

MISO Damping Controller Design for a TCSC using Particle Swarm

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Abstract

This paper presents a new approach for designing multi-input-single-output (MISO) damping controller for a TCSC in a multi-machine power system. The damping controller design uses particle swarm optimization (PSO) to determine the coefficients of single or multi-stage lead-lag compensators. The classical technique works well in the design of lead-lag compensators for SISO controllers. But, there is no proper step-by-step procedure to achieve the desired performance characteristics for a MISO controller. Hence, in this paper, a computational optimization tool has been used to determine the optimal gains and time constants of a linear MISO damping controller. The damping controller is implemented for a TCSC on a multi-machine multi-modal power system and has shown considerable improvement in minimizing system oscillations.

Introduction

In the modern world, power system grids are interconnected with numerous buses and transmission lines. The existing network is in operation for decades without major additions in generation or transmission capacity. But the consumption is ever increasing. Among many problems like increase in transmission bottlenecks, loop-flows, suboptimal utilization of capacity; an issue of concern is inadequate damping of electro-mechanical slow frequency modes of a system. After the advent of Flexible AC transmission System (FACTS) [1], different shunt and series FACTS devices have been under study and implementation for alleviating different emerging problems of the stressed network. Shunt FACTS devices like Static Synchronous Compensator (STATCOM), Static Var Compensator (SVC) has been used for voltage and reactive power compensation. Series FACTS devices like Thyristor-Controlled Series Compensator (TCSC), Static Synchronous Series Compensator (SSSC) have been used mostly for real power flow control. But, several researchers have shown that an auxiliary benefit in terms

of improvement in damping of system modes can be obtained from the series and shunt FACTS devices with appropriate control action. For that, an auxiliary damping controller is needed.

Several publications have presented different techniques for local and wide area damping controller designs from classical lead-lag compensator to advanced H^∞ controllers [2-5]. The lead-lag compensator based designs using pole placement or root locus technique are quite effective for single input single output (SISO) controllers. But multi-input-single-output (MISO) and multi-input-multi-output (MIMO) controllers are not straight-forward to design using lead-lag compensators with classical techniques. With the associated improvements, advanced techniques have its higher cost of design and implementation. According to most researchers, there is a trade off between the cost of design and implementation and the performance of the controller. Hence, an easy to design controller with an acceptable performance can be more attractive than a complex controller with slightly better performance.

This paper presents a new approach for designing multi-input-single-output (MISO) damping controller for a TCSC in a multi-machine power system. A simple lead-lag compensator based control architecture has been designed using pole-placement and a fast and effective optimization tool, Particle Swarm Optimization (PSO) [6]. After the proposition of the basic PSO algorithm by Eberhart and Kennedy, different modifications and hybrids have been reported in later years. But, the original PSO algorithm has been found quite effective in finding optimal solutions i.e. minima or maxima for given objective functions in most of the problems [7]. Hence, this paper has used the original version of the PSO algorithm to optimize the gains and time constants of the lead-lag damping controller for a TCSC installed in a large multi-modal power system. To verify the feasibility of the PSO-based optimization techniques, a state-feedback controller is also designed using PSO. Both

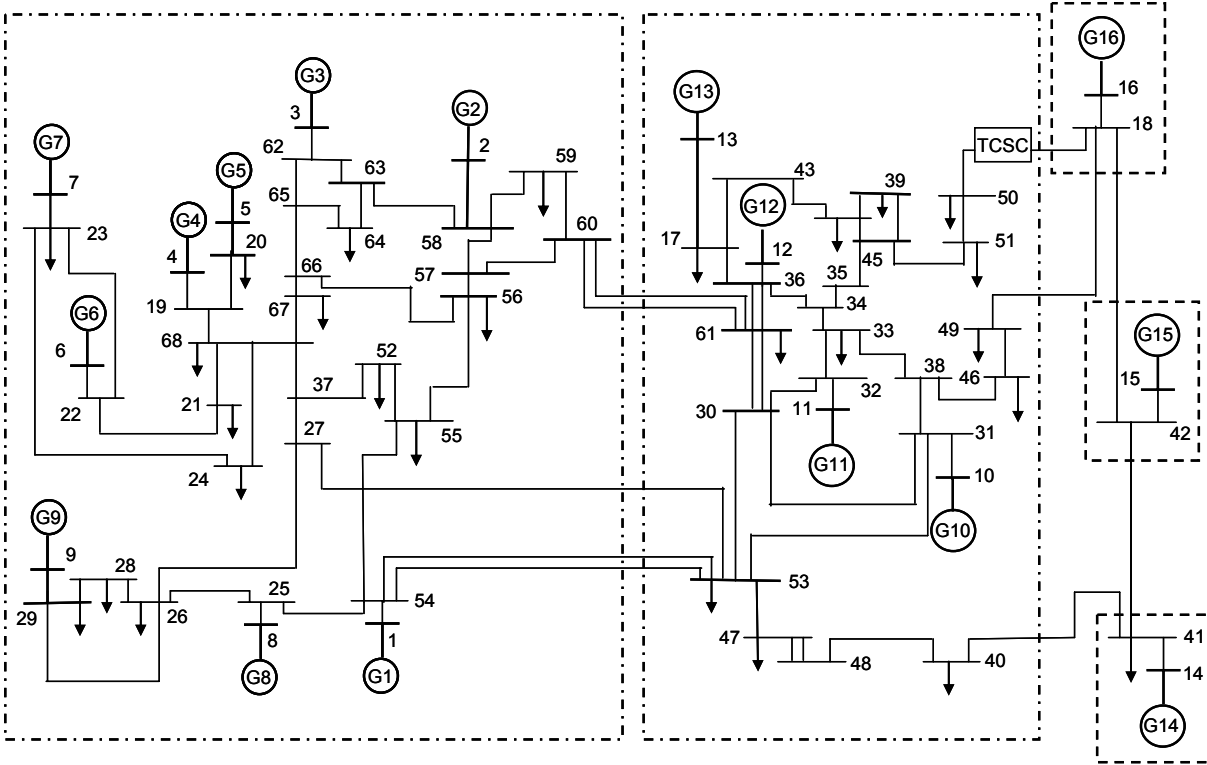


Fig. 1 16-machine 68-bus system with a TCSC.

controller designs and implementation results are presented and compared in this paper.

Multi-machine Power System

The test system used in this paper is a 16-machine 68 bus power system [4-5], shown in Fig. 1. This is a reduced order equivalent of the interconnected New England Test System (NETS) and New York Power System (NYPS). There are five geographical regions. NETS and NYPS are represented by groups of generators and other three neighboring regions are approximated by equivalent generator models. Generators G1 to G9 represent the generation of the NETS and G10 to G13 represent the generation of the NYPS. G14 to G16 are the equivalent of other three areas. There are three major transmission corridors between NETS and NYPS through double circuit tie-lines connecting buses 60 – 61, 53 – 54 and 27 – 53. The NYPS is required to import 1500 MW from Area 5. To facilitate the large amount of power transfer between these two areas, a series connected FACTS device like TCSC is connected in the line between buses 18 and 50.

In this paper, a damping controller is designed to enhance damping of the three inter-area modes (0.39 Hz, 0.50 Hz and 0.62 Hz) present in the system with the TCSC. The choice of measurement signals are chosen based on the

modal controllability, observability and residue analysis detailed in [5]. The highest residues were found for line flows P_{51-45} , P_{18-16} and P_{13-17} corresponding to 0.39 Hz, 0.50 Hz and 0.62 Hz respectively. Hence, these measurements are used as inputs to the controller in this paper.

Damping Controller Design

Lead-Lag Damping Controller:

The damping controller is designed to provide additional damping to system inter-area modes using a TCSC. Three remote measurements are inputs to the controller and one output is the percentage compensation of the TCSC. The simplest conventional damping controller comprises of one low pass filter (time constant = 0.01s), one washout filter (Time constant = 10 s) and two identical lead-lag blocks in series to provide the output signal corresponding to each input. The lead-lag time constants T_1 to T_6 and gains K_1 to K_3 are optimized using the PSO algorithm. Three outputs of three such control blocks are summed to yield final control signal. The damping controller block diagram is given in Fig. 2.

State-feedback Damping Controller:

An observer-based state-feedback design is also implemented for the MISO damping control using PSO. The block diagram of the observer-based state-feedback controller is shown in Fig. 3. A 10th order reduced linear

model of the closed loop system is used for the state-feedback design. The controller gain K is a 10×10 matrix whose elements are optimized using the PSO algorithm. The observer gain L is calculated with a desired pole location of 10 times the desired closed loop system poles. L is 3×10 matrix.

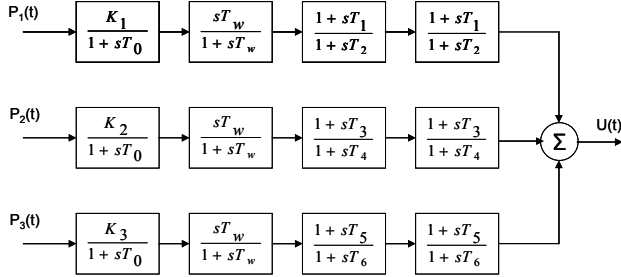


Fig. 2 Block diagram of MISO damping controller with lead-lag compensators.

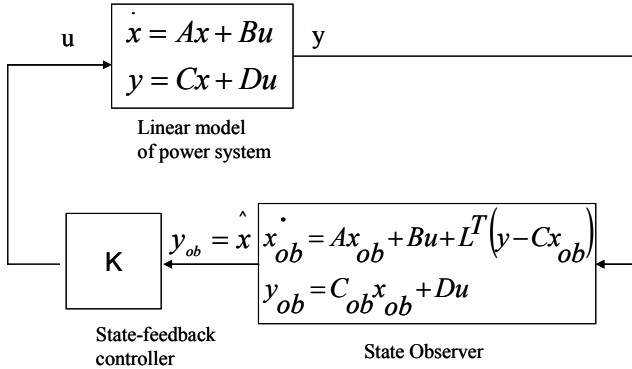


Fig. 3 Block diagram of state-feedback controller.

As the design relies on the linear model analysis, the closed loop eigenvalues are calculated for each set of parameters. The objective function or performance index (which is a function of different criteria such as damping ratio, negative real part of eigenvalues etc) is evaluated and PSO equations (1) and (2) are implemented to update the parameters in each particle. This update procedure is continued until the fitness of the candidate solutions becomes small enough and it does not change significantly with iterations. The complete procedure is presented with the help of flowchart (Fig. 4).

PSO Optimization of Linear MISO Controller

Particle swarm optimization is a guided random search technique [5]. This is an effective optimization tool for continuous and discrete objective functions. Initially, the particles consisting of the parameters to be optimized are given random position and velocity and during optimization, they are updated using (1) and (2).

$$V_i(k+1) = wV_i(k) + c_1 \cdot rand \cdot (P_{ibest}(k) - P_i(k)) + c_2 \cdot rand \cdot (G_{best}(k) - P_i(k)) \quad (1)$$

$$P_i(k+1) = P_i(k) + V_i(k+1) \quad (2)$$

Here, V_i and P_i are the velocity and position of particle I respectively. w , and c_1 and c_2 are the inertia weight, and cognitive and social components of acceleration respectively. P_{ibest} is the best position found by i^{th} particle, G_{best} is the global best found by all particles. The optimal solution is obtained when the fitness of G_{best} is less than the tolerance or the fitness does

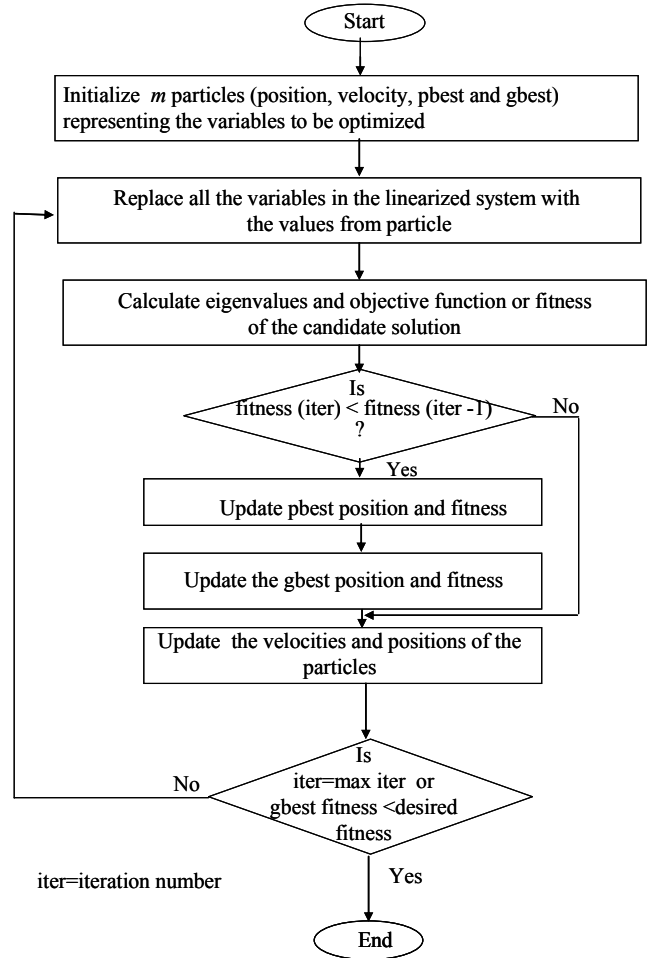


Fig. 4 Flowchart for PSO based linear control design.

not change for significant number of iterations. PSO parameters w , c_1 and c_2 are selected as 0.8, 2.0 and 2.0 respectively[5].

The optimization of the linear controller is carried out by proper placement of poles or eigenvalues of the linearized closed loop system. The objective function to be minimized is given in (3),

$$PI = \alpha PI_1 + (1 - \alpha) PI_2 \quad (3)$$

where,

$$PI_1 = \left(\sum_{i=1}^m (\xi_{0i} - \xi_i)^2 \right) \quad (4)$$

$$PI_2 = \sum_{i=1}^m (\sigma_{0i} - \sigma_i)^2 \quad (5)$$

and ξ and σ are the damping ratio and real part of the eigenvalues respectively within the range of frequencies of interest. The objective function is selected to shift the critical mode (eigenvalues or poles) inside the conic section defined by the real part and damping ratio. After a few iterations, the choice of ξ_0 and σ_0 as 0.3 and -1.0 respectively, provided the best performance. For slow mode of oscillation, the frequency range is typically between 0.2 to 3.0 Hz. α is a weighting factor and it has been seen that a value of 0.08 to 0.2 is best suited for damping inter-area modes. A large penalty is added with the objective function if any eigenvalue lies in the right half of the complex plane. This helps in faster convergence.

For the design of the lead-lag based MISO damping controller, 20 different solutions candidates are chosen randomly for the first PSO iteration. After, 500 iterations the best fitness does not change significantly any more. The corresponding parameters are selected for the lead-lag controller gains and time constants.

For the state-feedback controller design, due to large number of parameters to be optimized, 35 particles or candidate solutions are chosen randomly at the starting PSO iteration. After 800 iterations, the best fitness value stabilizes and corresponding parameters are used for the optimized gain matrix (K) of the controller.

Application and Results

The proposed method for a MISO damping controller design is implemented on a 68-bus NETS-NYPS interconnected power system with a TCSC in line 18-50 [4]. The real power flow of three different lines 51-45, 18-16 and 13-17 are used as inputs to the damping controller due to the predominant existence of inter-area modes in those signals. A single stage lead-lag damping controller (Fig. 2) is developed by optimizing 9 parameters (K_1 to K_3 and T_1 to T_6) using PSO. Several case studies are reported in this paper as given below.

Case Study 1: A 3- Φ line to ground fault at bus 60 is simulated for 80 ms and the fault is cleared by opening line 60-61 with auto-reclosing. Fig. 5 shows the oscillations of rotor angles between generators G1 - G15 and G16 - G13. The PSO based optimization shows good damping performance with the proposed MISO damping controller for both lead-lag and state-feedback type design. The order of the state feedback controller is the same as that of the reduced system, 10 in this case. Fig. 6 shows the control signals for both lead-lag and state-feedback controller. The state-feedback controller shows greater excursion of control signal compared to the lead-lag controller.

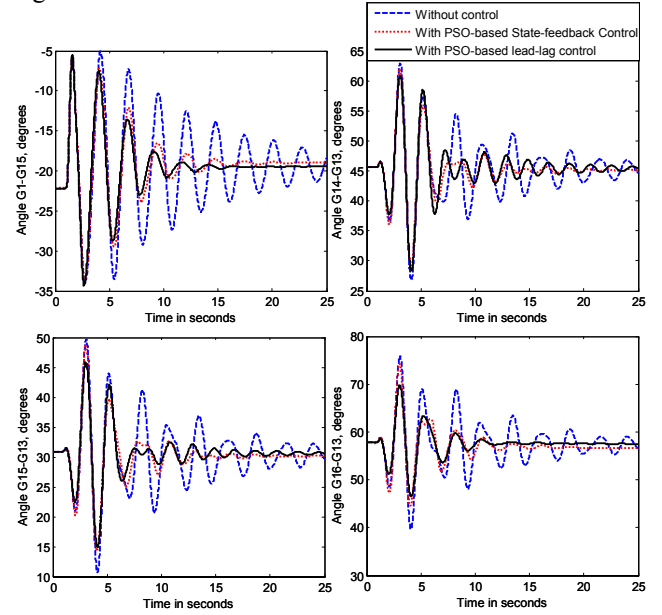


Fig. 5 Generator angle oscillation for case study 1.

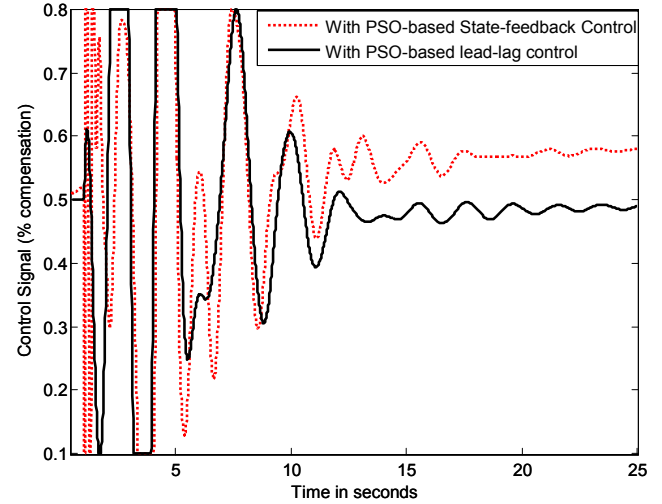


Fig. 6 Control signal for case study 1.

Case Study 2: A 3- Φ short circuit is applied at bus 53 for a duration of 5 cycles (80ms) and cleared by opening line 27 - 53. Fig. 7 shows generator angle differences. The

proposed PSO-based lead-lag controller exhibits good performance in minimizing both overshoot and settling time with less control effort than the PSO-based state-feedback controller. The control efforts are shown in Fig. 8.

Case study 3: To observe the robustness of such design with linear controller, a 3- Φ line to ground short circuit at bus 27 is simulated and the fault is cleared by opening line 27-53 after 80 ms thus creating a change in the post-fault topology of the system. Fig. 9 shows generator angle differences with different modal oscillations. Though both PSO-based lead-lag and state-feedback controller show improved damping for all three inter-area modes which are least damped in the open loop system, the control effort is minimum for the lead-lag controller. Fig. 10 shows the control signals of the two controllers.

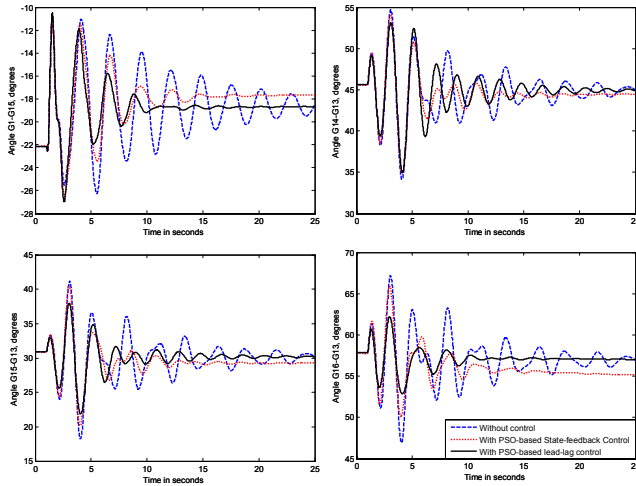


Fig. 7 Generator angle oscillations for case study 2.

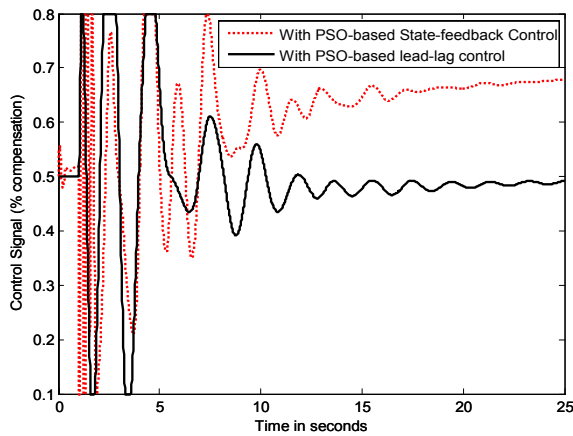


Fig. 8 Control signal for case study 2.

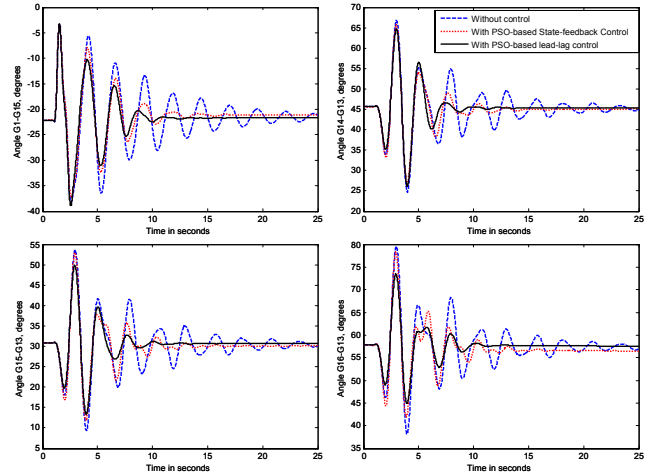


Fig. 9 Generator angle oscillations for case study 3.

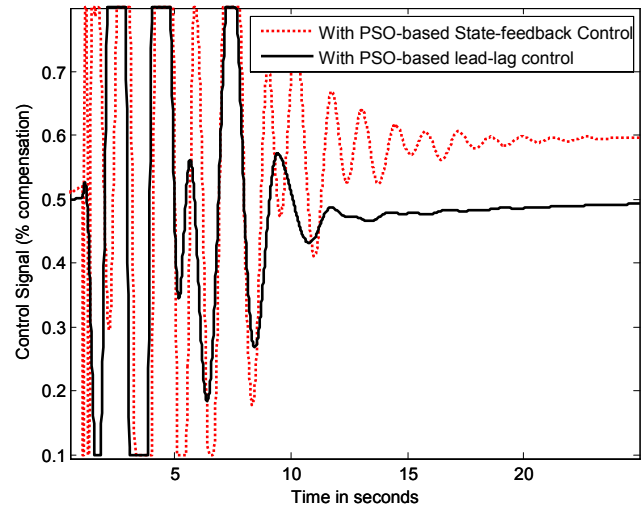


Fig. 10 Control signal for case study 3.

Case study 4: In a more severe contingency, where a 3- Φ line to ground short circuit at bus 40 is simulated and the fault is cleared by opening line 40-41 after 80 ms, Fig. 11 shows generator angle differences with different modal oscillations. PSO-based lead-lag controller shows superior damping compared to the PSO-based state-feedback controller. The overshoot and settling time both are minimized with the use of proposed PSO-based lead-lag controller. On the other hand PSO-based state-feedback controller performance degrades as the topology of the system is changed significantly. The control effort is minimum for the PSO-based lead-lag controller as seen from Fig. 12. The state-feedback controller signal hits the minimum limit and does not provide any contribution for damping. Hence, it can be inferred that the lead-lag controller shows more robustness compared to the state-feedback controller though they are trained with the same design methodology.

Eigenvalue Analysis

An eigenvalues analysis is also carried out for the open loop system and the closed loop system with two types of controller as designed in this study. The eigenvalues are calculated from the linearized model of the open loop and closed loop system using 'linmod' command in the MATLAB/SIMULINK environment. Fig. 13 presents the pole locations for the open loop system and closed loop system with PSO-based lead-lag controller. Fig. 14 shows the pole locations of open loop system and closed loop system with PSO-based state-feedback controller. There are observable differences for the two designs regarding pole-placement. The PSO-based design does not directly specify the pole locations, instead it tries to optimize certain objective function chosen by the designer. Though the objective functions are chosen similarly for both types of controller design, the PSO-based lead-lag controller moves more number of inter-area modes further in the left half of imaginary plane than the PSO-based state-feedback design. This is mostly due to the observer involved in the state-feedback controller whose poles are chosen to be 10 times the intended closed loop poles of the system.

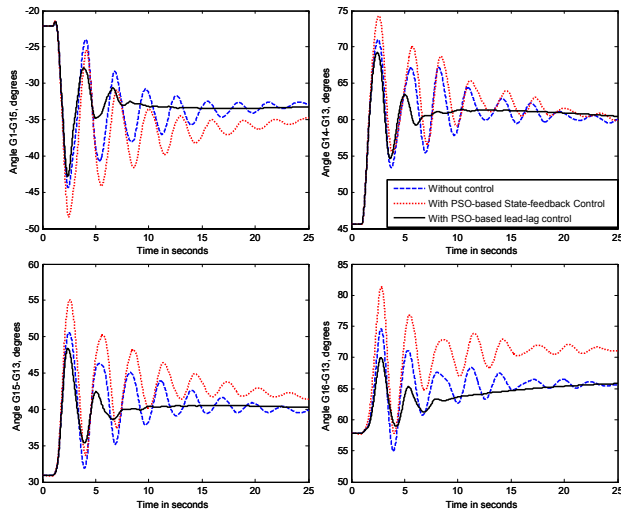


Fig. 11 Generator angle oscillations for case study 4.

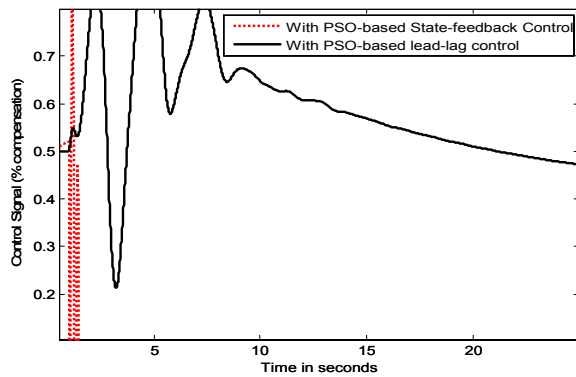


Fig. 12 Control signal for case study 4.

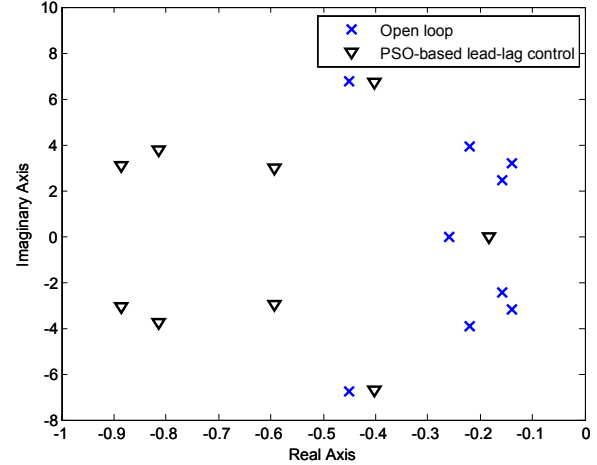


Fig. 13 Pole locations of open loop system and closed loop system with PSO-based lead-lag controller.

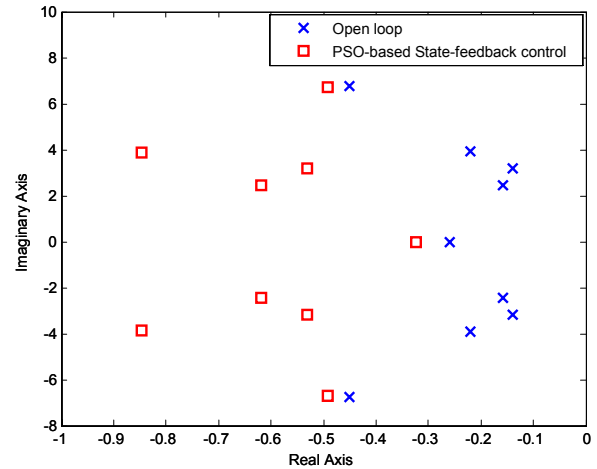


Fig. 14 Pole locations of open loop system and closed loop system with PSO-based state-feedback controller.

Conclusion

This paper has proposed a simple and effective optimization tool to design a linear MISO damping controller for improving modal oscillations in a large multi-modal power system. For a MISO controller design using classical technique, most convenient but simple approach is the observer-based state-feedback design. But, order of the controller is the same as that of the system and practical implementation can be a concern even if a reduced equivalent of a large system is used for design. Moreover, the control effort is not optimized, asking for larger excursion of the actuator output (FACTS device rating) to achieve the same performance. The design methodology of a SISO controller with lead-lag compensators is well established. But conventional techniques are not convenient for MISO or MIMO controller designs with multiple lead-lag blocks in parallel. The novelty of the proposed approach is that the same linear control design is applied with pole-placement

technique using a guided random search algorithm. Particle swarm optimization is a powerful tool to find global minima for any linear or nonlinear optimization problem. PSO also provides multiple solutions which can be used to meet different criteria. As a comparative study, the same PSO algorithm is also utilized to design a state-feedback controller. The optimized lead-lag controller performance is found better than the optimized state-feedback controller for a change of topology of the system. Hence, the lead-lag design using PSO shows more robustness than the state-feedback design using PSO.

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