [4]. Currently, many literatures used Conventional PSS (CPSS) to damped low frequency oscillations [2]. However, these controllers don’t have appropriate revenue in different load conditions. Consequently, a lot of intelligent methods have been introduced to optimal tuning of the PSSs parameters [5].

For this purpose the intelligent techniques has been proposed to solve the mentioned problem. Accordingly, in industry, Proportional Integral (PI) controllers have been broadly used for decades as the load frequency controllers. Actually, several techniques have been proposed to design PI controller [5], where the controller parameters of the PI controller are tuned using trial-and-error approach. However, it gives poor performance in the system transient response. Moreover, a Proportional Integral Derivative (PID) method is one of the techniques that used to improve the performance of the fuzzy PI controller [6]. But, it is clear that the mentioned technique needs three dimensional rule base which leads to difficult design process.

To overcome the mentioned backwards the Multi-stage fuzzy PID is proposed in this paper to solve the stability problem in multi machine power system. Actually, the proposed technique has two dimensional rules. And this method needs fewer resources to operate. In fact, best designs of the fuzzy controllers are depended to choosing appropriate membership function, rule bases inference mechanism and the defuzzification [7-8]. In these factors, exact

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tuning of membership function is really important to proposed controller reflex. Maybe, the tuning of the membership function by human experts is appropriate; however experts may not be available. For this purpose the intelligent techniques are proposed to find the mentioned factor.

Accordingly to tackle of the mentioned backwashes the MSFL technique is proposed in this paper to solve the oscillation problem in multi-machine power system. SFLA is a decrease based stochastic search method that begins with an initial population of frogs whose characteristics, known such as memes, represent the decision variables. For this algorithm, the individual frogs are not the important parts; rather they are seen as hosts for memes and described as a memetic vector. The algorithm uses memetic evolution in the form of influencing of ideas from one individual to another in a local search. In SFL, the population consists of a set of frogs (solutions) partitioned into subsets, referred to as memeplexes. Actually the different memeplexes are considered as different cultures of frogs, each performing a local search. The effectiveness of the proposed technique is applied on Single-machine Infinite Bus System (SMIB) and 3 machine 9 bus IEEE standard power system in comparison of GA-PSS and CPSS [9] in first case study and PSOPSS and CPSS [9] in 3-9 bus test system through Integral of the Time multiplied Absolute value of the Error (ITAE) and the Figure of Demerit (FD) performance indices [10].

2. Power System Model

For stability assessment of power system adequate mathematical models describing the system are needed. The system behaviour following such a disturbance is critically dependent upon the magnitude, nature and the location of fault and to a certain extent on the system operating conditions. The stability analysis of the system under such conditions, normally termed as 'Transient-stability analysis' is generally attempted using mathematical models involving a set of non-linear differential equations. Figure 1 shows the main model of power system with location of controller [10].

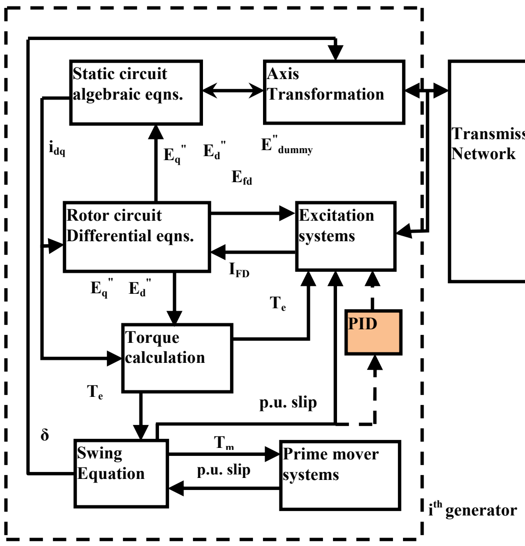


Figure 1. Structure of PSS in power systems

A. Single-machine Infinite Bus System

The Single-machine Infinite Bus system considered for small-signal performance study which is shown in Figure 2.

The generator is represented by the third-order model comprising of the electromechanical swing equation and the generator internal voltage equation [11-12]. The swing equations of this system are:

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

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

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

$$\dot{E}_{fdi} = \frac{1}{T_{Ai}}(K_{Ai}(v_{refi} - v_i + u_i) - E_{fdi}) \quad (4)$$

$$T_{ei} = E'_{qi} i_{qi} - (x_{qi} - x'_{di}) i_{di} i_{qi} \quad (5)$$

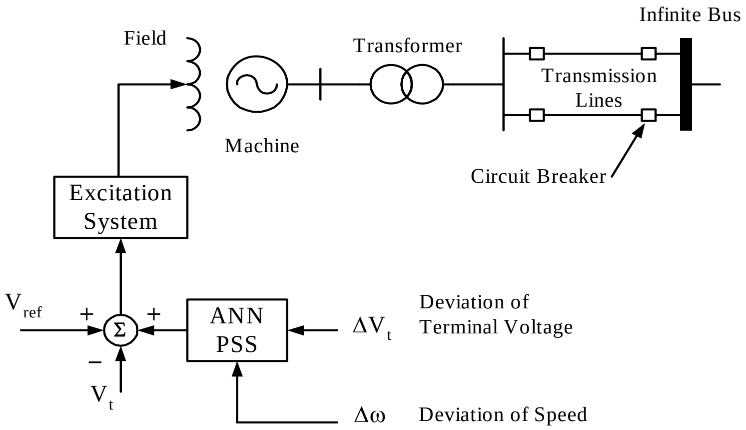


Figure 2. Schematic diagram of single machine infinite bus system

B. 3-9 bus IEEE Power System

The proposed approach is extended to a multi-machine power system as a second case study. The widely used Western Systems Coordinating Council (WSCC) 3-machine, 9-bus system shown in Figure 3 is considered. The simplified IEEE type-ST1A static excitation system has been considered for all three generators [13]. Also, the proposed controller is connected to all of the generators. The system data are given in [9].

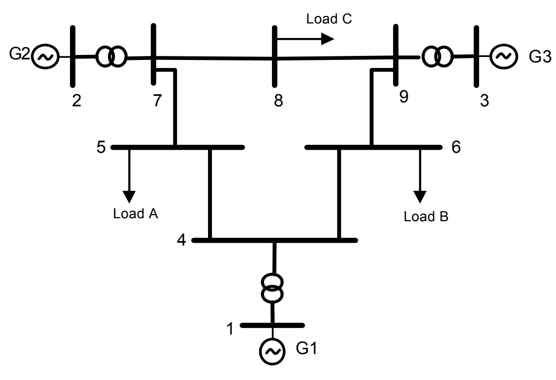


Figure 3. Three-machine nine-bus power system

C. Multi-stage Fuzzy Controller

According to the backwards of the classic PID, this paper proposed the multi-stage fuzzy controller to LFC problem. In this controller, input values are converted to truth value vectors and applied to their respective rule base. It is clear that the output truth value vectors are not defuzzified to crisp values as with a single stage fuzzy logic controller however are passed on to the next stage as a truth value vector input.

In this structure, the membership function is defined as triangular partitions with seven segments from -1 to 1 as shown in Figure 4. Zero (ZO) is the center membership function. For the remaining parts of the partition it can describe as: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Positive Small (PS), Positive Medium (PM) and Positive Big (PB). Also in this controller there are two rule bases. The first one is the PD rule base as it operates on truth vectors from the error (e) and change in error (e) inputs. And the second one is PID switch rule base while, if the PD input is in the zero fuzzy set, the PID switch rule base passes the integral error values (∫e) that are presented in [14]. The truth value vectors are indicated in Figure 5, by darkened lines [14-15].

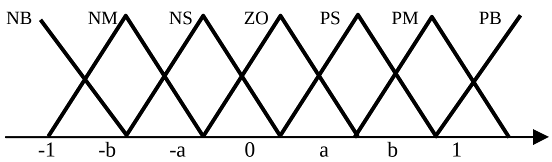


Figure 4. Symmetric fuzzy partition

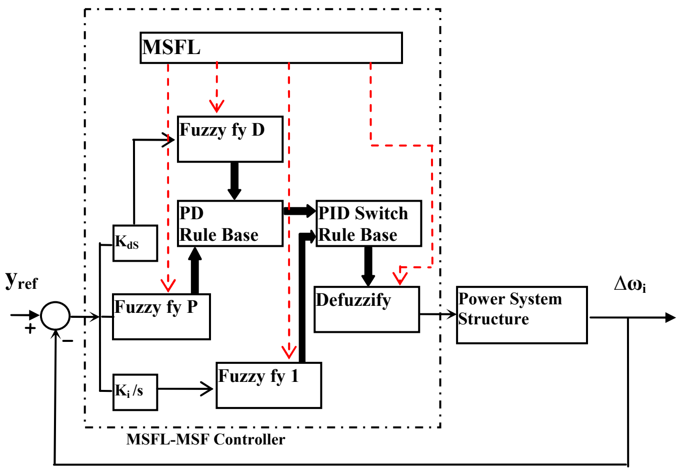


Figure 5. Structure of the proposed controller.

3. Proposed Algorithm

Shuffled Frog Leaping (SFL) algorithm, has been introduced by Eusuff and Lansey for water distribution system optimization, is a meta-heuristic for solving optimization problems [7]. SFLA is a decrease based stochastic search method that begins with an initial population of frogs whose characteristics, known such as memes, represent the decision variables. For this algorithm, the individual frogs are not the important parts; rather they are seen as hosts for memes and described as a memetic vector [8]. The algorithm uses memetic evolution in the form of influencing of ideas from one individual to another in a local search. In SFL, the population consists of a set of frogs (solutions) partitioned into subsets, referred to as memeplexes. Actually the different memeplexes are considered as different cultures of frogs, each performing a local search [14].

Hence, the positions of the frogs are presented as:

$$D_i = rand \times (X_b - X_g) \tag{6}$$

And for new position:

$$X_{i+1} = X_i + D_i, -D_{max} \le D_i \le D_{max} \tag{7}$$

Where,
rand = random number between 0 and 1.
D_{max} = the maximum allowed change in a frog's position.

Modified Shuffled Frog Leaping Algorithm

The original SFLA algorithm has good performance when dealing with some simple problems. However, it is difficult for SFLA algorithm to overcome local minima when handling some complicate functions [18]. MSFLA starts with an initial population of "X" frogs created randomly like other evolutionary algorithms. The whole population of frogs is then partitioned into subsets referred to as memeplexes. The various memeplexes are considered as different cultures of frogs. And they are located at different places in the solution space (i.e., global search). Each culture of frogs performs a deep local search. Within each memeplex, the individual frogs hold information that can be influenced by the information of their frogs within their memeplex, and evolve through a process of change of information among frogs from different memeplexes [18]. After a defined number of evolutionary steps, information is passed among memeplexes in a shuffling process. The local search and the proposed processes continue until a defined convergence criterion is satisfied.

It is necessary to note that the mutation vector dimension is equal to the memeplexes number. Therefore, a position changing formula turns to the following form.

$$D_i = rand \times C \times (f(X_b) - f(X_w)) \times (X_b - X_w) \tag{8}$$

And for new position:

$$X_{i+1} = X_i + D_i \tag{9}$$

Where,
C € [0, C_{max}],
C_{max} = case dependant upper limit
$f(X_b)$= The best fitness functions that are found by the frogs in each memeplexs.
$f(X_w)$= The worst fitness functions that are found by the frogs in each memeplexs.

Similar to the original *SFL*, if the process produces a better solution, the worst frog is replaced by the better one.

4. Simulation Results

In this paper the considered performance indices are; Time multiplied Absolute value of the Error (ITAE) and the Figure of Demerit (FD). Where are described in literature as:

$$FD = (500 \times OS)^2 + (8000 \times US)^2 + 0.01 \times T_s^2 \tag{10}$$

$$ITAE = 100 \times \int_0^{t_{sim}} t(|\Delta\omega|).dt \tag{11}$$

SMIB

For this case study the fitness function trend of proposed technique is presented in Figure 7. This case is compared with GAPSS and Classic PSS (CPSS) [9]. Accordingly, Figure 8, shows the response of system against 6-cycle three-phase fault in different load condition as a first scenario. The results of the second scenario are presented in Figure 9. The numerical results for the scenarios are presented in Table. 3. Also, the optimum parameters for case studies achieved by MSFL are presented in Table. 1-2.

Table 1. Optimum PID controller parameters in Case 1

Membership Function		ω_i	$\Delta\omega_i$	$\int\omega$	**Output**
MSFL	a	0.21	0.0321	0.02	0.12
Results	b	0.18	0.21	0.27	0.043

Table 2. Optimum PID controller parameters in Case 2

Membership Function		ω_i	$\Delta\omega_i$	$\int\omega$	**Output**
MSFL	a	0.32	0.0810	0.04	0.17
Results	b	0.25	0.24	0.37	0.065

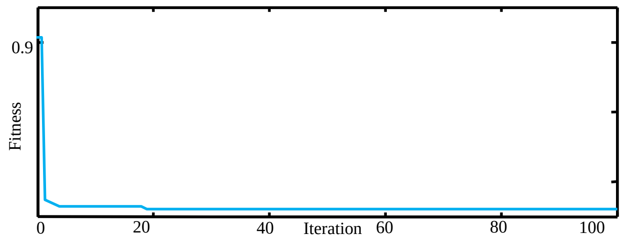


Figure 6. Optimal trend of fitness function evaluation

The convergence of the proposed technique over second case study is shown in Figure 10. Actually, the performance of the proposed controller under transient conditions is verified by applying a 6-cycle three-phase fault at t=1 sec, on bus 7 at the end of the line 5-7. The fault is cleared by permanent tripping the faulted line. The speed deviation of machines under the nominal loading conditions is shown in Figure 11. This case study is compared with PSOPSS and CPSS [9].

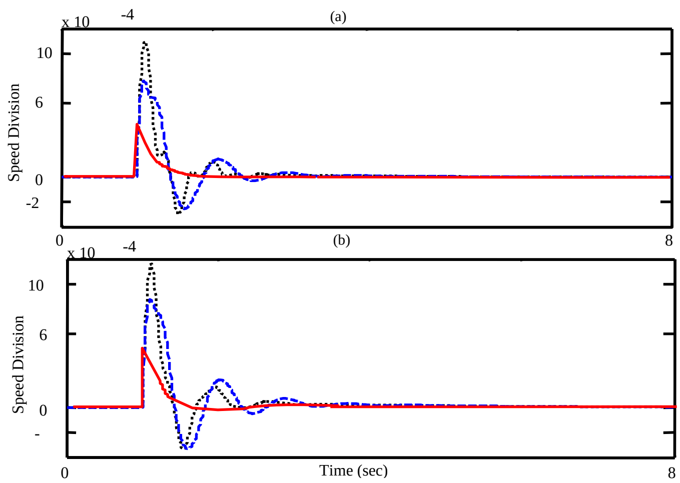


Figure 7. System response by applying a 6-cycle three-phase fault at t=1: Solid (MSF- MSFL - PSS), Dashed (GA-PSS) Doted (CPSS).
a: P=0.8,Q=0.4,Xe=0.3 b: P=0.5,Q=0.1,Xe=0.3

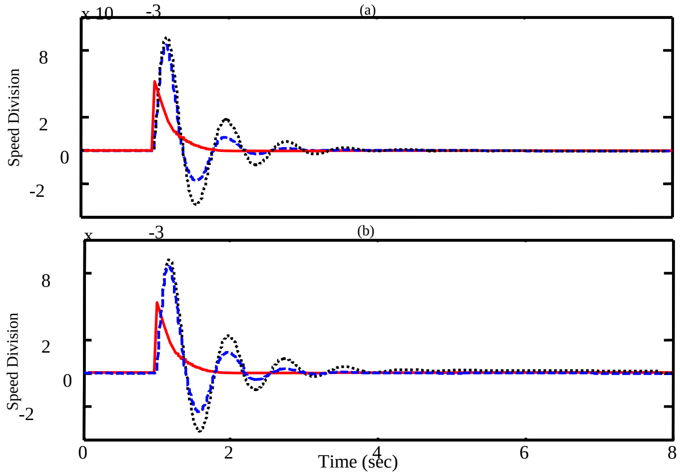


Figure 8. System response by applying a 0.2 p.u. step in torque at t=1: Solid (MSF- MSFL -PSS), Dashed (GA-PSS) Doted (CPSS).
a: P=0.8,Q=0.4,Xe=0.3 b: P=0.5,Q=0.1,Xe=0.3

According to the numerical results, it can be seen that the values of these system performance characteristics with the proposed controller are much smaller to other compared techniques. This demonstrates that the overshoot, undershoot settling time and speed deviations of all machines are greatly reduced by applying the proposed algorithm based fuzzy PSSs. The numerical results of ITAE and FD are listed in Table 3-4.

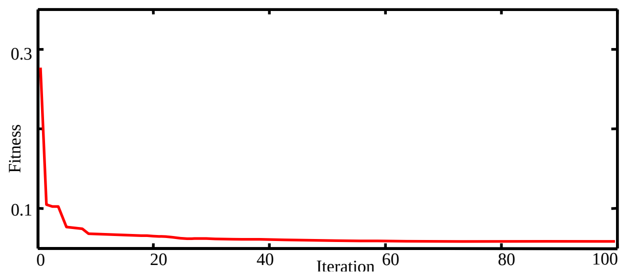
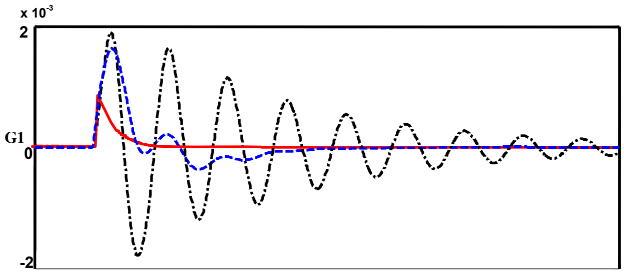


Figure 9. Optimal trend of fitness function evaluation



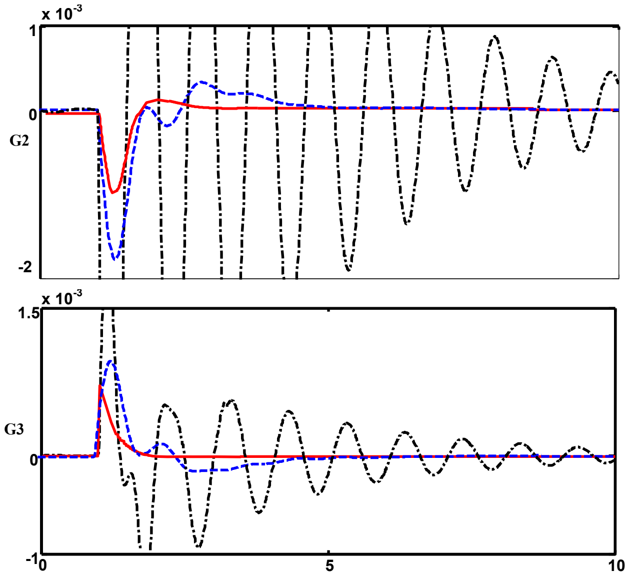


Figure 10. System response under scenario 1 with heavy loading condition: Solid (MSF- MSFL -PSS) Dashed (PSOPSS) Doted (CPSS).

For more testing, a 0.2 p.u. step increase in mechanical torque was applied at t=1.0 as a second scenario. The results of system response are presented in Figure 11.

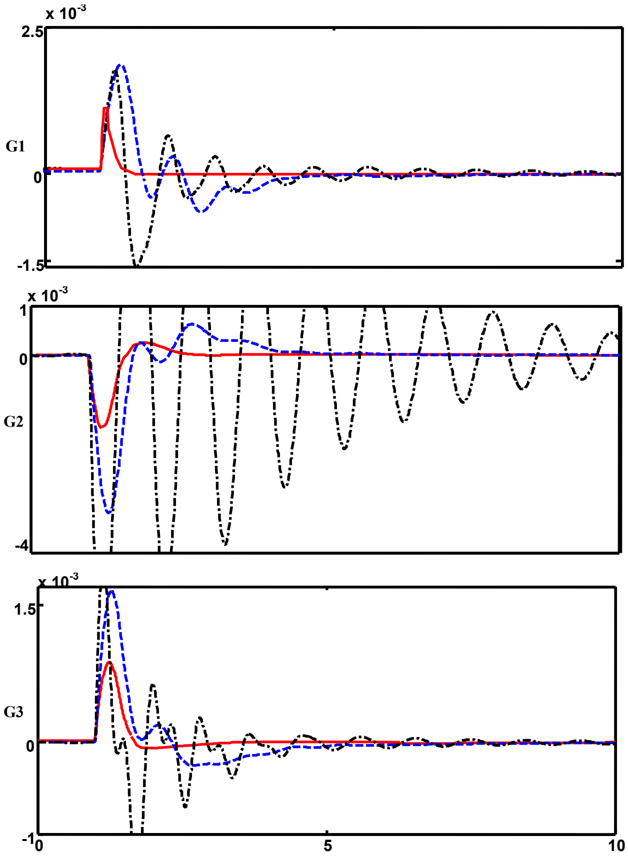


Figure 11. System response under scenario 2 with nominal loading condition: Solid (MSF-MSFL -PSS) Dashed (PSOPSS) Doted (CPSS).

Table 3. Value of ITAE in Different Techniques

Method	Scenario 1			Scenario 2		
	Nominal	Light	Heavy	Nominal	Light	Heavy
MSF- MSFL	0.32	0.33	0.34	0.32	0.34	0.35
GA-FPSS	0.76	0.73	0.84	0.73	0.70	0.79
CPSS	37.1	36.7	38.5	36.03	36	37.4

Table 4. Value of FD in Different Techniques

Method	Scenario 1			Scenario 2		
	Nominal	Light	Heavy	Nominal	Light	Heavy
MSF- MSFL	1.35	1.35	1.56	1.54	1.45	1.64
PSO-PSS	2.45	2.86	3.04	2.36	2.64	2.71
CPSS	55.4	58.6	60.4	54.1	55.4	57.7

5. Conclusion

In this paper, a new multi-stage fuzzy controller is proposed to damp the power system oscillation in multi-machine environment to provide the stability of the power system in low frequency oscillation problem. The presented controller is optimized by MSFL which inspired by mating process of the honey bee and is strong optimization technique with good accuracy and speed. The proposed technique demonstrates the highest ability, great potential and good perspective, for solving optimization problems. Accordingly, this method is efficient in handling large and complex search spaces. This control strategy was chosen because of the increasing complexity and changing structure of the power systems. Actually, the proposed technique has two dimensional rules. And this method needs fewer resources to operate. The exact tuning of membership function is really important to proposed controller. For this purpose the MSFL is used which is based on natural selection. The effectiveness of the proposed technique is tested over two case studies as SMIB and 3-9 bus IEEE power systems. The results are compared with Genetic Algorithm, Particle Swarm Optimization and Classic controllers through ITAE and FD. Simulation results show the effectiveness of the proposed controller strategy based on MSFL which can work effectively over a wide range of the loading conditions and is superior to other compared methods.

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