

Optimum Design of POD Controller for FACTS Device in Interconnected Power System

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Abstract

In this paper, a design method of the power oscillation damping (POD) controller for thyristor controlled series capacitor (TCSC) is presented so as to improve transient stability and dynamic performance of multi-machine power system. The design problem of the POD controller is converted to an optimization problem with the time domain-based objective function which is solved by a new simple strategy of PSO algorithm called using θ - Particle swarm optimization (θ -PSO) technique. The effectiveness of the proposed controller is demonstrated through the nonlinear time-domain simulation of over a wide range of loading conditions. The simulation results demonstrate that the controller may improve transient stability and dynamic performance of power systems significantly.

Keywords: *Thyristor Controlled Series Capacitor (TCSC), θ -PSO, Power Oscillation Damping, Power System Stability*

1. Introduction

A problem of interest in the power industry is the mitigation of power system oscillations. These oscillations are related to the dynamics of system power transfer and often exhibit poor damping [1].

Flexible AC transmission systems devices are one of the recent propositions to alleviate such situations by controlling the power flow along the transmission lines and improving power oscillations damping [2-3]. The use of these controllers increases the flexibility of the operation by providing more options to the power system operators. Amongst the available FACTS devices for transient stability enhancement, the TCSC is the most versatile one [4-6]. 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 [7].

Different control schemes for a TCSC such as variable structure controller, nonlinear predictive controller, H_∞ -based controller, and nonlinear adaptive control [8-11] were proposed. However, the parameters adjustments of these controllers need some trial and error procedure. Also, although using the robust control methods, the uncertainties are directly introduced to the synthesis, but due to the large model order of the power systems, the order resulting controller will be very large 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 POD controller structure [12]. Unfortunately, the problem of the conventional lead-lag POD controller design is a multimodal optimization problem (*i.e.*, there exists more than one local optimum).

Hence, the conventional 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. The PSO approach, first introduced by Kennedy and Eberhart in 1995, is a population based stochastic algorithm. Recently, the PSO technique is used for optimal tuning of the TCSC damping controller [10]. The PSO is a novel population based meta-heuristic, 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. This algorithm has also been found to be robust in solving problems featuring non-linearity, non-differentiability and high-dimensionality [11-13]. 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 this paper a new and simpler strategy PSO algorithm called θ -PSO [14] which is based on phase angle vector but not the velocity vector, is firstly applied for TCSC damping controller design problem in power systems. In θ -PSO, an increment of phase angle vector replaces velocity vector and the positions are adjusted by the mapping of phase angles. The problem of TCSC based POD 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 CPSO based POD controller through the nonlinear time simulation.

2. Review of the CPSO and θ -PSO Techniques

2.1 CPSO

The PSO is a population-based algorithm 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, the PSO works with a population of potential solutions rather than with a single individual [13]. In the PSO technique a number of simple entities and the particles are placed in the search space of some problem or function and each evaluates the objective function at its current location. Then, each particle determines its movement through the search space by combining some aspect of the history of its own current and best locations by those of other 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 [12].

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 position and the 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 fitness function, let us say the best position of each particle, which corresponds to the best fitness value ($pbest$) 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 ($gbest$), 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.

$$v_{id} = w \times v_{id} + c_1 \times r_1 \times (P_{id} - x_{id}) + c_2 \times r_2 \times (P_{gd} - x_{id}) \quad (1)$$

$$x_{id} = x_{id} + v_{id} \quad (2)$$

Where, P_{id} and P_{gd} are $pbest$ and $gbest$. 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 $pbest$ and $gbest$, respectively. Variable r_1 and r_2 are random functions based on uniform probability distribution functions in the range $[0, 1]$. The inertia weight w 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. The following inertia weight is used in Eq. (1):

$$w = w_{max} - \frac{w_{max} - w_{min}}{iter_max} \cdot iteration \quad (3)$$

Where, $iter_max$ is the maximum number of iterations and $iteration$ is the current number of iteration. The Equation (3) presents how the inertia weight is updated, considering w_{max} and w_{min} are the initial and final inertia weights, respectively.

2.2 θ -Particle Swarm Optimization

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 . It 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 $\Delta\theta$ and its position decided by a mapping function [14]. By considering the mentioned differences equations (1) and (2) are modified and the particles move according to the following iterative equations. The θ -PSO can be described with the following equations.

$$\Delta\theta_{id}(t+1) = w \times \Delta\theta_{id}(t) + c_1 r_1 (\theta p_{id} - \theta_{id}(t)) + c_2 r_2 (\theta g_{gd} - \theta_{id}(t)) \quad (4)$$

$$\theta_{id}(t+1) = \theta_{id}(t) + \Delta\theta_{id}(t+1) \quad (5)$$

$$x_{id}(t) = f(\theta_{id}(t)) \quad (6)$$

$$F'_i(t) = fitness\ value(x_i(t)) \quad (7)$$

With $\theta_{id} \in (\theta_{min}, \theta_{max})$, $\Delta\theta_{id} \in (\Delta\theta_{min}, \Delta\theta_{max})$, $x_{id} \in (x_{min}, x_{max})$ and f is being a monotonic mapping function. In this paper,

$$\theta_{id} \in (-\pi/2, \pi/2), \Delta\theta_{id} \in (-\pi/2, \pi/2)$$

$$f(\theta_{id}) = \frac{x_{max} - x_{min}}{2} \sin \theta_{id} + \frac{x_{max} + x_{min}}{2} \quad (8)$$

Where $d=1, 2, \dots, D$; $i=1, 2, \dots, S$; the $D, S, c_1, c_2, w, r_1, r_2$ and $x_i(t)$ are the same as those in equations (1) and (2). The $\theta_i(t)$ is the phase angle of particle i th at time t ; the $\Delta\theta_i(t)$ is the increment of particle i th phase angle at time t ; $\theta p_i(t)$ is the phase angle of the personal best solution of particle i th at time t ; $\theta g_g(t)$ is the phase angle of global best solution at time t ; $F'_i(t)$ is the fitness value of particle i th at time t which is identified by the function fitness value. The procedure of the θ -PSO can be summarized as following:

Initialize a population with random phase angle $\theta_i(t)$ and the increment of the phase angle $\Delta\theta_i(t)$;

Repeat $t=1, 2, \dots, t_{max}$;

For each particle $i=1, 2, \dots, S$

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 $F'_i(t) < F'_{pi}(t)$

$F'_{pi}(t) = F'_i(t); \theta_{pi}(t) = \theta_i(t);$

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;

The $F'_{pi}(t)$ is the personal best fitness value of particle i^{th} at time t and $F'_g(t)$ is the global best fitness value at time t .

3. Case Study System

A four-machine, two-area study system, shown in Figure 1, 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.

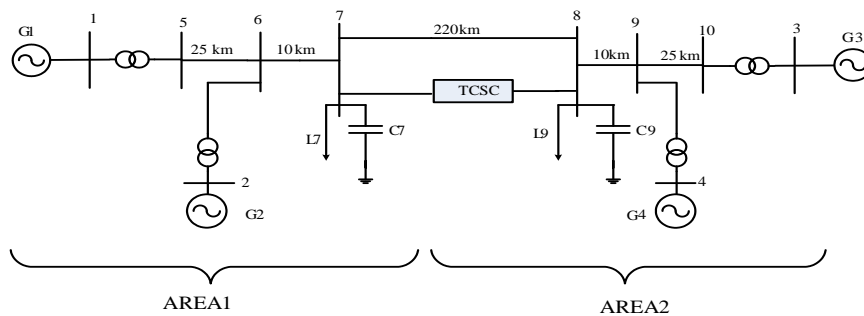


Figure 1. Multi-machine power system with TCSC

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 in [15]. A first order model of a static type automatic voltage regulator was used, and its block diagram is shown in [15].

3.1 TSCS Modeling

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 [16].

The TCSC is assumed to be connected between buses i and j in a transmission line as shown in Figure 2, where the TCSC is simplified like a continuously capacitive controllable reactance. From Figure 2 we have:

$$I_{se} = \frac{V_i - V_j}{r_l + j(x_l - x_c)} \quad (9)$$

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 Figure 3. In Figure 3, $V_s = -jx_c I_{se}$, and from Fig. 2, we have:

$$I_s = \frac{V_s}{r_l + jx_l} = -\frac{jx_c I_{se}}{r_l + jx_l} \quad (10)$$

Current source model of the TCSC is shown in Figure 4. Current injections into nodes i and j are calculated as follows:

$$I_{si} = \frac{jx_c}{r_l + jx_l} \cdot \frac{V_i - V_j}{r_l + j(x_l - x_c)} = -I_{sj} \quad (11)$$

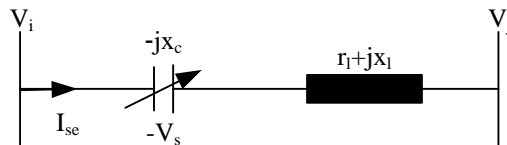


Figure 2. TCSC located in a transmission line

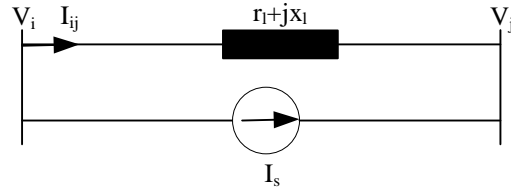


Figure 3. Replacement of a voltage source by a current source

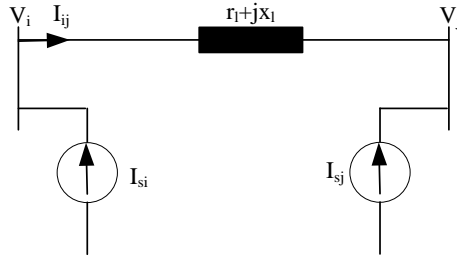


Figure 4. Current injection model for a TCSC

3.2 POD Controller

The POD controller is designed to produce an electrical torque in phase with the speed deviation according to the phase compensation method. The structure of the TCSC based damping controller is shown in Figure 5. This controller may be considered as a lead-lag compensator. It comprises gain block, signal-washout block and two stages of lead-lag compensator. The parameters of the damping controller are obtained using the θ -PSO algorithm. Transmission line active power has been proposed as an effective input signal in [4-5] 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 impedance reference point determined by the higher level controller, which is usually considered to be constant.

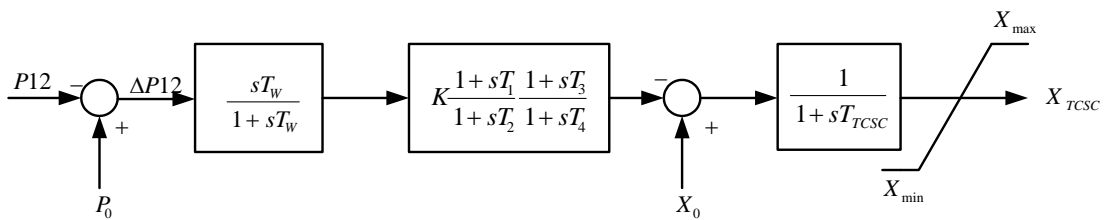


Figure 5. Block diagram of the POD controller

3.3 θ -PSO Based POD Controller

Since the selection of the TCSC based POD 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 ITAE is taken as the objective function can be rewritten in the following form [10]:

$$J = \int_0^{t_{sim}} t. (|w_1 - w_2| + |w_1 - w_3| + |w_1 - w_4| + |w_3 - w_4|) dt \quad (12)$$

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 J Subject to

$$K^{\min} \leq K \leq K^{\max}$$

$$T_1^{\min} \leq T_1 \leq T_1^{\max}$$

$$T_2^{\min} \leq T_2 \leq T_2^{\max}$$

$$T_3^{\min} \leq T_3 \leq T_3^{\max}$$

$$T_4^{\min} \leq T_4 \leq T_4^{\max}$$
(13)

Table 1. The Three Operating Loading (pu)

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

Table 2. Optimal Parameter

Type of algorithm	K	T ₁	T ₂	T ₃	T ₄
CPSO	14	1.77	0.083	0.045	0.433
θ -PSO	28	0.911	0.327	0.028	0.092

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 using both the proposed θ -PSO method and CPSO method are given in Table 1. The process of optimal tuning of the POD controller parameters using the proposed algorithm is shown in Figure 6.

4. Nonlinear Time-Domain Simulation

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 2.

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 tripping and the original system is restored upon the clearance of the fault. The inter-area and local mode of oscillations is shown in Figure 7, respectively. The performance of the θ -PSO based damping controller is quite prominent in comparison with the CPSO based damping controller [10] and the overshoots and settling time are significantly improved for the proposed method.

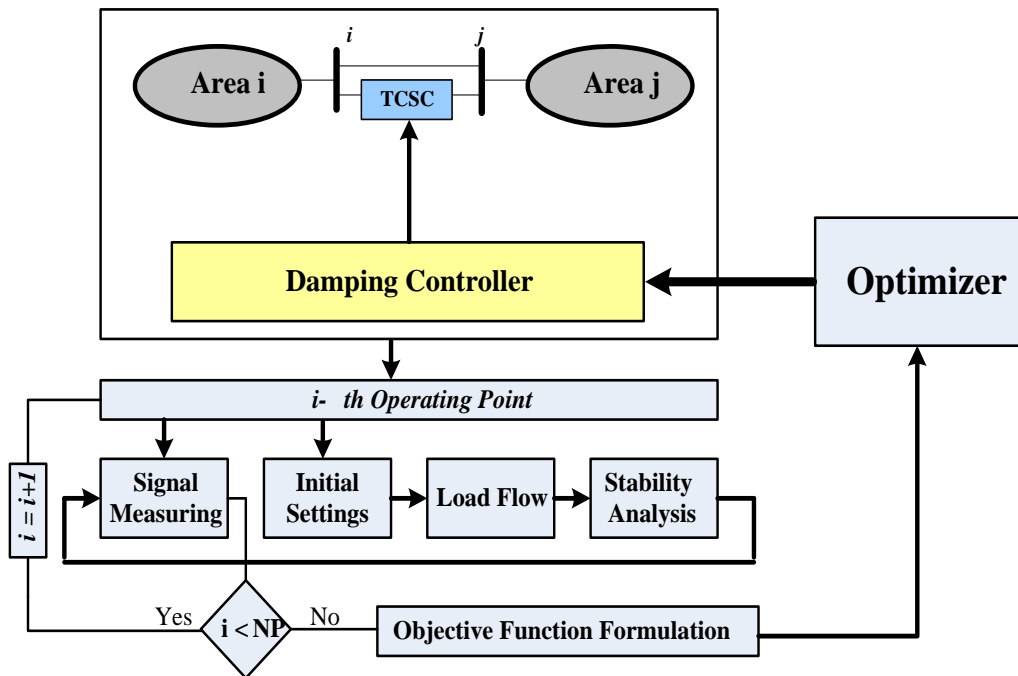


Figure 6. The process of optimal POD controller

In order to test the effectiveness of the proposed controller, the same fault is simulated for a case 2 and case 3. The responses are shown in Figure 8. From these simulations, it is observed that the proposed controller performs significantly in damping low frequency oscillations.

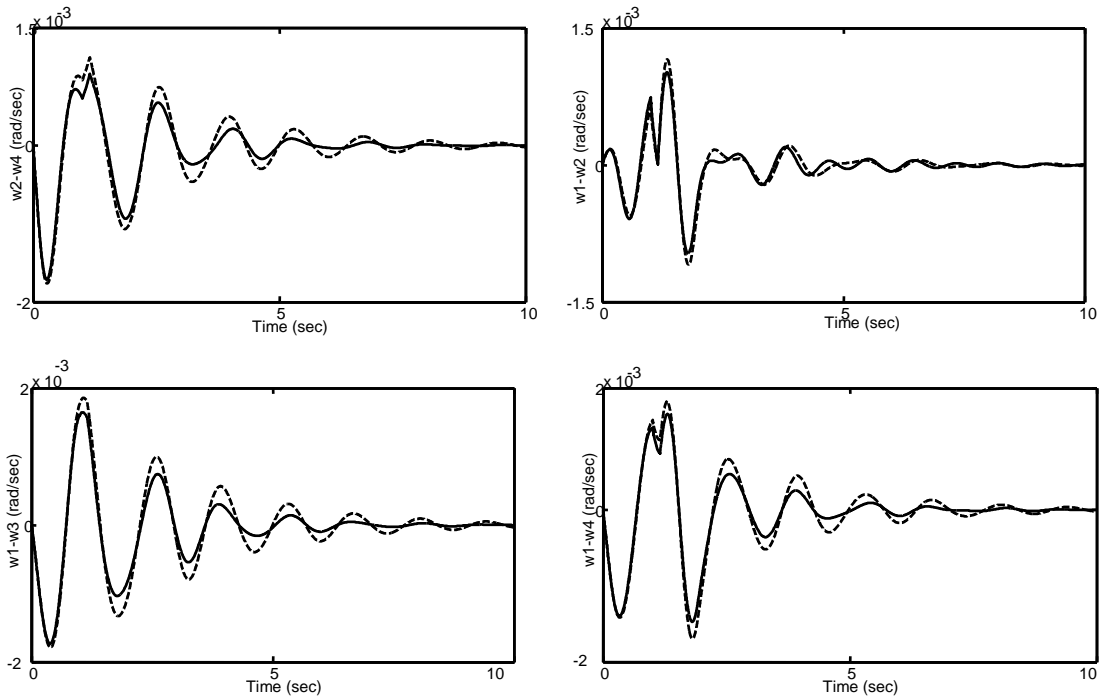


Figure 7. Inter-area and local mode of oscillations for case 1: Solid (θ -PSO) and Dashed (CPSO [10])

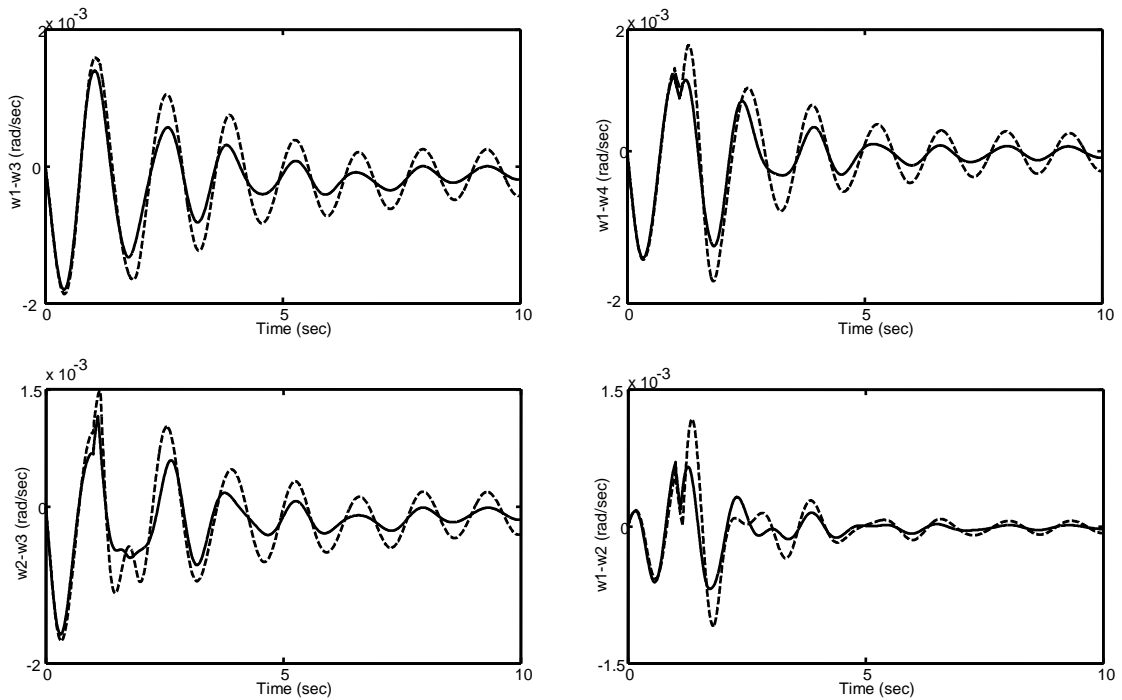


Figure 8. Inter-area and local mode of oscillations for case 2: Solid (θ -PSO) and Dashed (CPSO [10])

5. Discussion

The principles of the proposed method and simulation results have the following essential features:

1. The analysis presents the signals to be used and the optimal parameters within a unified framework. The stabilizing signals used have to be only locally available measurements.
2. The location of the TCSC damping controller is crucial for the damping of a particular inter-area mode, however, damping of other swing modes is also improved but it may not be significant. Thereby, it is best to place a damping controller at a location that all the critical inter-area modes can be damped out.
3. The results obtained show that the TCSC has better oscillations damping characteristics, hence making these types of controllers a competitive alternative against available series controllers for dynamic series compensation of transmission systems.

6. Conclusions

This paper has proposed a simple and effective optimization algorithm to design a POD controller for the TCSC series FACTS device in order to improve electromechanical oscillations in a multi-machine power system. Therefore, controller design problem is formulated as a constrained optimization problem according to the time domain-based objective function which is solved using θ -PSO technique remarkably enhances the optimization performance. The effectiveness of the proposed controller has been tested on a four-machine power system through the simulation studies under different operating conditions. Simulations showed that the proposed method led automatically to an improvement of the damping characteristic under different operating conditions.

References

- [1] R. A. Ramos, A. C. P. Martins and N. G. Bretas, "An improved methodology for the design of power system damping controllers", *IEEE Trans, Power Syst*, vol. 20, no. 4, (2005), pp. 1938-1945.
- [2] P. K. Dash, S. Morris and S. Mishra, "Design of a nonlinear variable gain fuzzy controller for FACTS devices", *IEEE Trans, Control Syst Technology*, vol. 12, no. 3, (2004), pp. 428-438.
- [3] N. G. Hingorani and L. Gyugyi, "Understanding FACTS: concepts and technology of flexible AC transmission systems", Wiley-IEEE Press, (1999).
- [4] Y. H. Song and A. T. Johns, "Flexible ac transmission systems (FACTS)", UK: IEE Press; (1999).
- [5] A. D. Dell Rosso, C. A. Canizares and V. M. Dona, "A study of TCSC controller design for power system stability improvement", *IEEE Trans. Power Syst.*, vol. 18, no. 4, (2003), pp. 1487-1496.
- [6] D. Jovcic and G. N. Pillai, "Analytical modeling of TCSC dynamics", *IEEE Trans. Power Deliv.*, vol. 20, no. 2, (2005), pp. 1097-1104.
- [7] D. Chatterjee and A. Ghosh, "TCSC control design for transient stability improvement of a multimachine power system using trajectory sensitivity", *Elec. Power Syst. Res.*, vol. 77, (2007), pp. 470-483.
- [8] T. GT and T. SK, "Refinement of conventional PSS design in multimachine system by modal analysis", *IEEE Trans PWRs*, vol. 8, no. 2, (1993), pp. 598-605.
- [9] M. A. Abido, "Pole placement technique for PSS and TCSC based stabilizer design using simulated annealing", *Elect Power Energy Syst.*, vol. 22, (2000), pp. 543-554.

- [10] H. Shayeghi, H. A. Shayanfar, S. Jalilzadeh and A. Safari, "TCSC Robust Damping Controller Design Based on Particle Swarm Optimization for a Multi-Machine Power System", *Energy Conver. Manage.*, vol. 51, (2010), pp. 175-184.
- [11] H. Shayeghi, H. A. Shayanfar, S. Jalilzadeh and A. Safari, "Design of output feedback UPFC controllers for damping of electromechanical oscillations using PSO", *Energy Coners Manage*, vol. 50, (2009), pp. 2554-2561.
- [12] H. Shayeghi, H. A. Shayanfar, S. Jalilzadeh and A. Safari, "A quantum particle swarm optimizer for the tuning of Unified Power Flow Controller", *Energy Conver. Manage.*, vol. 51, (2010), pp. 2299-2306.
- [13] T. K. Das, G. K. Venayagamoorthy and U. O. Aliyu, "Bio-inspired algorithms for the design of multiple optimal power system stabilizers: SPPSO and BFA", *IEEE Trans. Ind Appl*, vol. 44, no. 5, (2008), pp. 1445-1457.
- [14] W. Zhong, S. Li and F. Qian, " θ -PSO: a new strategy of particle swarm optimization", *J. Zhejiang Univ. Sci.*, vol. 9, no. 6, (2008), pp. 786-790.
- [15] P. Kundur, "Power system stability and control", New York: McGrew Hill, (1994).
- [16] R. Sadikovic, "Damping controller design for power system oscillations", Internal Report, Zurich, (2004).

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