# IPSO Based Coordinated Design of PSS and SVC for Damping Power System Electromechanical Oscillations

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**Abstract**—In this paper, a modified algorithm based on Particle Swarm Optimization (PSO) for simultaneous coordinated design of static Var compensator (SVC) and power system stabilizers (PSSs) in a multi-machine power system. It is presented to enhance system damping over a wide range of systems' operating conditions in order to improve the power system oscillation performance. The coordinated design problem is formulated as an optimization problem which is solved using the modified PSO; Iteration Particle Swarm Optimization (IPSO). The IPSO algorithm is responsible for searching for optimal controller parameters. PSS and SVC are independently designed on one hand and on the other hand, the coordinated design is performed to compare the performance. The IPSO based controller is compared with the standard PSO based controllers for optimal performance. It has been observed that the results of simultaneously coordinated IPSO design give the most desirable damping performance over the uncoordinated design.

**Keywords**: Coordinated design, IPSO, PSS, SVC

## 1. Introduction

The demand of electrical power usually grows very rapidly and the expansion in generation and transmission is restricted with the limited availability of resources and with the strictness in environmental constraints. Today's power systems are much more loaded than previous times, which results in power systems operating very close to their stability margins. Not only that, power systems are widely interconnected which causes low frequency oscillations between 0.2–3.0 Hz (Shayeghi 2009). If these low frequency oscillations are not well damped, it will keep increasing in size and may eventually result in loss of synchronism or power system separation (Abido and Abdel-Magid 2004, Shayeghi 2009, Karnik 2011).

To overcome this effect of low frequency oscillations, a damping device must be provided to reduce the system oscillatory instability. Hence, Power System Stabilizers (PSSs) are efficient and economically feasible in carrying out that task over the years (Abido and Abdel-Magid 2004, Mahabuba 2009, Amin Khodabakhshian 2012, Mondal D. 2012, Peric, Saric et al. 2012, Simfukwe 2012). However, "PSSs are sometimes confronted with some drawbacks of serious variation in the voltage profiles and it may also results in leading power factor operations which may cause loss of system stability(Abido and Abdel-Magid 2004). In integrated power systems, small signal stability, transient stability and voltage stability are the main constraints to the power transfer capability (Abd-Elazim 2012, Abd-Elazim 2012, Ali 2012).

Recently, there have been a surge of interest in the development and the application of Flexible AC Transmission System (FACTS) devices for stability in transmission lines. In the field of power electronics, FACTS devices have generated lots of opportunities for their applications as one of the most reliable and available path for improving power system operations and power system transfer capabilities(P. M. Anderson 1977, Kundur 1994, Hingorani N.G. 2000). During steady-state operations, FACTS devices can cause a reasonable increase in power transfer limits through the regulation of bus voltage, transmission line reactance and modifying the phase shifts between buses. FACTS-devices have been showing great potential in their operations particularly power system damping enhancement, because of their characteristics of fast control action (Hingorani, Gyugyi et al. 2000).

It has been observed that utilizing a feedback supplementary control signal produced by PSSs and in addition to the FACTS-device primary control, can notably enhance system damping and can also achieve a better system voltage profile. Among the FACTS devices SVC has gained popularity in terms of practical application and relevance (Abd-Elazim and Ali 2012). SVC is known very well in improving power system properties especially steady state stability limits, voltage regulation and Var compensation, dynamic over voltage and under voltage control, and damp power system oscillations. Recently lots of researchers have presented methodologies for the SVC design to improve the electromechanical oscillations damping of power systems and enhance power systems stability (Ding, Du et al. 2010, Bian, Tse et al. 2011, Liu, Huang et al. 2011, Shahgholian and Movahedi 2011, Abd-Elazim and Ali 2012). An adaptive network based fuzzy inference system (ANFIS) for SVC is illustrated in (Ellithy 2000) to improve the damping of power systems. A robust control theory in designing SVC controller to damp out power system swing modes is presented in (Abido and Abdel-Magid 2003). Suggested in (Haque 2007) is a technique for ascertaining the position of SVC to enhance power system stability in interconnected power systems. An extension to the probabilistic method in coordinated design of PSS and SVC controller and a systematic approach to analyze probabilistic eigenvalues is introduced in (Bian, Tse et al. 2011). The nonlinear coordination control of generator excitation and SVC in multi-machine power systems is carried out in (Cong 2004) with the help of decentralized robust control theory and the direct feedback linearization technique. A Robust damping of multiple inter-area modes employing SVC, controllable series capacitor (CSC), and controllable phase shifter (CPS) is presented in (Chaudhuri 2003). Many approaches have been employed to mitigate and improve the damping of power system oscillations in (Chang and Xu 2007, Panda 2008, Li 2012).

In Recent years, so much attention has been attracted towards global optimization methods such as Genetic Algorithm (GA) (Abdel-Magid, Abido et al. 1999) and particle swarm optimization (PSO) (Babaei 2010) in the field of controller parameter optimization. A GA technique unlike other techniques is a population based search technique that works with a population of a linear sequence of character that represents different solutions. Therefore, GA has an implicit performance that enhances its search capability and the optimal solution can be located quickly when applied to complex optimization problems. Unfortunately recent researchers have identified some deficiencies in GA performance (Fogel 2005) and the premature convergence of GA cause to suffer a severe loss in its performance and reduces its search capability. However, the performance of the traditional PSO as a member of stochastic search algorithms has some disadvantages. Despite it constitutes a very large success and converges to an optimal value much faster than other evolutionary techniques, as the number of iteration increases, it cannot improve the solution outcome and it often suffers the problem of premature convergence in the early stage of the search. It is then liable to be trapped in local optimal solution and unable to locate the global optimum solution, especially when multimodal problems are being optimized.

In this paper, Iteration particle swarm optimization (IPSO) is proposed as a solution to the above aforementioned drawbacks that causes the improvement in searching process due to the developed dynamic acceleration constant. Authors tend to assume parameters especially the washout time constant ($T_W$) and other lead-lag compensation time constant. In this research no assumption is made, all the parameters will be optimized to achieve the optimal settings.



## 2. Problem Statement

*2.1 Modeling of a Power Systems*

The fact that Power systems are nonlinear in nature, a power system can be modeled by a set of nonlinear differential equations as in equation (1).

$$\dot{X} = f(X,U) \qquad (1)$$

Where $X$ is the vector of the state variables and $U$ is the vector of input variables. In this study $X = [\omega, \delta, E_{fd}, E_q^{'}, V_s]^T$ and $U$ is the PSS and SVC output signal. The vector of the state variables; $\omega$ is the rotor speed of the machine, $\delta$ is the rotor angle, $E_{fd}$ , $E_q^{'}$ and $V_s$ are the field, internal and the excitation voltages respectively

In this paper, the linearized incremental models around an equilibrium point is employed (Abd-Elazim 2012). Therefore, the state equation of a multi-machine power system with $m$ number of generators and $n$ number of PSS and SVC can be obtained. To test for small signal stability the system's dynamic equations are linearized about a steady state operating point to get a linear set of state equations as in equation (2).

$$\begin{aligned} \dot{X} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \qquad (2)$$

Where $A$ is a square matrix of $5m \times 5m$ and is equal to $\partial f/\partial X$. $B$ is $5m \times n$ matrix and is equal to $\partial f/\partial U$. $A$ and $B$ are evaluated at certain operating point. $x$ is a state vector matrix of $5m \times 1$ and $u$ is an $n \times 1$ input vector matrix.

*2.2 modeling of Power System Stabilizer (PSS)*

Power system stabilizer's basic function is to enhance damping to the rotor oscillations of the generator by producing a component of electrical torque in phase with the rotor speed deviation so that the phase lag between the input of the exciter and the machine electrical torque is compensated. The widely used conventional lead-lag PSS is used in this paper and can be illustrated in equation (3).

$$U_i = K_{STABi}\frac{sT_W}{1+sT_W}\frac{(1+sT_{1i})(1+sT_{31})}{(1+sT_{2i})(1+sT_{4i})}\Delta\omega_i \qquad (3)$$

Where $U_i$ *is* the PSS output signal at the $i_{th}$ machine, $T_W$ is the washout time constant, and $\Delta\omega_i$ is the rotor speed deviation of the machine. The time constants $T_W$, $T_{2i}$, and $T_{4i}$ are mostly pre-specified while the stabilizer gains $K_i$ and compensation time constants $T_{li}$ and $T_{3i}$ are left to be optimized. But in this paper, only $T_W$ is pre-specified; all other parameters will be optimized for optimum solution. Fig. 1 shows the PSS block diagram with thyristor excitation system and Automatic Voltage Regulator (AVR) attached. This stabilizer has the gain block, washout filter and two stage phase compensation block. The time constant $T_W$ of the signal washout block which serves as a high-pass filter should be high enough to allow signals that are identified with oscillations in the rotor speed to flow unchanged and is also used to reset the steady state offset in the output of the PSS. The value of $T_W$ is not critical and can be in the range of 1-20 sec. The $\Delta\omega_i$ is the speed deviation from the synchronous speed and the output signal ($U_i$) of the PSS is fed as a supplementary input signal to the excitation system. The two stage phase compensation block contains $T_{1i}$-$T_{4i}$ time constants and they provide phase lead compensation for the phase lag that is introduced in the system between the exciter input and the electrical torque.

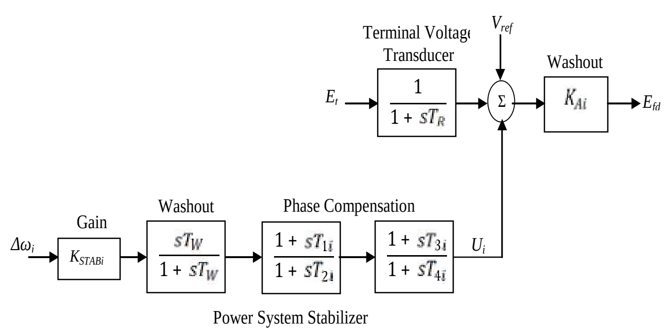


Fig. 1 PSS with thyristor Excitation system and AVR

*2.3 Modeling of Static VAr Compensator (SVC)*

An SVC is a shunt connected static VAr generator that have an output arranged to transfer inductive and capacitive current in order to keep or adjust the specific variables of the electrical quantities such as bus voltage (Hingorani N.G. 2000). The arrangement of the SVC used in this paper contains a parallel combination of thyristor controlled reactor and a static capacitor as shown in Fig. 2. Primarily SVCs are provided for the control of voltages at the buses, the level at which they contribute to the system oscillation damping that comes from voltage regulation alone are normally very small (Pal and Chaudhuri 2005). The small signal dynamic model of an SVC with supplementary control is shown in Figure 3 and is design in such a way that it can improve the power system electrical damping significantly.

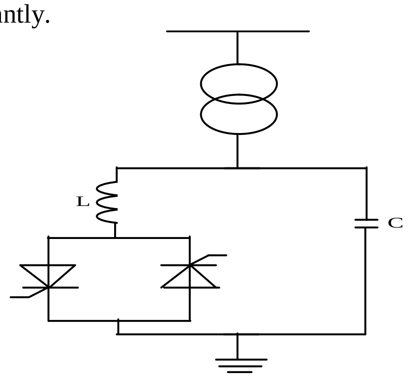


Fig. 2 Thyristor controlled reactor SVC

The reactive power injection of the SVC linked to bus $k$ is obtained by:

$$Q_k = V_k^2 B_{SVC} \qquad (4)$$

Where $B_{SVC}=B_C-B_L$, while $B_C$ and $B_L$ are the susceptance of the fixed capacitor and the thyristor controlled reactor respectively.

In the small-signal dynamic model of an SVC in Fig. 3, $T_{svc}$ is the response time of the switching circuitry, $T_m$ is the time constant representing the delay in measurement and $T_{v1}$ and $T_{v2}$ are the time constants of the voltage regulator block. Then $\Delta B_{svc}$ is given by equation (5).

$$\Delta B_{SVC} = \Delta B_C - \Delta B_L \qquad (5)$$

Therefore the dynamic equations are given in equations (6) to (8).

$$\frac{d}{dt}\Delta B_{SVC}=\frac{1}{T_{svc}}\left[-\Delta B_{SVC}+\left(1-\frac{T_{v1}}{Tv2}\right)\Delta V_{r-svc}-\frac{K_vT_{v1}}{T_{v2}}\Delta V_{t-svc}\right] + \frac{K_vT_{v1}}{T_{v2}T_{svc}}\left[\Delta V_{ss-svc}+\Delta V_{ref}\right] \qquad (6)$$

$$\frac{d}{dt}\Delta V_{r-svc}=\frac{1}{T_{svc}}\left(-\Delta V_{r-svc}-K_v\Delta V_{t-svc}+K_vV_{ref}+K_vV_{ss-svc}\right) \qquad (7)$$

$$\frac{d}{dt}\Delta V_{t-svc} = \frac{1}{T_m}\left(\Delta V_t - \Delta V_{t-svc}\right) \qquad (8)$$

The $\Delta V_{ref}$ is the reference input signal and it is defined to a certain point to keep the acceptable voltage at the SVC bus, basically the supplementary input signal $\Delta V_{ss-svc}$ is controlled to damp inter-area oscillations. In this paper, a thyristor controlled reactor of 150 MVAr capacity is recognized in parallel with a fixed capacitor of 200 MVAr. At the voltage of 1.0 pu, it matches the susceptance range of -1.50 pu to 2.0 pu and that controls the boundaries of the SVC outputs..

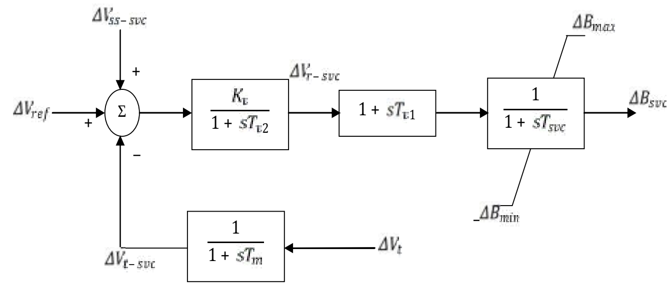


Fig. 3 A Small signal dynamic model of SVC

## 3. Study System

The single line diagram of a 3-machine, 9-bus system in Fig. 4 is the test system that is considered in this paper. The system data is detailed in (Peter W. Sauer 1998). During the eigenvalue analysis, the eigenvalues and the frequencies that are connected with the rotor oscillation modes of the system is given on table 1.

By analyzing table 1, the bolded eigenvalue has the smallest damping ratio of -0.0123 and a frequency of 0.4979 representing interarea oscillation, this means that the system is unstable with the positive real part of the eigenvalue and $G_1$ swings against $G_2$ and $G_3$. Other frequencies indicate local oscillation and they are local to the generators $G_2$ and $G_3$ themselves. The eigenvalues of $G_2$ and $G_3$ represent stable situations with the negative real parts and larger damping ratios.



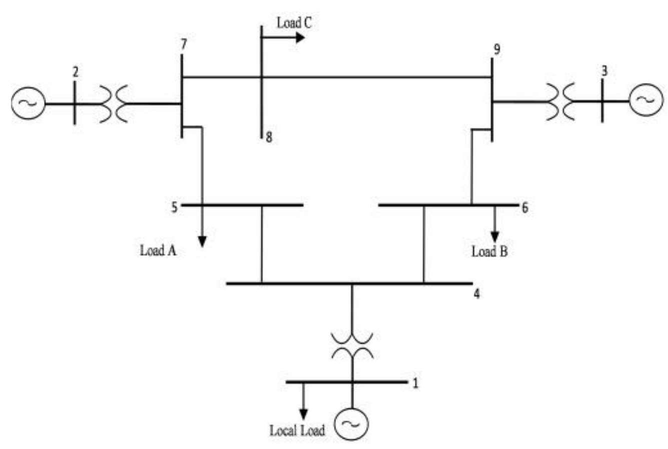


Fig. 4 Single line diagram of 3 machines, 9 bus test system

Table 1. The systems' rotor modes of oscillations

| Generators | Eigenvalues | Damping ratios ζ | Frequencies |
|---|---|---|---|
| $G_1$ | **+0.0384 ± j3.1294** | **- 0.0123** | **0.4979** |
| $G_2$ | -0.5943 ± j8.2134 | 0.0721 | 1.3070 |
| $G_3$ | -0.5904 ± j8.9681 | 0.0665 | 1.4271 |

## 4. Objective function

PSS and SVC parameters may be selected to minimize an objective function, the indexes are based on the integral of the Mean of the Squared Error (MSE) and the Integral of Time multiplied by Absolute Error (ITAE). Accordingly, the objective function *J* is set to be:

$$J = \frac{1}{t}\int_0^{z}\left(t(\mu_i)\right)^2 dt \tag{9}$$

$$J = \int_0^{z} t(\mu_i) dt \tag{10}$$

The controllers are used to minimize the error signals, can also be defined more rigorously, in the term of error criteria, to minimize the value of performance indexes mentioned above. The advantage of this selected performance index is that, minimal dynamic system information is needed. Generally the value of signal washout time constant is not critical and can be selected within 0.2 to 20 seconds because the signal washout block $T_W$ act as a high-pass filter which allows oscillations to pass unaltered in this block, while denying modification of the terminal voltage (Kundur 1994). In this paper, $T_W$ is chosen to be 10 seconds to reduce the computational burden. The values of $K_{STAB}$, $T_{1i}$, $T_{2i}$, $T_{3i}$ and $T_{4i}$ are tuned using the proposed algorithm and they are undertaken to achieve the net phase lead required by the system for stability. Based on the objective function *J*, the optimization problem can be stated as:

*Minimize J*

Subject to:

$$\begin{aligned} K_{STAB}^{\min} &\le K_{STAB} \le K_{STAB}^{\max} \\ T_1^{\min} &\le T_1 \le T_1^{\max} \\ T_2^{\min} &\le T_2 \le T_2^{\max} \\ T_3^{\min} &\le T_3 \le T_3^{\max} \\ T_4^{\min} &\le T_4 \le T_4^{\max} \end{aligned} \tag{11}$$

The proposed Iteration Particle Swarm Optimization is applied to solve for the coordinated design problem and to search for the optimal set of PSS and SVC parameters. The boundaries for the constraints are $1 \le K_{STAB} \le 50$ and $0.01 \le T_1, T_2, T_3, T_4 \le 1.0$

This optimization is aimed to search for the optimum controller parameters setting that can enhance the damping characteristics of the system. Moreover, all controllers are designed simultaneously, taking into consideration the interaction among them.

## 5. Proposed Optimization Technique

This section provides the description of the optimization methods that has been used in this paper to analyze the effectiveness of the proposed IPSO against the standard PSO. After presenting the important guide on the operation of PSO, the procedural form of Standard PSO is given on which the IPSO is developed.

### *5.1 Particle Swarm Optimization*

The PSO approach was initially developed by Kennedy & Eberhart in 1995. The process was demonstrated by using a simulation of social behavior of creatures for example fish schooling and birds flocking where they're moving forward the crowd for the source of food position. The primary benefit of PSO in comparison to other optimization strategies is because the PSO notions that has been easy and make the technique require a few memories only. In addition, the actual PSO formulation called for small computational time for the optimization in comparison with some sort of optimization techniques.

In the instance that birds are taken as an example, some of these birds are striving together when searching for food in the real life. These birds are only able to maintain within the group once the multitude of information is jointly possessed together throughout the scrambling. Therefore, at all times, the behavioral pattern on each individual bird in the group is changed based attitude authorized by the groups such as culture and the individual observations. These methods are classified as the fundamental concepts of PSO. The modification of the individual bird position is recognized through the previous position and velocity of information. Thus, the adjustment on the location of every bird (or referred to as particle) is introduced through the velocity principle as established in (10).

$$V_i^{k+1} = wV_i^k + c_1 r_1 (P_{best-i}^k - X_i^k) + c_2 r_2 (G_{best}^k - X_i^k) \tag{12}$$

From (10), the velocity of any particle will be based on the summation of three parts of equation that consist of specific coefficient individually. The *w* in the first part is an inertia weight which represents the memory of a particle during a search process while the $c_1$ and $c_2$ are showing the weights of the acceleration constant that guide each particle toward the individual best and the global best locations respectively. Furthermore, the $r_1$ and $r_2$ parameters are the random numbers that distributed uniformly between (0, 1). Therefore, the effect of each particle to move either toward the local or global best is not only dependent on $c_1$ and $c_2$ value, but it is based on the multiplication of $c_1r_1$ and $c_2r_2$. All these coefficients will give an impact on the exploration and exploitation of PSO in searching the global best result. As a result, every individual particle will change its location based on the updated velocity using the equation below:

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{13}$$

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{k_{\max}}.k \tag{14}$$

The features of the searching procedure have been summarized in (Panda, Padhy et al. 2008).

### *5.2 Iteration Particle Swarm Optimization*

In this paper, IPSO algorithm is considered for the design of lead lag type PSS. The IPSO technique is an advancement of the PSO algorithm which was proposed by Lee, T.Y. and C.L. Chen, (Lee and Chen 2007) to enhance the solution quality and computing time of the system. In the IPSO technique, there are three best values used to update the velocity and position of the agents which are $G_{best}$, $P_{best}$ and $I_{best}$. The definitions pattern and the procedure to find the $P_{best}$ and $G_{best}$ values in the IPSO are similar as traditional PSO where $P_{best}$ is known as the particle best solution that has been attained by individual particle until the current iteration, while the $G_{best}$ is the global best value among all particles in the group. In other word, each particle will have its own $P_{best}$ value but the $G_{best}$ is only a single value at any iteration. However, the new parameter $I_{best}$ is defined as the best point of fitness function that has been attained by any particle in that present iteration and causes the improvements in searching process of IPSO. Similar to $P_{best}$ and $G_{best}$, the $I_{best}$ value will be updated when the present $I_{best}$ value is better than previous $I_{best}$ value. If not, the previous $I_{best}$ value will remain as the optimum $I_{best}$ result. Furthermore, the dynamic acceleration constant parameter was also introduced by the authors, the parameter $c_3$ which is presented as follows:

$$c_3 = c_1(1-e^{-c_1 k}) \tag{15}$$

Where $k$ = the number of iterations. Furthermore, the new velocity of the proposed algorithm can be updated as follows:

$$V_i^{k+1} = wV_i^k + c_1 r_1 (P_{best}^k - X_i^k) + c_2 r_2 (G_{best}^k - X_i^k) + c_1(1-e^{-c_1 k})(I_{best}^k - X_i^k) \tag{16}$$

The flow chart of the IPSO is shown in fig. 5. Most of the steps for the IPSO are similar to the traditional PSO; the slight difference appears during finding the new velocity for updating the new position. With the $I_{best}$ parameter, the improvement on searching capability and increases on the efficiency of the IPSO algorithm in achieving the desired results in power system stabilizers design is attained. The eigenvalues of the whole system can be obtained from the linearized test system model shown in Section 2. Furthermore, same as previous discussion, the fitness function for the IPSO is also;

$$J = \mathrm{Re}\max(\alpha_{i,k}),\ i = 1,2,3...N$$

Where $\lambda_i$ is the $K_{th}$ eigenvalue for the $i_{th}$ system and the total number of the dominant eigenvalues is $N$. The parameters to be tuned through the process are $K_{STAB}$, $T_1$, $T_2$, $T_3$ and $T_4$ of the system generator.

## 6 Results and Discussion

The evaluation of the coordination control of PSS and SVC is considered for different clearing fault time and operating conditions. Three operating conditions are considered:

- Light operating condition (20% below the normal loading values).
- Normal operating condition.
- Heavy operating condition (50% above the normal loading values).

During the normal operating condition a 3-phase fault at the bus 1 is introduced and triggered at time t = 1 sec, and the fault is cleared 0.25 sec. Iteration particle swarm optimization (IPSO) compared with particle swarm optimization (PSO) is used to perform the simultaneous coordination of the PSS and SVC and the results are presented on tables 2 and 3, while the convergence characteristics for comparison of the convergence rate for PSO and IPSO algorithm is shown in figure 6, IPSO algorithm converges at around 12th iteration with a fitness of -0.602 and a computational time of 39.82 sec., but PSO could only converge around 56th iteration later with a fitness function of -0.63 and a computational time of 71.56 sec, which shows that the IPSO based controllers can converge faster than PSO based controllers.

The Eigenvalues and damping ratios under different loading conditions with controllers are shown on table 4. Clearly observed that the system's real parts of the eigenvalues are all negative (-) with a reasonable magnitude of the damping factor for all the operating conditions which means that it has the capability to shift the electromechanical mode of eigenvalues to the left side of the s-plane. The damping factors with coordinated design are greater than the damping factors of individual design, which shows that the coordinated controllers can greatly enhance the stability of the system than the individual design.

The results shown in figures 7-15 are the speed deviations between the generators under different operating conditions when coordinated and uncoordinated. The response of the speed deviations during the light loading conditions are presented in figures 7-9, that of normal loading is in figures 10-12 and for the heavy loading condition is presented in figures 13-15 for coordinated and uncoordinated design.

The system loading is reduced by 20% and the robustness of the proposed algorithm for the coordination of PSS and SVC is verified. A 3-phase fault occurred at time (1 sec.) close to bus 7 and is cleared after 0.255 sec; the system response during the process for $\Delta\omega_{12}$, $\Delta\omega_{13}$ and $\Delta\omega_{23}$ is shown in figures 7-9. It has been observed clearly that the amplitude of oscillation is wider and higher for the system with only SVC as compared to the PSS based controllers, and it is smoother when coordinated. The coordinated design has relatively small settling time (5.5 sec.) when compared with that of the individual design (8 sec. and 10sec) for IPSOPSS and IPSOSVC respectively.

Figures 10 -12 are the response of the $\Delta\omega_{12}$, $\Delta\omega_{13}$ and $\Delta\omega_{23}$ due to the same disturbance for the normal loading conditions. It can be observed that the system responses with the coordinated design using IPSO based PSS and SVC coordination has the best capability in damping low frequency oscillation which greatly enhances the dynamic stability of the system. The result in terms of the settling time is 2 sec., 3.8 sec. and 6 sec. for coordinated design, IPSOPSS and IPSOSVC respectively. These results show that the proposed controller sufficiently produces damping for the system oscillation.

In Figures 13-15, this shows the heavy loading condition of the system. The fact is not different where the coordinated design offers a better result than the individual design. It can be observed that the proposed coordinated design offers a good damping behavior for low frequency oscillation and the quick stability of the system than the IPSOPSS and IPSOSVC.

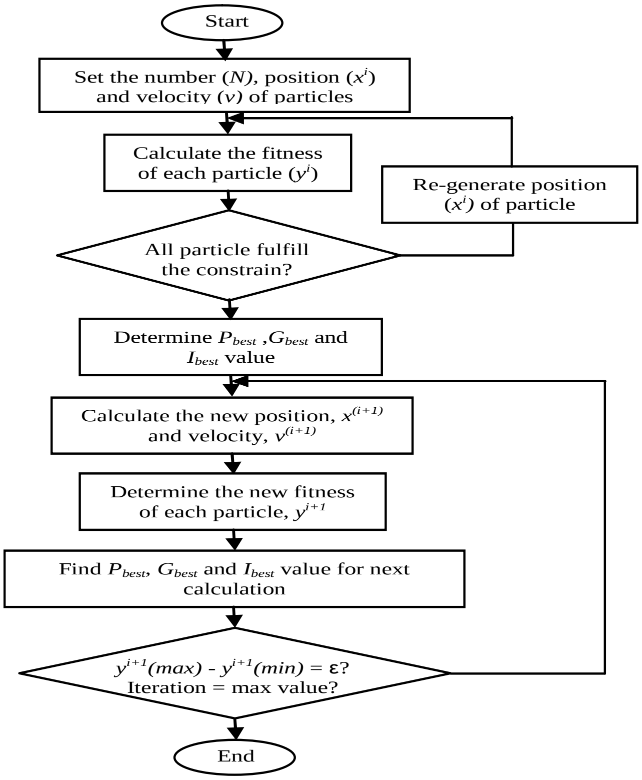


Fig.5 Flow chart of IPSO used for the optimization of PSS parameters

The settling time of these oscillations were found to be 1.9sec., 3.2 sec. and 5.5 sec. for the coordinated controller, IPSOPSS and IPSOSVC respectively. Therefore the simulation results reveal that the coordinated design of the damping controllers demonstrates its superiority over uncoordinated design and also shows that the superiority of the IPSO based controllers over the PSO based controllers. Moreover, figure 16 shows the response of the rotor speed deviation ($\Delta\omega_{12}$), where the figure demonstrates how the IPSO algorithm outperforms the PSO algorithm for designing the coordinated controllers.

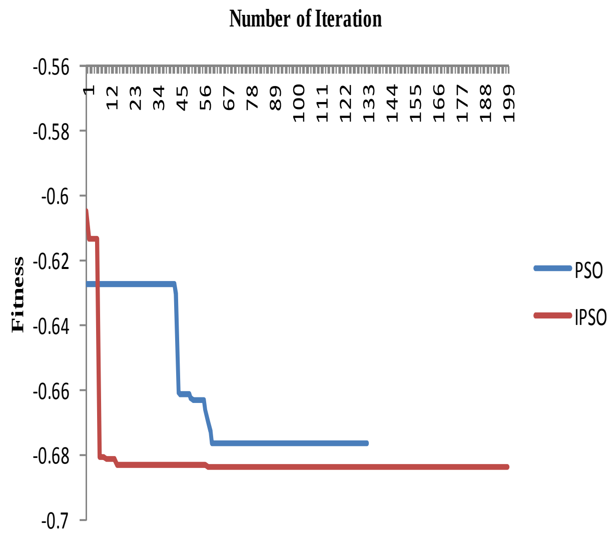


Fig.6 Convergence Characteristics of PSO and IPSO based Optimization



Table 2- Optimal Parameters for PSS and SVC for PSO based coordination

| Parameters | $K_{STAB}$ | $T_1$ | $T_2$ | $T_3$ | $T_4$ |
|---|---|---|---|---|---|
| PSS (G1) | 12.14 | 0.1316 | 0.1482 | 0.0689 | 0.0150 |
| PSS (G2) | 11.29 | 0.3471 | 0.0624 | 0.8652 | 0.2682 |
| PSS (G3) | 17.23 | 0.5169 | 0.2434 | 0.4991 | 0.2346 |
| SVC | 15.81 | 0.2157 | 0.1974 | 0.6013 | 0.7419 |

Table 3 Optimal Parameters for PSS and SVC for IPSO based coordination

| Parameters | $K_{STAB}$ | $T_1$ | $T_2$ | $T_3$ | $T_4$ |
|---|---|---|---|---|---|
| PSS (G1) | 31.67 | 0.0441 | 0.0124 | 0.0353 | 0.0136 |
| PSS (G2) | 27.84 | 0.2437 | 0.2054 | 0.1982 | 0.2053 |
| PSS (G3) | 38.90 | 0.1050 | 0.1369 | 0.0391 | 0.1436 |
| SVC | 18.89 | 0.9004 | 0.2136 | 0.5654 | 0.1984 |

Table 4 Eigenvalues and damping ratios under different loading conditions with controllers

| | Light load | Normal load | Heavy load |
|---|---|---|---|
| With only PSS | -1.0198 ± 4.7285i, 0.2101 | -0.9984 ± 6.4532i, 0.1529 | -1.0098 ± 6.4692i, 0.1542 |
| | -5.1819 ± 6.5092i, 0.6228 | -5.1459 ± 8.9673i, 0.4977 | -5.0836 ± 6.6300i, 0.6085 |
| | -5.0476 ± 7.4231i, 0.5623 | -5.1024 ± 7.5649i, 0.5592 | -5.2464 ± 6.9602i, 0.6019 |
| With only SVC | -1.0054 ± 2.0632i, 0.4380 | -1.0396 ± 3.7845i, 0.2649 | -1.0389 ± 2.1540i, 0.4344 |
| | -1.3694 ± 1.9489i, 0.5749 | -1.3472 ± 4.6323i, 0.2793 | -1.3482 ± 2.0658i, 0.5467 |
| | -1.3479 ± 3.9845i, 0.3204 | -1.0456 ± 4.5801i, 0.2226 | -1.3971 ± 2.1578i, 0.5435 |
| With coordination | -1.2987 ± 4.8920i, 0.2566 | -1.2683 ± 6.5268i, 0.1908 | -1.1095 ± 4.8876i, 0.2214 |
| | -5.6754 ± 6.7844i, 0.6416 | -5.6747 ± 6.8365i, 0.6387 | -5.6894 ± 6.6583i, 0.6496 |
| | -5.6892 ± 6.8093i, 0.6412 | -5.7206 ± 4.9802i, 0.7542 | -5.7512 ± 6.7468i, 0.6487 |

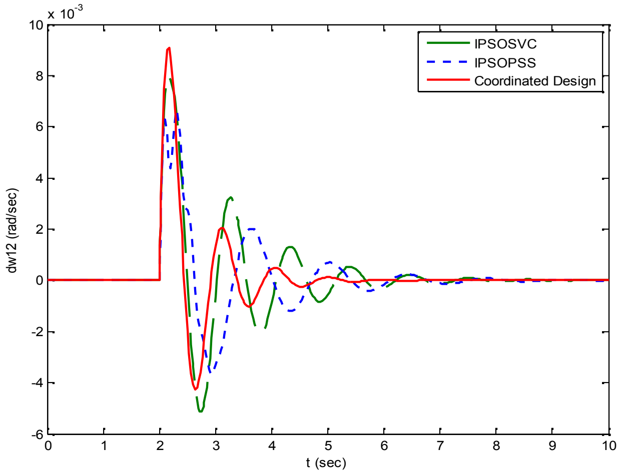


Fig.7 Rotor speed deviation under light condition

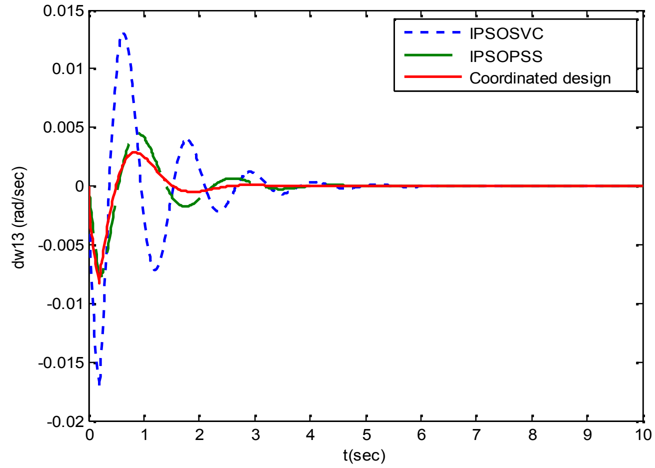


Fig.8 Rotor speed deviation under light condition

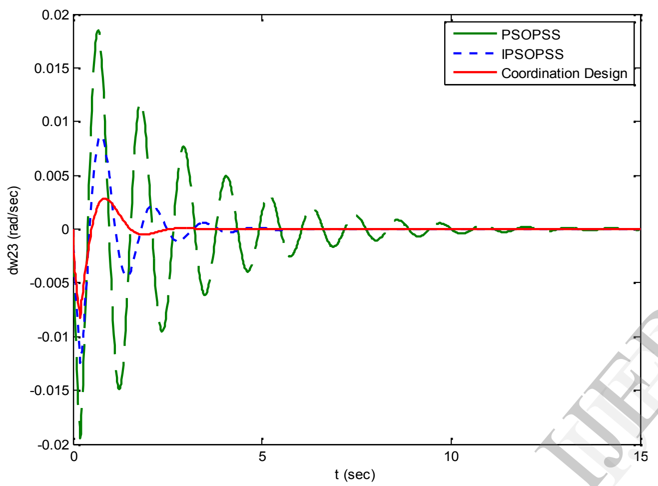


Fig. 9 Rotor speed deviation under light condition.

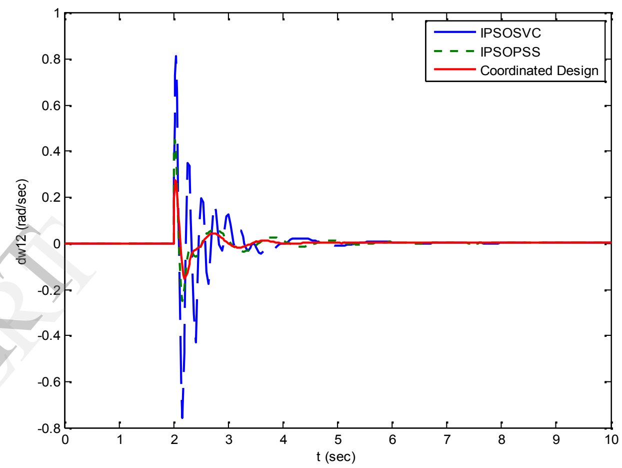


Fig.10 Rotor speed deviation under normal condition



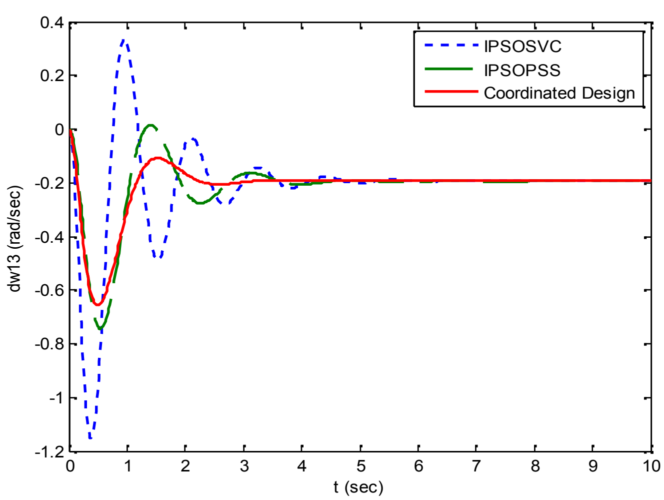


Fig. 11 Rotor speed deviation under normal condition

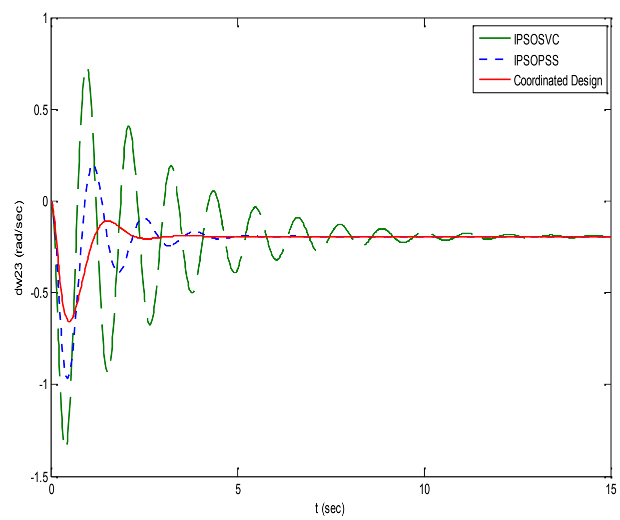


Fig.12 Rotor speed deviation under normal conditio

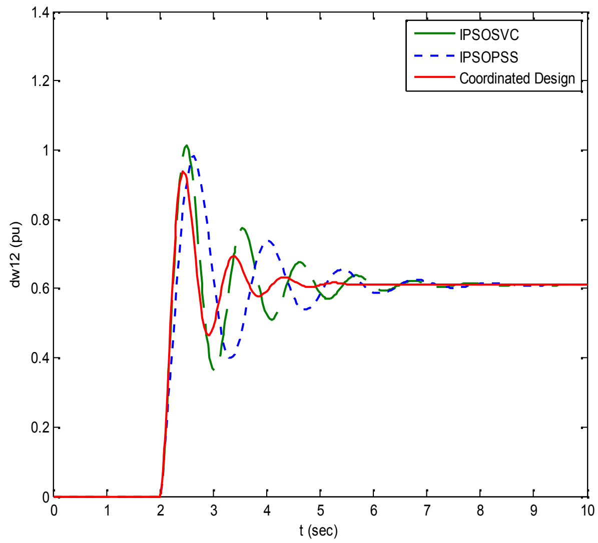


Fig. 13 Rotor speed deviation under heavy condition

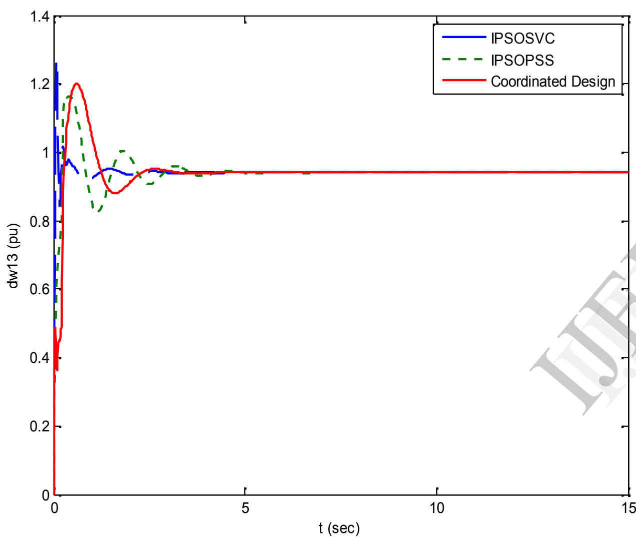


Fig. 14 Rotor speed deviation under heavy condition

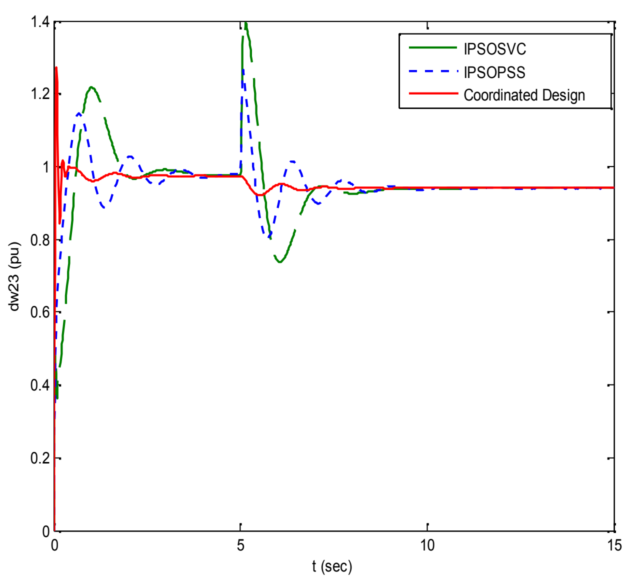


Fig. 15 Rotor speed deviation under heavy condition

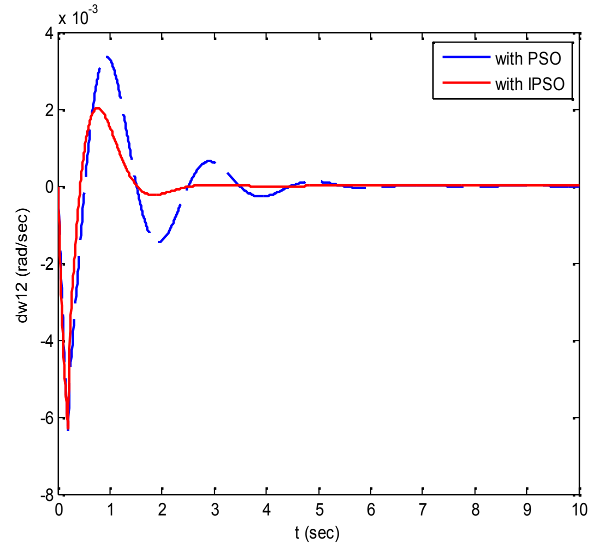


Fig. 16 Rotor speed deviation for different optimizations

## 7. Conclusions

This paper presents a robust design technique for the simultaneous coordinated design of the PSS and SVC damping controller in a multi-machine power systems. This problem is formulated as an optimization problem which is tackled using IPSO algorithm to search for the optimal parameter sets of the controllers. By minimizing the objective function, where the indexes are based on the integral of the Mean of the Squared Error (MSE) and the Integral of Time multiplied by Absolute Error (ITAE) of the speed deviations, the dynamic stability performance of the system is improved and hence, the proposed coordinated controller can extend the power system stability limit and the power transfer capability effectively. The IPSO results obtained are better compared to that obtained in (Abd-Elazim and Ali 2012). Simulation results assured the effectiveness of the proposed coordinated controller in providing good damping characteristic to system oscillations over a wide range of loading conditions and large disturbance. Also, the proposed algorithm is superior to the uncoordinated controller of the PSS and the SVC damping controllers.

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