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Damping Controller Design for TCSC using Theta-Particle Swarm Optimization Technique

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Abstract: In this study, optimal tuning of the Thyristor Controlled Series Capacitor (TCSC) damping controller in a multi-machine power system is proposed using Theta-Particle Swarm Optimization (θ-PSO) technique. The design problem was converted to an optimization problem with the time domain-based objective function for a wide range of operating conditions. The effectiveness of the proposed controller is demonstrated on a multi-machine power system through the nonlinear time-domain simulation and some performance indices studies in comparison with the PSO based damping controller. The results analysis revealed that the tuned θ-PSO based TCSC damping controller using the proposed method has an excellent capability in damping power system inter area and local oscillations in comparison with designed Classical PSO (CPSO) based TCSC controller and enhances greatly the dynamic stability of the power system.

Key words: TCSC, θ-PSO, multi-machine power system, damping controller

INTRODUCTION

Electromechanical oscillations in modern power systems are a problem that has been challenging engineers for many years. These oscillations may be very poorly damped in some cases, resulting in mechanical fatigue at the machines and unacceptable speed variations the across important transmission lines. For this reason, the use of the controllers to provide better damping for these oscillations is of utmost importance (Ramos *et al.*, 2005). Amongst the available Flexible AC Transmission Systems (FACTs) devices for transient stability enhancement, the Thyristor Controlled Series Capacitor (TCSC) is the most versatile one (Dell Rosso *et al.*, 2003). The TCSC is a series FACTs device which allows rapid and continuous changes of the transmission line impedance. It has great application and potential in accurately regulating the power flow on a transmission line, damping inter-area power oscillations and improving the transient stability (Jovcic and Pillai, 2005; Chatterjee and Ghosh, 2007).

In dynamic application of the TCSC, various control techniques and designs have been presented for damping power oscillations to improve the system dynamic response. Some authors proposed fuzzy logic theory for designing the TCSC damping controller (Khan and Lo, 2006; Hameed *et al.*, 2008). The proposed approaches may not have enough robustness against the different kinds of uncertainties and disturbances. In addition, different control schemes for a TCSC such as variable structure controller, nonlinear predictive controller, H_8-based controller and nonlinear adaptive control (Jiang and Chen, 2006; Luor and Hsu, 1998; Mei *et al.*, 2001; Zhou and Liang, 2002) were proposed. However, the parameters adjustments of these controllers need some trial and error procedure. Also, the order resulting controller in the robust control methods will be high in general which is not feasible because of the computational and economical difficulties in implementation.

Despite the potential of the modern control approaches with different structures, the power system utilities still prefer the conventional lead-lag Power Oscillation Damping (POD) controller structure (Tse and Tso, 1993). The reasons behind that might be the ease of on-line tuning and the lack of assurance of the stability related to some adaptive or variable structure approaches. On the other hand, it was shown that the appropriate selection of the conventional lead-lag controller parameters results in effective damping to low frequency electromechanical oscillations (Abido, 2000). Unfortunately, the problem of the conventional lead-lag POD controller design is a multimodal and complex optimization problem. Hence, the conventional

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optimization techniques are not suitable for such a problem. Thus, it is required that the heuristic methods which are widely used for the global optimization problems be developed. Recently, the Particle Swarm Optimization (PSO) technique is used for optimal tuning of the TCSC damping controller (Shayeghi *et al.*, 2010). The PSO is a novel population based metaheuristic which utilizes the swarm intelligence generated by the cooperation and competition between the particle in a swarm and has emerged as the useful tool for engineering optimization. However, the performance of the classical PSO greatly depends on its parameters and by increasing the number of variables, the complexity of the search space increases dramatically and it often suffers the problem of being trapped in local optima. In order to overcome this drawback and improve optimization synthesis, in this paper, a new and simpler strategy of the PSO algorithm called θ-PSO (Wei-Min *et al.*, 2008) which is based on phase angle vector but not the velocity vector, is applied for TCSC damping controller design problem to enhance the damping of power system low frequency oscillations. It is a simpler algorithm and the results show that θ-PSO performs better than standard PSO and is a promising algorithm due to its global convergence guaranteed characteristic.

In this study, the problem of TCSC based damping controller is formulated as an optimization problem according to the time domain-based objective function and θ-PSO is used to solve it. The effectiveness of the proposed controller is tested on a two-area four machine power system under different operating conditions in comparison with the PSO based tuned damping controller through the nonlinear time simulation and some performance indices. Results evaluation show that the proposed method achieves good robust performance for damping the low frequency oscillations under different operating conditions and is superior to the designed controller using classic PSO technique.

θ-PSO TECHNIQUES

The PSO is a population-based method and is described by its developers as an optimization method which models the social behavior of the birds flocking or fish schooling for food (Shayeghi *et al.*, 2009; Kennedy *et al.*, 2001). The key concept is that the potential solutions are flown through the hyperspace and are accelerated towards better or more optimum solutions. In the PSO technique, 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 θ-PSO algorithm is newly introduced strategy of PSO which is a simple algorithm, easy to implement. It is based on phase angle vector instead of the velocity vector and an increment of phase angle $\Delta\theta_i$ vector replaces velocity vector V_i which is dynamically adjusted according to the historical behaviors of the particle and its companions. In the θ-PSO, the positions are adjusted by the mapping of phase angles, thus, a particle is represented by its phase angle θ and increment of phase angle Δθ and its position decided by a mapping function. The θ-PSO can be described with the following equations (Wei-Min *et al.*, 2008):

$$\Delta\theta_{id}(t+1) = w\times\Delta\theta_{id}(t)+c_1r_1(\theta p_{id}-\theta_{id}))+c_2r_2(\theta g_{gd}-\theta_{id}(t)) \tag{1}$$

$$\theta_{id}(t+1) = \theta_{id}(t)+\Delta\theta_{id}(t+1) \tag{2}$$

$$x_{id}(t) = f(\theta_{id}(t)) \tag{3}$$

$$F_j'(t) = \text{fitness value}(x_i(t)) \tag{4}$$

f is being a monotonic mapping function as follows:

$$f(\theta_{id}) = \frac{(x_{max}-x_{min})}{2}\sin\theta_{id}+\frac{(x_{max}+x_{min})}{2} \tag{5}$$

where: d = 1, 2, ..., D; i = 1, 2, ..., S;

The procedure of the θ-PSO can be summarized in Fig. 1, where, F'_{pi} is the personal best fitness value of particle i and F'_g is the global best fitness value.

MULTI-MACHINE POWER SYSTEM MODELING

A four-machine, two-area study system, shown in Fig. 2, is considered for the damping control design. It also has been modified to include FACTS devices for the study of inter-area mode oscillation damping improvement. 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. Each synchronous generator of the multi-machine power system is simulated using a third-order model and the FACTS device is considered using a current injection model. The detailed bus data, line data and the dynamic characteristics for the machines, exciters and loads are given by Kundur (1994). The loads are modeled as constant impedances. The dynamics of the machines are given Shayeghi *et al.* (2010). A first order model of a static type automatic voltage regulator was used and its block diagram is given Shayeghi *et al.* (2010).

```
Initialize a population with random phase angle $\theta_i$ (t) and the increment of the phase angle $\Delta\theta_i$ (t)
Repeat t=1, 2, …, $t_{max}$;
 For each particle i = 1, 2, …, S
 If t = 1
 Calculate $x_i$ (1) using Eq. (6);
 Calculate the fitness value $F'_i$ (1) using Eq. 7;
 $F'_{pi}(1) = F'_i(1)$; $\theta_{pi}(1) = \theta_i(1)$;
 $F'_g(1) = F'_i(1)$; $\theta_g(1) = \theta_i(1)$;
 Else
 Update the increment of the phase angle $\Delta\theta_i$ (t) using Eq.(11) and limit $\Delta\theta_i$ (t) to ($\Delta\theta_{min}$ (t)
 ,$\Delta\theta_{max}$ (t));
 Update $\theta_i$ (t) using Eq. (5) and limit $\theta_i$ (t) to ($\theta_{min}$ (t) , $\theta_{max}$ (t));
 Update $x_i$ (t) using Eq. (6);
 Update the fitness value $F'_i$ (t) using Eq. (7);
 If $F'_i$ (t) < $F'_{pi}$ (t)
 $F'_{pi}$ (t)=$F'_i$ (t) ; $\theta_{pi}(1)= \theta_i(1)$;
 End
 If $F'_i$ (t) < $F'_g$ (t)
 $F'_g(t)= F'_i(t)$; $\theta_g(t)= \theta_i(t)$;
 End
 End
 End
Until the stopping criterion is met
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Fig. 1: The algorithm procedure of θ-PSO

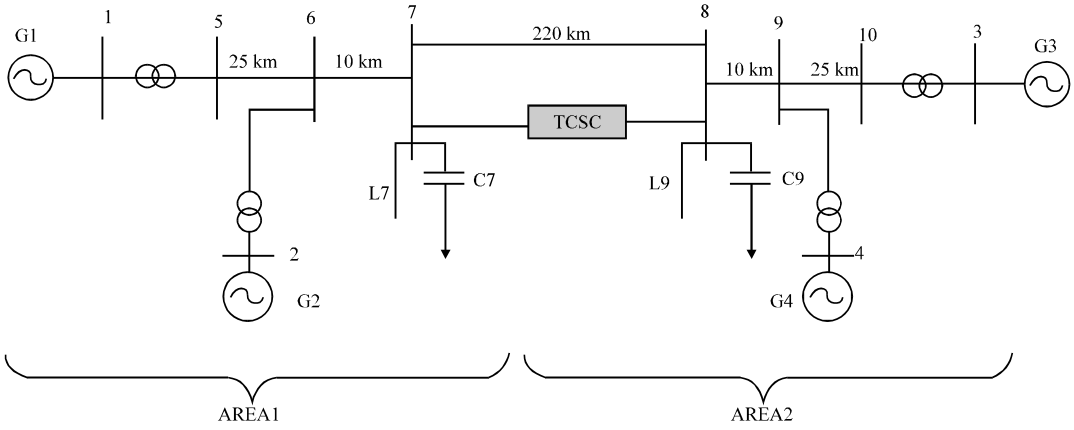

Fig. 2: Multi-machine power system with TCSC

TCSC MODELING AND BASIC CONTROL SCHEME

A typical TCSC module consists of a fixed series capacitor in parallel with a thyristor controlled reactor. The TCR is formed by a reactor in series with a bi-directional thyristor valve that is fired with a phase angle α ranging between 90 and 180 degrees with respect to the capacitor voltage. For the load flow and dynamic stability analysis studies, a TCSC can be modeled as a variable reactance. In this modeling approach, the effect of the FACTS devices on the power flow is represented as variable current injection at the terminal buses of the lines. The power injection varies with the FACTS control parameters (Zhou and Liang, 2002). The TCSC is assumed to be connected between buses *i* and *j* in a transmission line as shown in Fig. 3, where the TCSC is simplified like a continuously capacitive controllable reactance. From Fig. 3 we have:

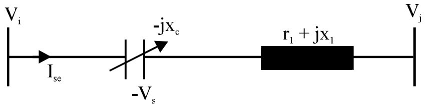

Fig. 3: TCSC located in a transmission line

$$I_{se} = \frac{V_i - V_j}{r_l + j(x_l - x_c)} \tag{6}$$

The influence of the capacitor is equivalent to a voltage source which depends on voltages V_i and V_j. The current injection model of the TCSC is obtained by replacing the voltage across the TCSC by an equivalent current source, I_s, in Fig. 4. In Fig. 3, V_s=-jx_cI_{se} and from Fig. 4, we have:

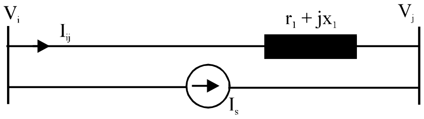

Fig. 4: Replacement of a voltage source by a current source

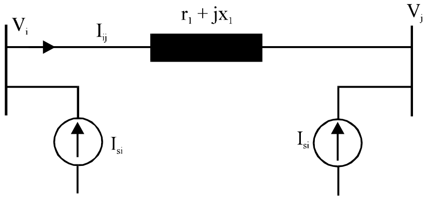

Fig. 5: Current injection model for a TCSC

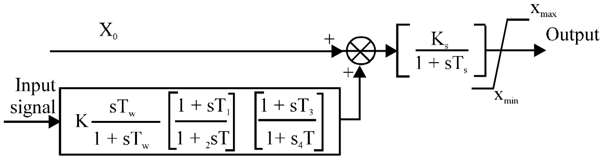

Fig. 6: Block diagram of the TCSC damping controller

$$I_s = \frac{V_S}{r_1 + jx_1} = \frac{-jx_c I_{se}}{r_1 + jx_1} \tag{7}$$

Current source model of the TCSC is shown in Fig. 5. Current injections into nodes i and j are calculated as follows:

$$I_{si} = \frac{jx_c}{r_1 + jx_1} \cdot \frac{V_i - V_j}{r_1 + j(x_1 - x_c)} = -I_{sj} \tag{8}$$

The structure of the TCSC based damping controller is shown in Fig. 6. This controller may be considered as a lead-lag compensator. It comprises gain block, signal-washout block and two stages of lead-lag compensator. Transmission line active power has been proposed as an effective input signal in (Dell Rosso *et al.*, 2003; Ishimaru *et al.*, 2002) for series FACTS devices damping controller design. For this reason, here, the active power of the transmission line is selected as the input signal. Where, X_0 is the impendence reference point determined by the higher level controller which is usually considered to be constant.

The output is the variable reactance of the TCSC. Time T_1 is a measurement time constant and T_w is the washout time constant. The time constant T_s represents the finite delay caused by the firing controls and the natural response of the TCSC.

DAMPING CONTROLLER DESIGN USING θ-PSO

Since the selection of the TCSC based damping controller parameters is a complex optimization problem. Thus, to acquire an optimal combination, this paper employs the θ-PSO algorithm to improve the optimization synthesis and find the global optimum value. In this study, an Integral of Time multiplied Absolute value of the Error (ITAE) is taken as the objective function which can be rewritten in the following form (Shayeghi *et al.*, 2010):

$$J = \int_0^{tsim} t.\ (|w_1 - w_2| + |w_1 - w_3| + |w_1 - w_4| + |w_3 - w_4|)\ dt \tag{9}$$

where, t_{sim} is the time range of the simulation. It is aimed to minimize this objective function in order to improve the system response in terms of the settling time and overshoots. The design problem can be formulated as the following constrained optimization problem, where the constraints are the POD controller parameter bounds:

Minimize JSubject to

$$K^{min} \le K \le K^{max}$$
$$T_1^{min} \le T_1 \le T_1^{max}$$
$$T_2^{min} \le T_2 \le T_2^{max}$$
$$T_3^{min} \le T_3 \le T_3^{max}$$
$$T_4^{min} \le T_4 \le T_4^{max}$$

In order to acquire better performance the input parameters that control the θ-PSO, i.e., number of particle, dimension size (D), the number of iteration, c_1 and c_2 is chosen as 40, 5, 80, 1.7 and 1.7, respectively. Results of the controller parameter set values based on the multi objective function for the operating condition as given in Table 1 using both the proposed θ-PSO method and CPSO method is listed in Table 1.

SIMULATION RESULTS

In any power system, the operating load varies over a wide range. It is extremely important to investigate the variation of the loading condition on the dynamic performance of the system. The operating conditions are given in Table 1.

To study the effectiveness and performance of the optimized controller, simulation studies are carried out under a wide range of loading conditions. Therefore, transient stability is verified by applying a 6-cycle three-phase fault at the middle of the transmission lines between bus-7 and bus-8. The fault is cleared without line

Table 1: Operating condition (pu) and optimal controller parameters

Operating condition	P_1	Q_1	P_2	Q_2	P_3	Q_3	P_4	Q_4
Case 1	0.7778	0.2056	0.5556	0.2611	0.8020	0.0697	0.8889	0.2244
Case 2	0.5556	0.2056	0.5556	0.2611	1.3739	0.1502	0.5556	0.2244
Case 3	0.9911	0.1722	0.9444	0.3944	0.0095	0.0712	1.1111	0.2222

Method	K	T_1	T_2	T_3	T_4
Optimal controller parameters					
CPSO	14	1.77	0.083	0.045	0.433
θ-PSO	28	0.911	0.327	0.028	0.092

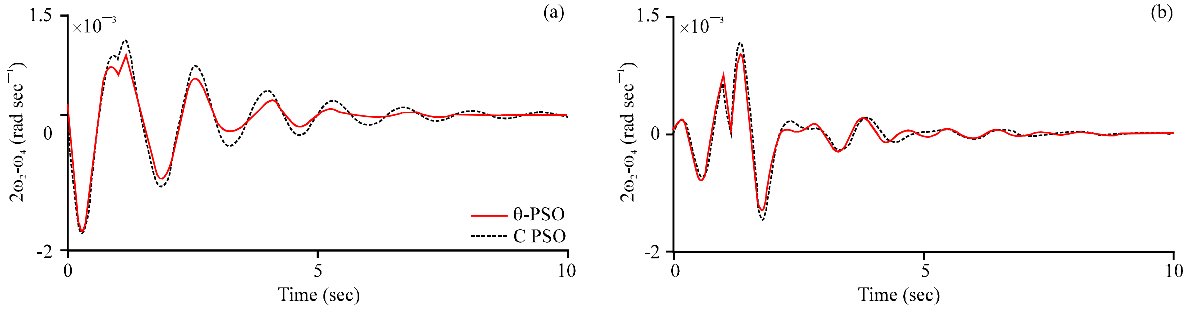

Fig. 7: Inter-area and local mode of oscillations for case 1. (a): ω_2-ω_4 (rad/sec), (b) ω_1-ω_2 (rad sec^{-1})

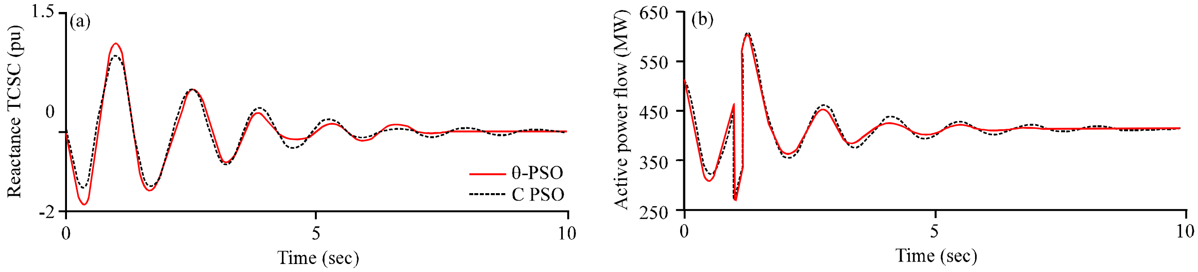

Fig. 8: Dynamics response of the system for case 1. (a): Deviation of TCSC reactance (pu), (b): Active power flow (MW)

tripping and the original system is restored upon the clearance of the fault. The inter-area and local mode of oscillations is shown in Fig. 7. The performance of the θ-PSO based damping controller is quite prominent in comparison with the CPSO based damping controller and the overshoots and settling time are significantly improved for the proposed method. This illustrates the potential and superiority of the proposed design approach to obtain an optimal set of TCSC damping controller parameters. Figure 8 shows the reactance of the TCSC and active power flow, respectively. It can be seen that the system response with the θ-PSO based damping controller settles faster and provides superior damping.

In order to test the effectiveness of the proposed controller, the same fault is simulated for the case 2 and case 3 loading conditions as given in Table 1. The responses are shown in Fig. 9 and 10. From these simulations, it is observed that the using the proposed controller damping of the low frequency oscillations is significantly improved.

To demonstrate the performance robustness of the proposed algorithm, two performance indices: the ITAE and Figure of Demerit (FD) indices based on the system performance characteristics are defined as:

$$\mathrm{ITAE} = 1000\int_0^{\mathrm{tsim}} t.\,(|\omega_1-\omega_2|+|\omega_1-\omega_3|+|\omega_1-\omega_4|+|\omega_3-\omega_4|)\,dt$$

$$\mathrm{FD} = (\mathrm{OS}\times 3000)^2 + (\mathrm{US}\times 3000)^2 + T_s^2 \tag{10}$$

where, ω is the speed rotor, Overshoot (OS), Undershoot (US) and settling time of $\Delta\omega_{13}$ of the system is considered for the evaluation of the ITAE and FD indices. It is worth mentioning that the lower the value of these indices is, the better the system response in terms of time-domain characteristics. Numerical results of proposed approach for all system loading cases are shown in Fig. 11 and 12. It can be seen that the values of these system

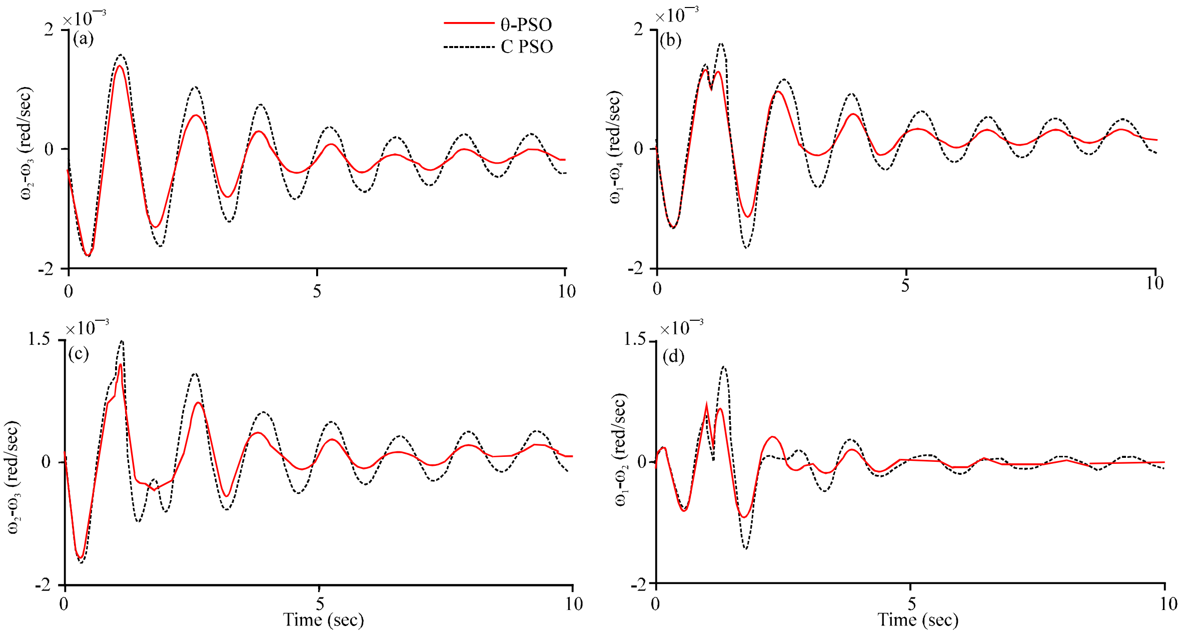

Fig. 9: Inter-area and local mode of oscillations for case 2. (a): ω_1-ω_3 (rad sec^{-1}), (b): ω_1-ω_4 (rad sec^{-1}), (c): ω_2-ω_3 (rad sec^{-1}) and (d): ω_1-ω_2 (rad sec^{-1})

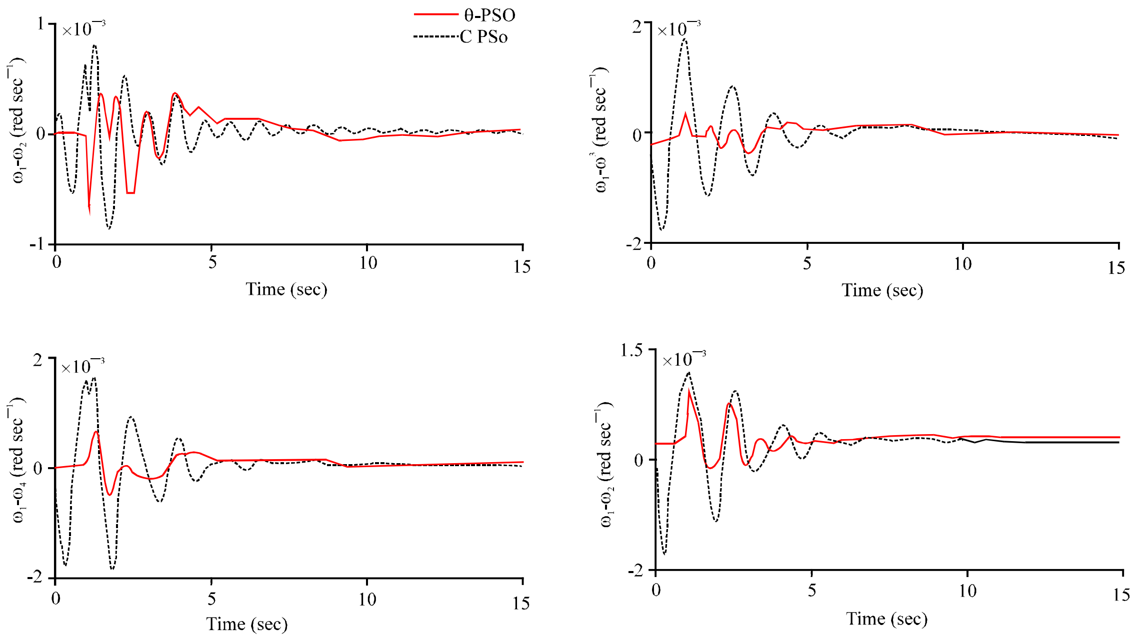

Fig. 10: Inter-area and local mode of oscillations for case 3.(a): ω_1-ω_2 (rad sec^{-1}), (b): ω_1-ω_2 (rad sec^{-1}), (c): ω_1-ω_4 (rad sec^{-1}), (d): ω_2-ω_4 (rad sec^{-1})

performance characteristics using the θ-PSO based tuned controller are much smaller compared to CPSO based tuned stabilizer. This demonstrates that the overshoot, undershoot, settling time and speed deviations of the all machine are greatly reduced by applying the proposed algorithm.

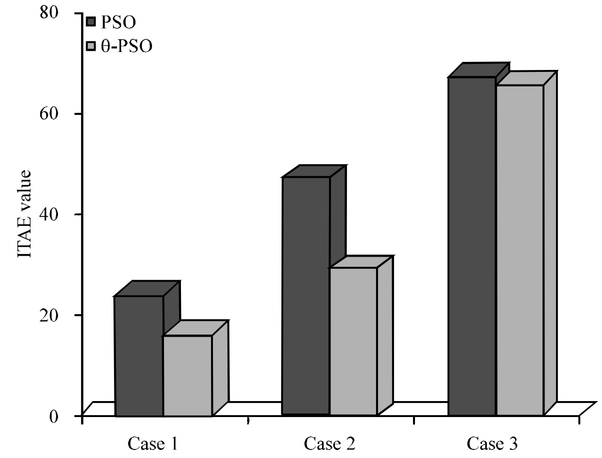

Fig. 11: Values of the performance index ITAE

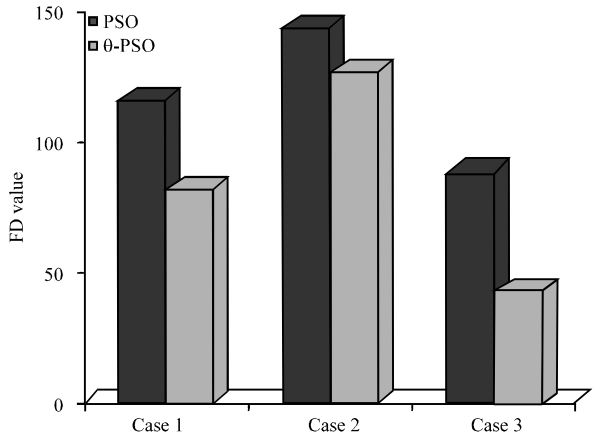

Fig. 12: Values of the performance index FD

CONCLUSIONS

In order to improve electromechanical oscillations in a multi-machine power system a simple and effective optimization algorithm which is solved using θ-PSO technique has been proposed for design of the TCSC damping controller. θ-PSO is a novel population based search technique and remarkably enhances the optimization performance. Also, it has stronger global search ability and more robust than PSO and other methods. The effectiveness of the proposed controller has been tested on a four-machine power system through the simulation studies under different operating conditions. Compared with the CPSO method the θ-PSO technique demonstrates its superiority in computational complexity, success rate and solution quality. The system performance characteristics in terms of 'ITAE' and 'FD' indices reveal that using the proposed θ-PSO based controllers, the overshoot, undershoot, settling time and power system inter-area oscillations are greatly reduced.

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