

PID Type Stabilizer Design for Multi Machine Power System Using IPSO Procedure

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Abstract This paper presents a modified Iteration Particle Swarm Optimization (IPSO) algorithm to tune optimal gains of a Proportional Integral Derivative (PID) type multiple stabilizers and non-smooth nonlinear parameters (such as saturation limits) for multi machine power system, simultaneously. The problem of robustly tuning of PID based multiple stabilizer design is formulated as an optimization problem according to the time domain-based objective function which is solved by a modified strategy of PSO algorithm called IPSO technique that has a strong ability to find the most optimistic results. In the proposed algorithm, a new index named, Iteration Best, is incorporated in standard Particle Swarm Optimization (PSO) to enrich the searching behavior, solution quality and to avoid being trapped into local optimum. To demonstrate the effectiveness and robustness of the proposed stabilizers, the design process takes a wide range of operating conditions and system configuration into account. The effectiveness of the proposed stabilizer is demonstrated through nonlinear simulation studies and some performance indices on a four-machine two areas power system in comparison with the classical PSO and PSO with Time-Varying Acceleration Coefficients (PSO-TVAC) based optimized PID type stabilizers. The results of these studies show that the proposed IPSO based optimized PID type stabilizers have an excellent capability in damping power system inter-area oscillations and enhance greatly the dynamic stability of the power system for a wide range of loading condition. Also, it is superior that of the PSO and PSO-TVAC based tuned stabilizers in terms of accuracy, convergence and computational effort.

Keywords Power System Stabilizer Design, IPSO, PID, Dynamic Stability, Multi-machine Power Systems

1. Introduction

Damping of small signal oscillations in power systems is a main problem that has been challenging engineers for years. These oscillations may be very poorly damped in some cases, resulting in mechanical fatigue at the machines and unacceptable power variations across the important transmission lines. For this reason, the applications of the controllers to provide better damping for these oscillations are of utmost importance[1]. The goal of the electromechanical oscillations in power systems in an interconnected power system is to maintain the frequency and to damp small signal oscillations at short time so as to accommodate fluctuating load demands. By the development of interconnection of large electric power systems, there have been spontaneous system oscillations at very low frequencies in order of 0.2-3.0 Hz. In some cases, they continue to grow and presented a limitation on the amount of the power to be transmitted within the system if no adequate damping is available [1]. Power System Stabilizers (PSSs) are auxiliary control

devices on synchronous generators, used in conjunction with their excitation systems to provide control signals toward enhancing the system damping of low frequency oscillations associated with the electromechanical modes and extend power transfer limits; thus maintaining reliable operation of the power system[2].

The conventional lead-lag compensators have been widely used as the PSSs. However, the problem of PSS parameter tuning is a complex exercise. These stabilizers have previously tuned both single and multiple operation points of the power system using various methods. The approaches used to the problem of PSS parameters tuning range from modern control theory[2-5], to the more recent one using many random heuristic techniques, such as like honey bee optimization technique[6], artificial bee colony search[7], chaotic optimization algorithm[8], genetic algorithm[9], rule based bacteria foraging[10] and strength Pareto evolutionary algorithm[11] for achieving high efficiency and search global optimal solution in the problem space.

Recently, the classical PSO based method[12, 13] has been represented to optimize of PSS parameters. The potential of this method was shown for PSS designing to improve low frequency oscillations damping at different operating conditions than the GA approach on a multi-machine power system. An Improved PSO with Time Varying Acceleration

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Coefficients (PSO-TVAC) has been undertaken to solve the PSS design problem by Shayeghi et al.[14] to improve the global search in the early stage of the optimization process and cheering the particles to converge toward the global optima at the end of it for effectively enhancement the convergence rate and the accuracy of the classical PSO. Using the numerical results it was shown that PSO-TVAC technique has better convergence property and can get superior low frequency oscillations than the classical one.

Despite the potential of the modern control techniques with different structure, Proportional Integral Derivative (PID) type controller is still widely used for industrial applications such as power systems control[15-17]. This is because it performs well for a wide class of process. Also, they give robust performance for a wide range of operating conditions and easy to implement. On the other hand, Shayeghi and Esmailnezhad[15] presented a comprehensive analysis of the effects of the different PID controller parameters on the overall dynamic performance of the PSS problem. It is shown that the appropriate selection of PID controller parameters results in satisfactory performance during system upsets. Thus, the optimal tuning of a PID gains is required to get the desired level of robust performance. Since optimal setting of PID controller gains is a *multimodal* optimization problem (i.e., there exists more than one local optimum) and more complex due to nonlinearity, complexity and time-variability of the real world power systems operation. Hence, local optimization techniques, which are well elaborated upon, are not suitable for such a problem. In order to overcome these drawbacks, a novel Iteration Particle Swarm Optimization (IPSO) technique is proposed for the optimal tune of the multiple PID type stabilizers in this paper to achieve desired level of low frequency oscillations damping and enhance dynamic stability of the multi machine power system. It should be noted that the performance of the classical PSO greatly depends on its parameters adjustments, and it often suffers the problem of being trapped in the local optima so as to be premature convergence. For this reason, in the proposed algorithm, a new term named, iteration best is incorporated in classical PSO to enrich the searching behavior, solution quality and to avoid being trapped into local optimum. The effectiveness of the proposed PID type stabilizer is tested on a multi-machine power system under different operating conditions in comparison with the PSO and PSO-TVAC[14] based tuned stabilizers through nonlinear time domain simulation and some performance indices. The simulation results reveal the robust performance of the proposed method for damping low frequency oscillations than the PSO, and PSO-TVAC one tuned PSS such that the relative stability is guaranteed and the time domain specifications concurrently secured. This presents a useful promising tool to choose enviable stabilizer from a set of optimally tuned PID type PSSs for the system operator, PSS manufacturer and customers.

2. Power System Modeling

A four-machine, two-area study system, shown in Fig. 1, is considered for the damping control design. Each area consists of two generator units. The rating of each generator is 900 MVA and 20 kV. Each of the units is connected through transformers to the 230 kV transmission line. There is a power transfer of 400 MW from Area 1 to Area 2. The detailed bus data, line data, and the dynamic characteristics for the machines, exciters, and loads are given in[18]. The loads are modeled as constant impedances. For the power system stability analysis a sufficient mathematical models considering a set of nonlinear differential-algebraic equations by assembling the models for each generator, load and other devices such as controls in the system is required. The two-axis model (fourth order)[2] given in is used for the time domain simulations study for each machine. The loads are modeled as constant impedances. A first order model of a static type automatic voltage regulator was used. Nonlinear dynamic equations of the each machine can be summarized as follows:

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

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

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

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

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

The nomenclature used is given in Appendix.

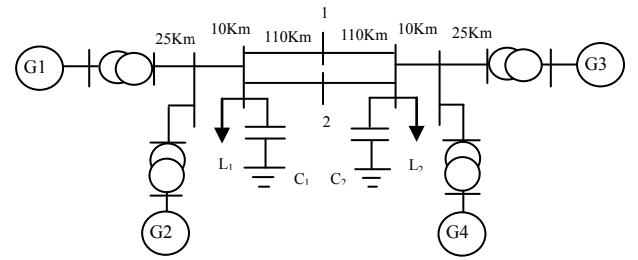


Figure 1. Single line diagram of a two area system

2.1. PSS Structure

The operating function of a PID type PSS is to produce a proper torque on the rotor of the machine involved in such a way that the phase lag between the exciter input and the machine electrical torque is compensated. The supplementary stabilizing signal considered is one proportional to speed. A widely speed based used PID is considered throughout the study[2]. The transfer function of the i^{th} PID type stabilizer is given by:

$$U_i = \frac{T_w s}{1 + T_w s} \cdot (K_p + \frac{K_i}{s} + \frac{K_d s}{1 + T_d s}) \Delta \omega_i(s) \quad (6)$$

Where, $T_D \ll 1$ and usually is considered $K_D/100$. $\Delta \omega_i$ is the speed deviation of the i^{th} generator and U_i is the output signal fed as a supplementary input signal to the regulator of

the excitation system. This type of PSS consists of a washout filter and a PID compensator. The washout filter, which really is a high pass filter, is regarded as to reset the steady-state offset in the output of the stabilizer. The value of the time constant T_w is usually not critical and it can range from 1 to 20 s. It should be noted that the PSS output must be limited to V_s^{\max} and V_s^{\min} for avoiding actuator system damaging. In this study, they are tunable. Thus, the optimized parameters of PID type PSS are:

- K_{P_i} , K_{I_i} and K_{D_i} PID Gains
- T_{w_i} Time constant of washout filter
- V_s^{\max} and V_s^{\min} PSS output saturations

3. Iteration PSO Algorithm

3.1. Classical PSO Review

The PSO is a population-based method and is described by its developers as an optimization paradigm, which models the social behavior of the birds flocking or fish schooling for food. Therefore, PSO works with a population of potential solutions rather than with a single individual[12].

In the PSO technique a number of simple entities, the particles, are placed in the search space of some problem or function, and each evaluates the objective function at its current location. Each particle then determines its movement through the search space by combining some aspect of the history of its own current and best locations by those of one or more members of the swarm with some random perturbations. The next iteration takes place after all particles have been moved. Eventually the swarm as a whole, like a flock of birds collectively foraging for food, is likely to move close to an optimum of the fitness function[19].

In the PSO, the trajectory of each individual in the search space is adjusted by dynamically altering the velocity of each particle, according to its own flying experience and the flying experience of the other particles in the search space. The position and velocity vectors of the i^{th} particle in the D-dimensional search space can be represented as $X_i = (x_{i1}; x_{i2}; \dots; x_{id})$ and $V_i = (v_{i1}; v_{i2}; \dots; v_{id})$, respectively. According to a user defined fitness function, let us assume that the best position of each particle, which corresponds to the best fitness value (P_{best}) obtained by that particle at time, be $P_i = (p_{i1}; p_{i2}; \dots; p_{id})$, and the global version of the PSO keeps track of the overall best value (G_{best}), and its location, obtained thus far by any particle in the population. Then, the new velocities and the positions of the particles for the next fitness evaluation are calculated using the following two equations[12]:

$$\begin{aligned} \vec{v}_{id}(t+1) &= \omega \times \vec{v}_{id}(t) + c_1 \times r_1 \times (\vec{P}_{id}(t) - \vec{x}_{id}(t)) \\ &\quad + c_2 \times r_2 \times (\vec{P}_{gd}(t) - \vec{x}_{id}(t)) \\ \vec{x}(t+1) &= \vec{x}(t) + \vec{v}(t+1) \end{aligned} \quad (7)$$

Where, P_{id} and P_{gd} are P_{best} and G_{best} . The positive constants c_1 and c_2 are the cognitive and social components that are the acceleration constants responsible for varying the particle velocity towards p_{best} and g_{best} , respectively. Vari-

ables r_1 and r_2 are two random functions based on uniform probability distribution functions in the range[0, 1]. The inertia weight, ω , is responsible for dynamically adjusting the velocity of the particles, so it is responsible for balancing between local and global searches and hence requiring less iteration for the algorithm to converge[19]. The following inertia weight is used in Eq. (7):

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{K_{\max}} \cdot K \quad (8)$$

Where, K_{\max} is the maximum number of iterations and K is the current number of iteration. The Eq. (8) presents how the inertia weight is updated, considering ω_{\max} and ω_{\min} are the initial and final weights, respectively.

3.2. Iteration PSO Procedure

In this paper, a new index named, Iteration Best, is incorporated in Eq. (7) to enrich the searching behavior, solution quality and to avoid being trapped into local optimum, IPSO technique is proposed, Eq. (9) shows the new form of Eq. (7)[20]:

$$\begin{aligned} \vec{v}_{id}(t+1) &= \omega \times \vec{v}_{id}(t) + c_1 \times r_1 \times (\vec{P}_{id}(t) - \vec{x}_{id}(t)) \\ &\quad + c_2 \times r_2 \times (\vec{P}_{gd}(t) - \vec{x}_{id}(t)) + c_3 \times r_3 \times (I_b - \vec{x}_{id}(t)) \end{aligned} \quad (9)$$

Where I_b is the best value of the fitness function that has been obtained by any particle in any iteration and c_3 shows the weighting of the stochastic acceleration terms that pull each particle toward I_b [20]. The motivation for using this method is enhancement the global search and to enrich the information sharing mechanism for effectively enhancement the convergence rate and the accuracy of the classical PSO.

4. IPSO Based Stabilizer Design

This section describes how the IPSO algorithm is employed to tune nonlinear parameters (V_s^{\max} and V_s^{\min}) and PID type PSS parameters for the two-area multi-machine power system as shown in Fig. 1. Just like any other optimization problem, a cost function needs to be formulated to determine optimal parameters of multiple PSSs. The goal of optimal tuning of stabilizer parameters task is to maximize low frequency oscillation damping; *i.e.*: minimize the settling time and overshoots in system response. In order to get the PSS design task a cost function that minimizes the time domain based system response characteristics is used in this study. It can be defined as follows:

$$J_i = \sum_{j=2}^4 \int_0^{t_{sim}} t^2 (\Delta\omega_{ij}^2 + 0.34\Delta\omega_{34}^2) dt \quad (10)$$

$$\begin{aligned} &+ 0.007 \max(OS_{\Delta\omega_{12}}^2, OS_{\Delta\omega_{13}}^2, OS_{\Delta\omega_{14}}^2, OS_{\Delta\omega_{34}}^2) \\ F &= \sum_{i=1}^{NP} J_i \end{aligned} \quad (11)$$

Where, t_{sim} is the time range of simulation; $\Delta\omega_{ij}$ is the relative rotor speed of the i th generator than the j th generator; OS_{ij} is the overshoot of $\Delta\omega_{ij}$. NP is the total number of operating points considered for optimization process. The sa-

lient feature of this objective function is that it needs the minimal dynamic plant information.

The design problem can be formulated as the following constrained optimization problem, where the constraints are the PSS parameters bounds:

$$\begin{aligned}
 &\text{Minimize } F \quad \text{Subject to} \\
 &T_{wi}^{\min} \leq T_{wi} \leq T_{wi}^{\max} \\
 &K_{Pi}^{\min} \leq K_{Pi} \leq K_{Pi}^{\max} \\
 &K_{Li}^{\min} \leq K_{Li} \leq K_{Li}^{\max} \\
 &K_{Di}^{\min} \leq K_{Di} \leq K_{Di}^{\max} \\
 &V_s^{\min} \leq V_s \leq V_s^{\max} \\
 &-V_s^{\min} \leq -V_s \leq -V_s^{\max}
 \end{aligned} \quad (12)$$

Typical ranges of the optimized parameters are [0.1-20] for T_w and [0.01-50] for PID controller parameters (K_{Pi} , K_{Li} and K_{Di}) and [0.05-0.5] for $V_{s\max}$ and $-V_{s\min}$. The IPSO approach was implemented in MATLAB software and used to solve this optimization problem and search for the optimal set of stabilizers parameters. To evaluate the effectiveness and robustness of the proposed optimization technique numerous operating conditions and the system configurations, simultaneously are considered. The multiple operation conditions are given in Table 1.

The optimal tuning of the PSS parameters is carried out by evaluating the fitness function as given in Eq. (12) for four operating conditions as given in Table 1 by applying a 6-cycle three-phase fault at the middle of one of the transmission line between bus-7 and bus-8. The fault is cleared by permanent tripping of the faulted line. In this study, the PSO module works offline. For the each PSS, the optimal setting of six parameters is determined by the IPSO, i.e. 24 parameters to be optimized.

Table 2. Control parameters for optimization

PSO-TVAC		IPSO		PSO	
C_{1f}	0.2	C_1	0.01	C_1	2.0
C_{1i}	2.5	C_2	0.01	C_2	2.0
C_{2f}	2.5	C_3	$c_1(1-e^{1-k})$	ω_{\min}	0.4
C_{2i}	0.2	ω_{\min}	0.4	ω_{\max}	0.9
ϕ	4.1	ω_{\max}	0.9	Population	40
ω_{\min}	0.4	Population	40	Iteration	100
ω_{\max}	0.9	Iteration	100	-	-
Population	40	-	-	-	-
Iteration	100	-	-	-	-

In order to facilitate comparison with the PSO and PSO-TVAC methods, the design and tuning of the stabilizers parameters for this multi-machine power system, the PSO and PSO-TVAC methods (For more details see the Ref.[24]) were used. Figure 2 shows the block diagram of IPSO based tuned PID type stabilizers procedure. In order to acquire better performance, the control parameters of the proposed IPSO, PSO-TVAC[14] and PSO[12] techniques is given in Table 2. Optimized multiple stabilizers parameter set values corresponding to the best fitness achieved by each algorithm after 10 trials based on the objective function as given in Eq. (12) using the above methods are listed in Table 3. Figure 2

shows the minimum fitness functions evaluating process.

Table 3. The optimal parameter settings of the proposed stabilizers

Method	Gen	T_w	K_P	K_I	K_D	V_{\max}	V_{\min}
IPSO	G ₁	9.781	32.23	1.01	6.56	0.098	-0.096
	G ₂	9.511	31.76	1.97	5.67	0.094	-0.097
	G ₃	9.678	33.39	2.01	4.83	0.097	-0.087
	G ₄	9.781	36.67	1.62	4.43	0.091	-0.094
PSO-TVAC	G ₁	8.675	16.16	1.45	5.12	0.054	-0.087
	G ₂	9.321	18.75	1.32	3.42	0.065	-0.052
	G ₃	8.986	27.49	0.86	4.45	0.086	-0.034
	G ₄	9.547	19.53	0.09	4.83	0.095	-0.045
PSO	G ₁	8.654	18.42	2.34	3.25	0.056	-0.065
	G ₂	9.564	25.49	2.03	4.43	0.038	-0.042
	G ₃	8.817	26.34	1.26	3.21	0.098	-0.046
	G ₄	9.557	16.32	1.25	4.76	0.065	-0.086

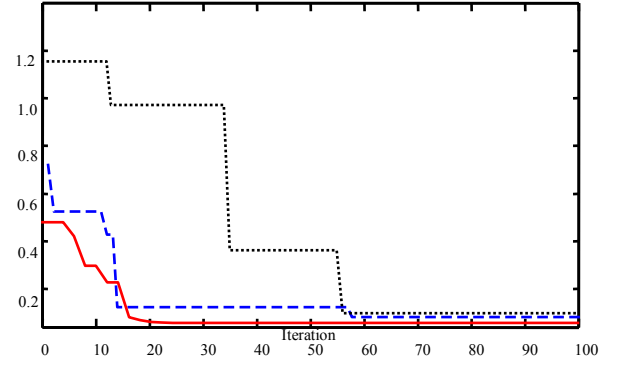


Figure 2. Fitness convergence, Dotted (PSO), Dashed (PSO-TVAC) and Solid (IPSO)

5. Simulation Results

The effectiveness and robustness of the performance of the proposed PID type stabilizer under transient conditions is verified by applying a three-phase fault of 100 ms duration at the middle of one of the transmission lines between bus-7 and bus-8. The fault is cleared by permanent tripping of the faulted line. To evaluate the performance of the proposed stabilizer design approach the response of the proposed PSS are compared with the response of the PSO and PSO-TVAC damping controller individual design.

The inter-area and local mode of oscillations with the above stabilizers for deferent operating conditions as given in Table 1 is shown in Figs. 3-5, respectively. The performance of the IPSO based optimized multiple PID type stabilizer is quite prominent in comparison with the other PSSs and the overshoots and settling time are significantly improved with the proposed stabilizer.

To illustrate robustness of the proposed method, some performance indices based on the system performance characteristics are defined as:

$$IAE = 10^4 \times \int_0^{tsim} (|\Delta\omega_{12}| + |\Delta\omega_{13}| + |\Delta\omega_{14}| + |\Delta\omega_{34}|) dt \quad (13)$$

$$ITAE = 10^4 \times \int_0^{tsim} t \cdot (|\Delta\omega_{12}| + |\Delta\omega_{13}| + |\Delta\omega_{14}| + |\Delta\omega_{34}|) dt \quad (14)$$

$$ISE = 10^4 \times \int_0^{tsim} (\Delta\omega_{12}^2 + \Delta\omega_{13}^2 + \Delta\omega_{14}^2 + \Delta\omega_{34}^2) dt \quad (15)$$

$$FD = (OS \times 4000)^2 + (US \times 1000)^2 + T_s^2 \quad (16)$$

Where, OS , US and T_s are mean overshoot, mean undershoot and mean settling time of four relative speed deviations of $\Delta\omega_{12}$, $\Delta\omega_{13}$, $\Delta\omega_{14}$ and $\Delta\omega_{34}$. It is merit mentioning that the lower the value of these indices is, the better the system response in terms of the time-domain characteristics. Numerical results of performance robustness for all system loading cases are shown in Table 4 with three PID type sta-

bilizers by applying a three-phase fault of 100 ms duration at the middle of one of the transmission lines between bus-7 and bus-8. Evaluation of these Table reveals that the using the proposed IPSO the speed deviations of all machines are greatly reduced, has small overshoot, undershoot and settling time. Also, it achieves good robust performance compared to that of designed stabilizers using the PSO and PSO-TVAC methods.

Table 1. Four operating condition (pu)

Operating Condition	G_1		G_2		G_3		G_4	
	P	Q	P	Q	P	Q	P	Q
Case 1 (Base Case)	0.7778	0.1021	0.7777	0.1308	0.7879	0.0913	0.7778	0.0918
Case 2 (20% increase for system load in case 1)	1.084	0.3310	0.7778	0.4492	0.7879	0.1561	0.7778	0.2501
Case 3 (20% decrease for system load in case 1)	0.7778	0.0502	0.2333	0.0371	0.7989	0.0794	0.7778	0.0704
Case 4 (Loss of a line between bus 7 and bus 8)	0.7778	0.1021	0.7777	0.1308	0.7989	0.0903	0.7778	0.0981

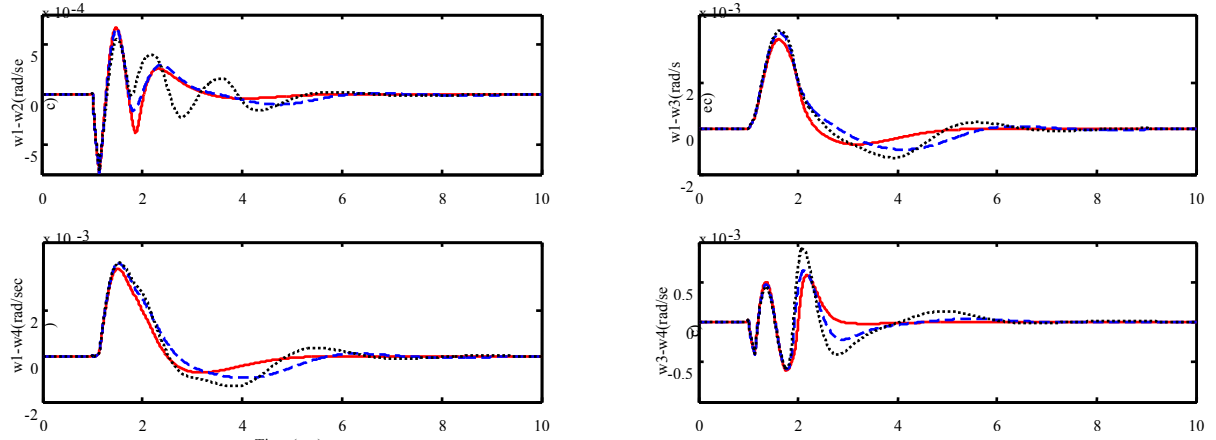


Figure 3. Inter-area and local mode of oscillations for case 1: Dotted (PSO), Dashed (PSO-TVAC) and Solid (IPSO)

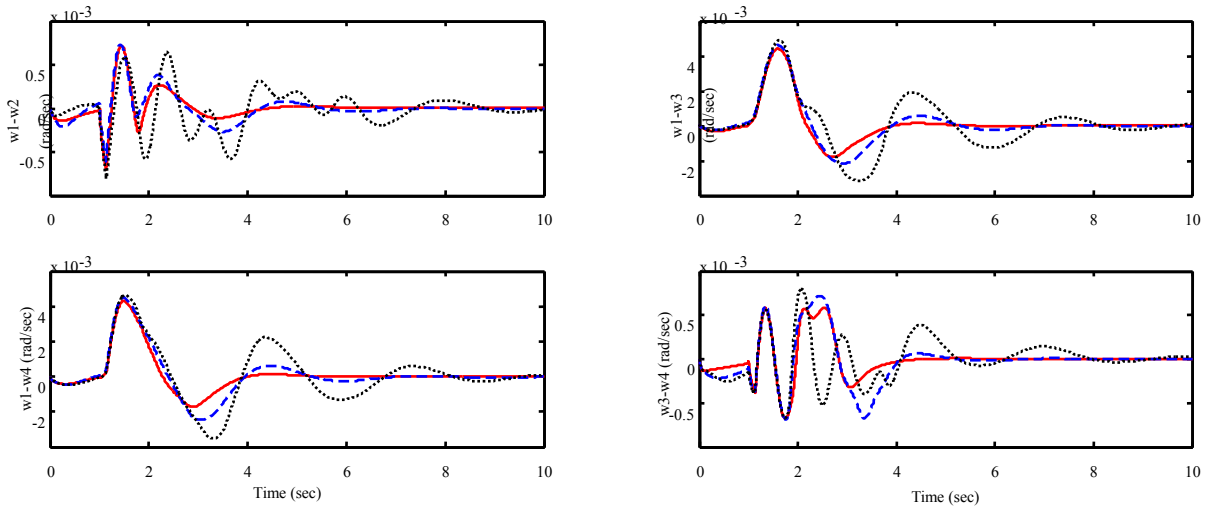


Figure 4. Inter-area and local mode of oscillations for case 2: Dotted (PSO), Dashed (PSO-TVAC) and Solid (IPSO)

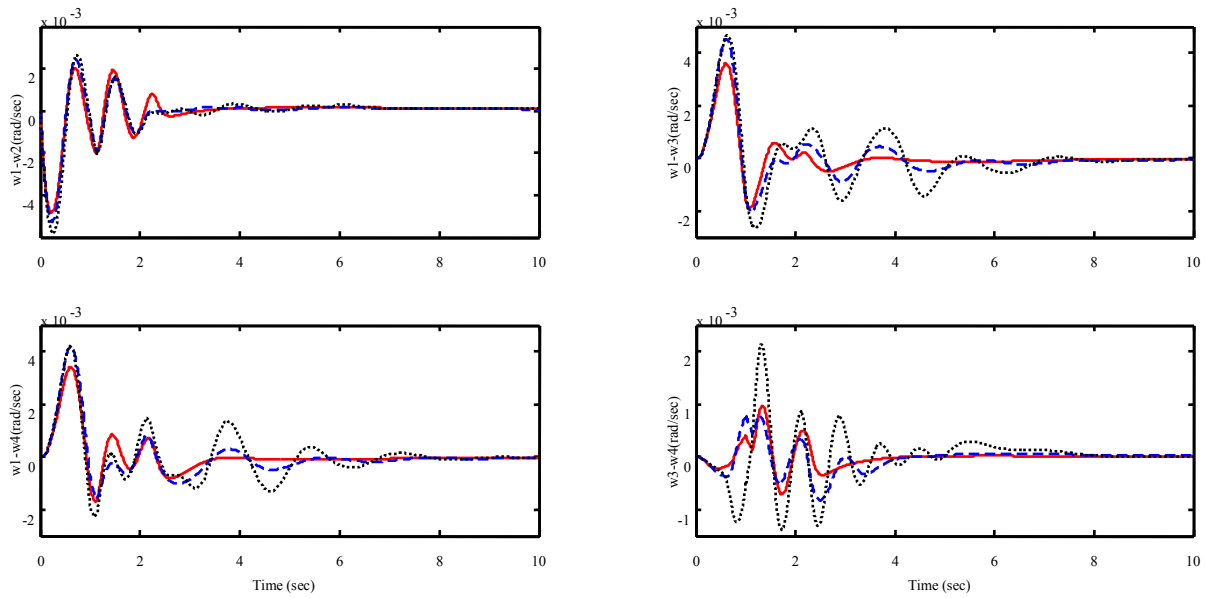


Figure 5. Inter-area and local mode of oscillations for case 4: Dotted (PSO), Dashed (PSO-TVAC) and Solid (IPSO)

Table 4. Values of the performance indices under different conditions

Algorithm	Scenario	Compare Index			
		ITAE	FD	IAE	ISE
IPSO	Base Case	16.533	12.342	7.1231	1.2532
	20% increase	18.563	19.564	8.4573	2.3459
	20% decrease	26.432	25.561	10.137	3.5466
	2 line tripe	16.437	16.855	6.5232	1.5671
PSO-TVAC	Base Case	20.562	35.643	11.349	2.2098
	20% increase	22.560	21.778	9.4590	3.4633
	20% decrease	32.451	27.400	10.354	3.8498
	2 line tripe	17.674	20.638	8.5266	1.7733
PSO	Base Case	54.563	101.33	36.658	8.6643
	20% increase	60.756	123.34	47.789	15.223
	20% decrease	63.675	103.42	55.897	19.264
	2 line tripe	56.642	131.33	38.904	10.928

5. Conclusions

In this paper, a novel Iteration Particle Swarm Optimization (IPSO) algorithm has been successfully applied to the robust design of multiple PID type stabilizers to improve damping of the low frequency oscillation in the multi machine power system. The design problem of the robustly selecting stabilizer parameters is converted into an optimization problem according to time domain-based objective function over a wide range of operating conditions that is solved by the IPSO technique. It has stronger global search ability and more robust than PSO and PSO-TVAC heuristic methods. The effectiveness of the proposed strategy was tested on a two-area four machine power system under different operating conditions. The nonlinear time-domain simulation results demonstrate the effectiveness of the proposed PID type stabilizers and their ability to provide good damping of low frequency oscillations. The system performance characteristics in terms of 'ITAE', 'IAE', 'ISE' and 'FD' indices reveal that the proposed IPSO algorithm is superior that of the PSO and PSO-TVAC in terms of accuracy and computational effort.

Appendix: Numenclature

δ	Rotor angle
P_m	Mechanical input power
P_e	Electrical output power
E'_q	Internal voltage behind x'_d
E_{fd}	Equivalent excitation voltage
T_e	Eclectic torque
T'_{do}	Time constant of excitation circuit
K_A	Regulator gain
T_A	Regulator time constant
V_{ref}	Reference voltage
v	Terminal voltage
T_w	Washout filter time constant
$\Delta\omega_i$	Speed deviation of the i th generator
X_i^k	Position of particle at iteration k
$Pbest_i^k$	The best position of particle until iteration k
$Gbest_i^k$	The best position of the swarm until iteration k
V_i^k	Velocity of particle in iteration k
ω	Inertia weight parameter
$c_1 - c_2$	Acceleration coefficients factors
t_{sim}	Time range of simulation

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