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OPTIMAL MULTI-STAGE FUZZY PID BUNDLED PSOTVAC IN MULTI-MACHINE ENVIRONMENT

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Abstract- In this paper presents a new strategy based on Multi-Stage Fuzzy (MSF) PID controller is proposed for damping Power System Stabilizer (PSS) in multi-machine environment. In the proposed strategy finding the parameters of PID controller is same as an optimization problem which is based on Particle Swarm Optimization with Time Varying Acceleration Coefficient (PSOTVAC). Thus, to reduce the design effort and find a better fuzzy system control, the parameters of proposed controller is obtained by PSOTVAC 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), IEEE 3-9 buses power system. The proposed technique is compared with other techniques through ITAE and FD which demonstrate the robustness of the proposed technique.

Keywords: Multi-Stage PID, PSOTVAC, Multi-Machine Environment.

I. INTRODUCTION

In early sixties, most of the generators were getting interconnected and the automatic voltage regulators (AVRs) were more efficient. With bulk power transfer on long and weak transmission lines and application of high gain, fast acting AVRs, small oscillations of even lower frequencies were observed. The stability of the system, in principle, can be enhanced substantially by application of some form of close-loop feedback control. Over the years a considerable amount of effort has been extended in laboratory research and on-site studies for designing such controllers. The problem, when first encountered, was solved by fitting the generators with a feedback controller which sensed the rotor slip or change in terminal power of the generator and fed it back at the AVR reference input with proper phase lead and magnitude so as to generate an additional damping torque on the rotor [1-3].

Damping power oscillations using supplementary controls through turbine, governor loop had limited success. With the advent fast valving technique, there is some renewed interest in this type of control [4]. This device came to be known as a Power System Stabilizer (PSS). The PSSs are auxiliary control devices on synchronous generators, used in conjunction with their excitation systems to provide control signals toward enhancing the system damping and extending power transfer limits.

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. 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]. In these factors, exact 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.

In this paper Particle Swarm Optimization with Time Varying Acceleration Coefficient (PSOTVAC) is proposed to solve the backwashes of mentioned problem. Intelligent methods are frequent techniques that can search not only local optimal solutions but also a global optimal solution depending on problem domain and execution time limit. The old optimization methods have the advantage of searching the solution space more thoroughly. The major difficulty is their sensitivity to the choice of parameters. Among intelligent methods, PSOTVAC is strong and simple. It requires less computation time and memory. It has also standard values for its parameters [8].

The effectiveness of the proposed technique is applied on Single-machine Infinite Bus System (SMIB) and 3 machines, 9 buses IEEE standard power system in comparison of GA-PSS and CPSS [9] in first case study and PSOPSS and CPSS [9] in 3-9 buses test system through Integral of the Time multiplied Absolute value of the Error (ITAE) and the Figure of Demerit (FD) performance indices [10].

II. POWER SYSTEM MODEL

The complex nonlinear model related to multi-machine interconnected power system, can be described by a set of differential-algebraic equations by assembling the models for each generator, load, and other devices such as controls in the system, and connecting them appropriately via the network algebraic equations. Figure 1 shows the main model of power system with location of controller [10].

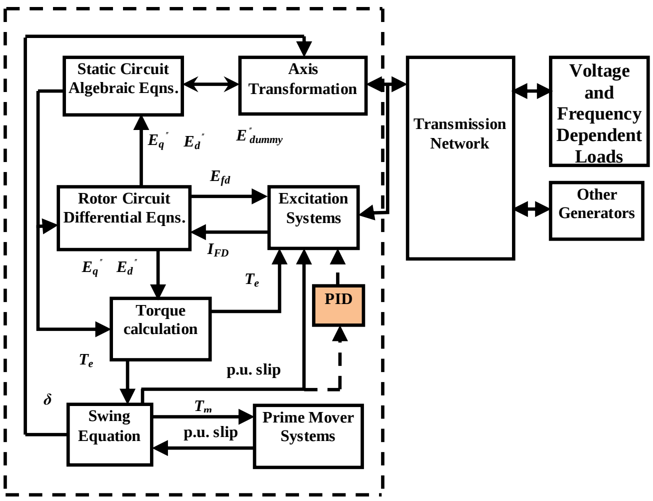

Figure 1. Structure of PSS in power systems [5]

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:

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

$$\dot{\omega} = \frac{1}{M}(P_m - P_e - D(\omega - 1)) \tag{2}$$

B. 3-9 Buses 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].

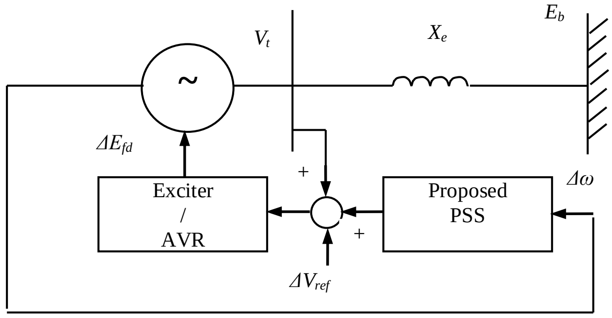

Figure 2. Schematic diagram of single machine infinite bus system [1]

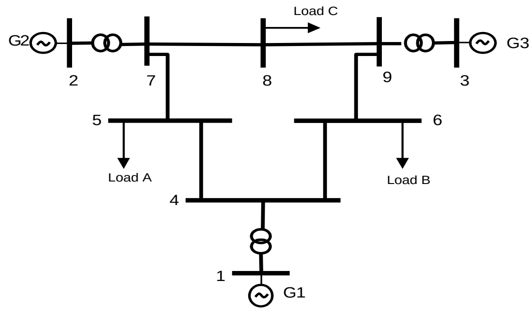

Figure 3. Three-machine nine-bus power system [5]

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 ($\int e$) that are presented in [14]. The truth value vectors are indicated in Figure 5, by darkened lines [14-15].

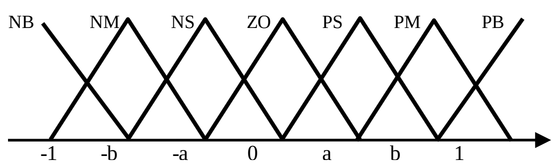

Figure 4. Symmetric fuzzy partition [14]

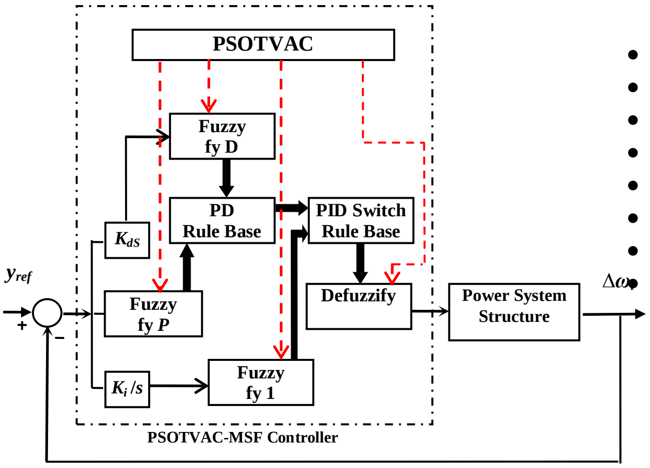

Figure 5. Structure of the proposed controller [14]

III. PARTICLE SWARM OPTIMIZATION WITH TIME VARYING ACCELERATION COEFFICIENTS

A. Particle Swarm Optimization

Classic PSO (CPSO) is one of the optimization techniques and a kind of evolutionary computation technique which is launched by Aberhart Rasel. The method has been found to be robust in solving problems featuring nonlinearity and non-differentiability, manifold optima, and high dimensionality through adaptation, which is isolated from the social-psychological theory. The characteristics of the method are as follows [16]:

- The method is improved from research on swarm such as fish schooling and bird flocking.
- It is based on a simple concept. Therefore, the time of calculation is short and requires few memories.
- It was originally developed for nonlinear optimization problems with continuous variables. It is simple expanded to treat a problem with discrete variables.

CPSO is basically improved through simulation of bird flocking in two-dimension space. The location of each agent is represented by *XY* axis position and also the velocity is expressed by V_X (the velocity of *X* axis) and V_Y (the velocity of *Y* axis). Correction of the agent position is realized by the position and velocity information [17]. Bird flocking optimizes a certain objective function. Each agent knows its best value so far (*pbest*) and its X_Y position. This information is deduction of personal experiences of each agent. Moreover, each agent knows the best quantity so far in the group (*gbest*) among *pbest*. This information is analogy of knowledge of how the other agents around them have performed. Videlicet, each agent tries to modify its position using the information of current positions (*x*, *y*), current velocities (V_X, V_Y), distance between the current position and (*pbest*, *gbest*)

This modification can be represented by the concept of velocity and the place of that. Velocity of each agent can be modified by the following equation:

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{3}$$

$$v_i(t+1) = wv_i(t) + c_1 r_1(t)[pbest_i(t) - x_i(t)] + \\ + c_2 r_2(t)[leader_i(t) - x_i(t)] \tag{4}$$

where,

- x_i: position of agent *i* at iteration *k*
- v_i: velocity of agent *i* at iteration *k*
- *w*: inertia weighting
- c_1, c_2: tilt coefficients
- r_1, r_2: random numbers between 0 and 1
- *leader*: archive of unconquerable particles
- $pbest_i$: *pbest* of agent *i*
- *gbest*: *gbest* of the group

Convergence of the PSO strongly depended on *w*, c_1 and c_2. While c_1 and c_2 are between 1.5 till 2, however the best choice to these factors is 2.05. Also, $0 \le w < 1$ whereas this value is really important factor to the system convergence and this is better that this factor define dynamically. While it should be between 0.2 and 0.9 and it should decrease linear through evolution process of population. Being extra value of w at first, provides appropriate answers and small value of that help the algorithm to convergence at the end [18].

B. PSO with Time-Varying Inertia Weight (PSO-TVIW)

The PSO-TVIW method is capable of locating a good solution at a significantly faster rate, when compared with other optimization techniques; its ability to fine tune the optimum solution is comparatively weak, mainly because of the lack of diversity at the end of the search. Also, in PSO, problem-based tuning of parameters is a key factor to find the optimum solution accurately and efficiently. The main concept of PSO-TVIW is similar to CPSO. However, for PSO-TVIW the velocity update equation is modified by the constriction factor *C* and the inertia weight *w* is linearly decreasing as iteration grows [18].

$$v_i(t+1) = C\{wv_i(t) + c_1 r_1(t)[pbest_i(t) - x_i(t)] + \\ + c_2 r_2(t)[leader_i(t) - x_i(t)]\} \tag{5}$$

$$w = (w_{\max} - w_{\min}).\frac{(k_{\max} - k)}{k_{\max}} + w_{\min} \tag{6}$$

$$C = \frac{2}{\left|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}\right|}\ ,\ 4.1 \le \varphi \le 4.2 \tag{7}$$

C. PSO with Time-Varying Acceleration Coefficients (PSO-TVAC)

Consequently, PSO-TVAC is extended from the PSO-TVIW. All coefficients including inertia weight and acceleration coefficients are varied with iterations. The equation of PSO-TVAC for velocity updating can be expressed as [18]:

$$v_i(t+1) = C\{wv_i(t) + ((c_{1f} - c_{1i})\frac{k}{k_{\max}} + c_{1i}). \\ .r_1(t)[pbest_i(t) - x_i(t)] + ((c_{2f} - c_{2i})\frac{k}{k_{\max}} + c_{2i}). \\ .r_2(t)[leader_i(t) - x_i(t)]\} \tag{8}$$

The procedure of PSO-TVAC for tuning the parameters is described in Figure 6. The simulation operated with multi objective with PSO-TVAC algorithm and the objective functions for optimization as follow:

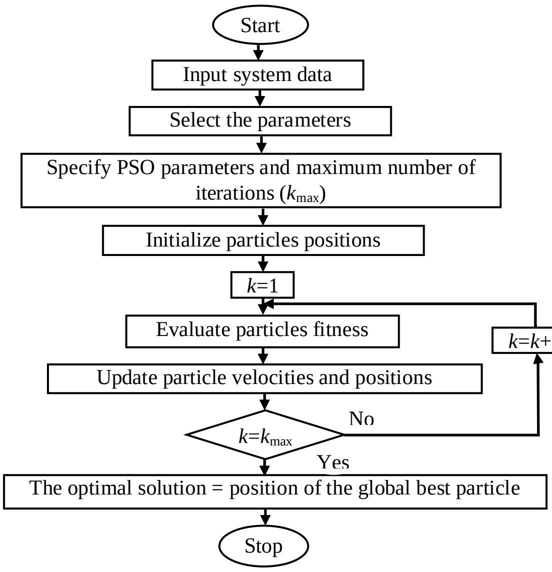

Figure 6. Flowchart of the PSO-TVAC [18]

D. De Jong Function

This function is one of simplest concave functions which is zero in absolute minimum [9]. The shape of this function is presented in Figure 7. The mathematical formula of this function is presented as:

$$f(x) = \sum_{i=1}^{n} x_i^2 \quad , \quad -5.12 \le x_i \le 5.12 \tag{9}$$

In this function is tried to presents the convergence capability of the proposed PSOTVAC algorithm. Hence, the achieved results for 10 iterations are presented in Table 1. Also the variation of the tested function is presented in Figure 8.

IV. 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:

$$ITAE_i = 100\int_0^{10} t(|\Delta\omega_i|)dt \tag{10}$$

$$FD = (OS \times 10^{-4})^2 + (US \times 10^{-4})^2 + T_s^{\ 2} \tag{11}$$

A. SMIB

For this case study the fitness function trend of proposed technique is presented in Figure 9. This case is compared with GAPSS and Classic PSS (CPSS) [9]. Accordingly, Figure. 10, 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 numerical results for 0.2 p.u. step increasing in mechanical torque. Also, the optimum parameters for case studies achieved by PSOTVAC are presented in Tables 2-3.

B. 3-9 Buses IEEE Power System

The convergence of the proposed technique over second case study is shown in Figure 11. 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 12. This case study is compared with PSOPSS and CPSS [9].

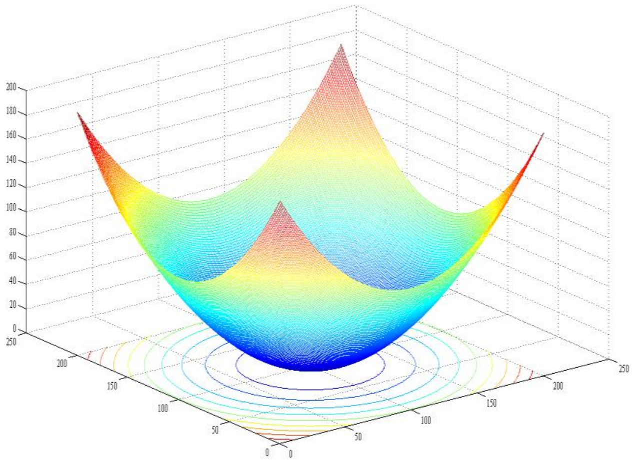

Figure 7. The shape of De Jong Function

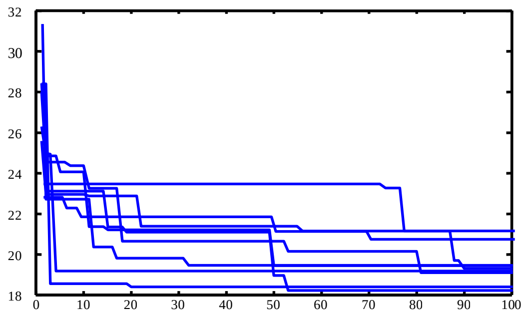

Figure 8. The variation of the De Jong Function

Table 1. PSOTVAC numerical results in 10 iteration for De Joung function

Run	x(1)	x(2)	Max	Ave	Min
1	1.0140	1.0013	45.3207	20.7712	2.4245
2	1.0036	1.0013	45.9420	20.5894	2.5244
3	1.0033	1.0365	45.6291	20.6194	2.4234
4	1.0150	1.0076	48.6984	21.1500	2.4222
5	1.0086	1.0261	45.0306	19.5679	2.2457
6	1.0275	1.0029	48.1777	21.4238	2.5266
7	1.0032	1.0519	45.9167	20.7739	2.6467
8	1.0222	1.0177	50.3832	20.6031	2.7532
9	1.0181	1.0085	48.6276	20.2021	2.3346
10	1.0234	1.0098	48.6017	20.6280	2.4435
Ave	1.0139	1.0164	48.9328	20.6329	2.5535
SD	0.0085	0.0161	1.9980	0.5154	0.3545

Table 2. Optimum PID controller parameters in case 1

Membership Function		ω_i	$\Delta\omega_i$	$\int\omega$	Output
PSOTVAC Results	a	0.20	0.0408	0.05	0.10
	b	0.13	0.17	0.33	0.04

Table 3. Optimum PID controller parameters in case 2

Membership Function		ω_i	$\Delta\omega_i$	$\int\omega$	Output
PSOTVAC Results	a	0.33	0.0725	0.05	0.23
	b	0.28	0.22	0.5	0.08

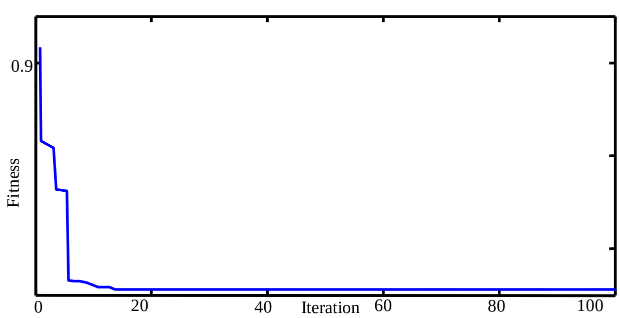

Figure 9. Optimal trend of fitness function evaluation

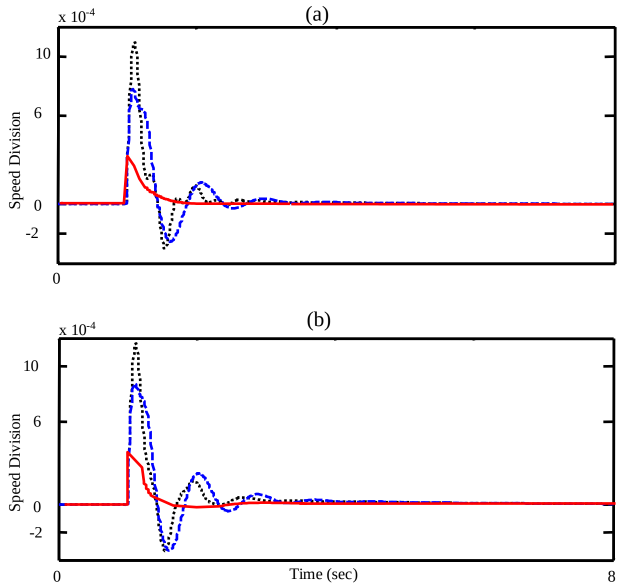

Figure 10. System response by applying a 6-cycle three-phase fault at t=1: Solid (MSF- PSOTVAC), Dashed (GA-PSS) Doted (CPSS)
(a) P=0.8, Q=0.4, X_e=0.3 (b) P=0.5, Q=0.1, X_e=0.3

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 Tables 4-5.

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 13.

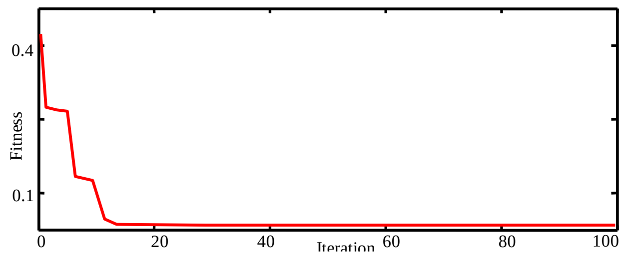

Figure 11. Optimal trend of fitness function evaluation

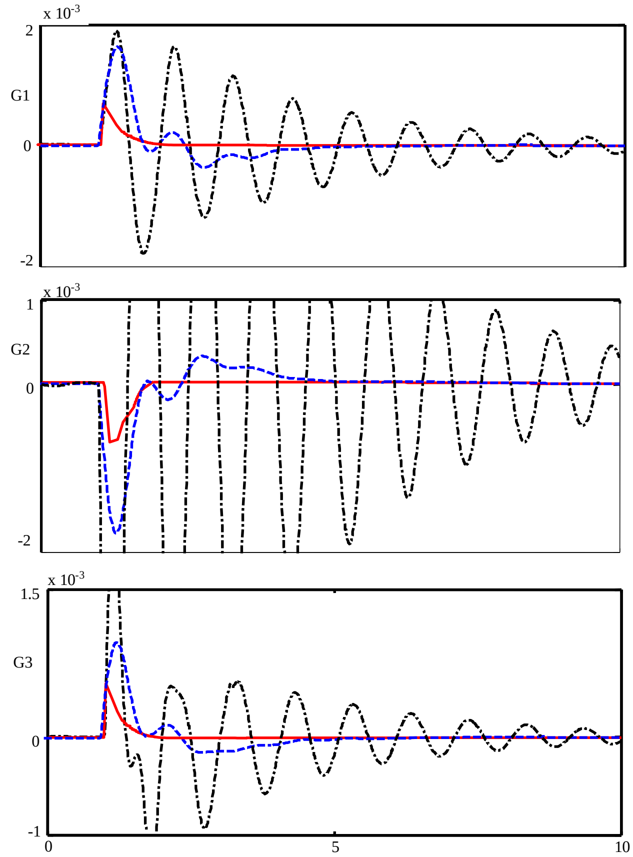

Figure 12. System response under scenario 1 with heavy loading condition: Solid (MSF- PSOTVAC) Dashed (PSOPSS) Doted (CPSS)

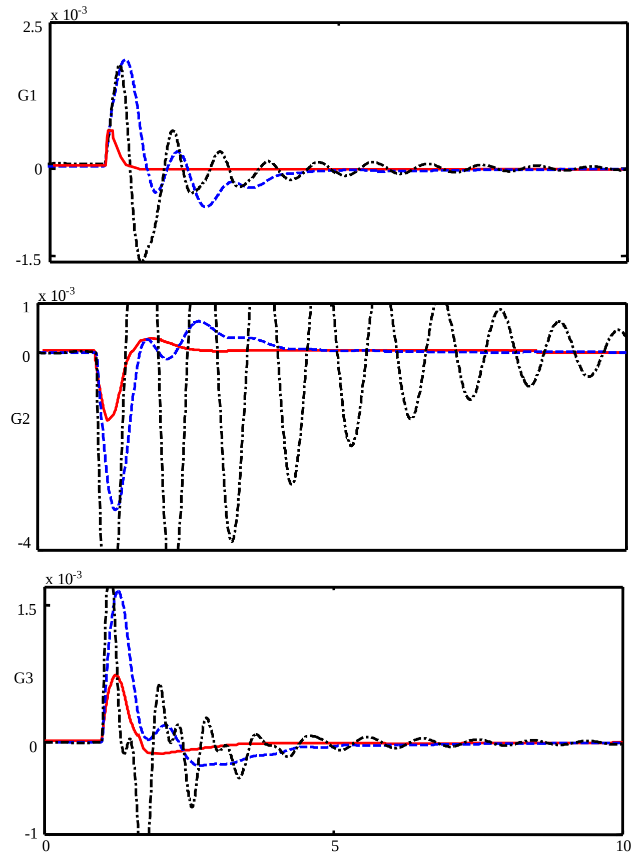

Figure 13. System response under scenario 2 with nominal loading condition: Solid (MSF- PSOTVAC) Dashed (PSOPSS) Doted (CPSS)

Table 4. Value of *ITAE* in different techniques

Method	Scenario 1			Scenario 2		
	Nominal	Light	Heavy	Nominal	Light	Heavy
MSF-PSOTVAC	0.38	0.38	0.40	0.35	0.36	0.37
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 5. Value of *FD* in different techniques

Method	Scenario 1			Scenario 2		
	Nominal	Light	Heavy	Nominal	Light	Heavy
MSF-PSOTVAC	1.22	1.28	1.39	1.17	1.33	1.40
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

V. CONCLUSIONS

In this paper, a new multi-stage fuzzy controller is proposed to solve the power system stabilizer problem to provide the stability of the power system in low frequency oscillation problem in multi machine. The presented controller is optimized by Swarm Optimization with Time Varying Acceleration Coefficient (PSOTVAC). Intelligent methods are frequent techniques that can search not only local optimal solutions but also a global optimal solution depending on problem domain and execution time limit. The old optimization methods have the advantage of searching the solution space more thoroughly. The major difficulty is their sensitivity to the choice of parameters. Among intelligent methods, PSOTVAC is strong and simple. It requires less computation time and memory. It has also standard values for its parameters. Hence, 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. Actually, exact tuning of membership function is really important to proposed controller. For this purpose the PSOTVAC 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 buses 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 PSOTVAC which can work effectively over a wide range of the loading conditions and is superior to other compared methods.

NOMENCLATURE

Machine models parameters

δ: Rotor angle

ω: Rotor speed

P_m: Mechanical input power

P_e: Electrical output power

E'_q: Internal voltage behind x'_d

E_{fd}: Equivalent excitation voltage

T_e: Electric torque

T'_{do}: Time constant of excitation circuit

K_A: Regulator gain

T_A: Regulator time constant

v_{ref}: Reference voltage

v: Terminal voltage

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BIOGRAPHIES

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