Optimal Designing of SSSC Based Supplementary Controller for LFO Damping of Power System Using COA

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ABSTRACT

In this study a linearized Heffron-Phillips model of a single machine power system installed with a static synchronous series compensator (SSSC) has been presented . The optimal selection of the parameters for the SSSC controller is converted to an optimization problem which is solved by recently developed cuckoo optimization algorithm (COA). COA, as a new evolutionary optimization algorithm, is used in multiple applications. This optimization algorithm has a strong ability to find the most optimistic results for dynamic stability improvement. The effectiveness of the proposed controller for damping low frequency oscillations(LFO) is tested to variations in system loading and results compared with particle swarm optimization (PSO). The results analysis reveals that COA minimized multi objective cost function and improved dynamic stability, better than PSO. Also, performance of proposed COA controller in 10 times run is the same as in 1 time run. In addition, designed COA based SSSC damping controller has an excellent capability in damping low frequency oscillations and enhances rapidly and greatly the dynamic stability of the power systems.

Keywords: SSSC, Cuckoo Optimization Algorithm, Particle Swarm Optimization, Single Machine Power System, Low Frequency Oscillation Damping.

1. INTRODUCTION

As power demand grows quickly and expansion in transmission and generation is restricted with the defined availability of resources and the strict environmental constraints, power systems are today much more loaded than before. This causes the power systems to be operated near their stability limits. When large power systems are interconnected by relatively weak tie lines, low frequency oscillations in the range of 0.2-3.0 Hz are observed. If these oscillations are not well damped, these may keep growing in magnitude until loss of synchronism results [1-3].

In the past three decades, power system stabilizers (PSSs) have been broadly used in order to damp these oscillations and increase dynamical stability. PSSs have proven to be efficient in performing their assigned tasks, which operate on the excitation system of generators. However, PSSs may unfavorably have an effect on the voltage profile, may result in a leading power factor, and may be unable to control oscillations caused by large disturbances such as three phase faults which may occur at the generator terminals [1, 2]. Some of these were due to the limited capability of PSS, in damping only local and not inter area modes of electro-mechanical oscillations [4].

Recently, the fast progress in the field of power electronics have opened new opportunities for the application of the flexible AC transmission systems (FACTS) devices as one of the most useful ways to improve power system operation controllability and solving various power system steady state control problems, such as voltage regulation, transfer capability enhancement, power flow control and damping of power system oscillations [1, 5, 6]. SSSC is one of the important members of FACTS family which can be installed in series in the transmission lines. With the capability to change its reactance characteristic from capacitive to inductive; the SSSC is very effective in controlling power flow in power systems. Although the main function of SSSC is to control power flow but it can be used, as an impressive devise, to control power system dynamical stability [7]. An auxiliary stabilizing signal can also be superimposed on the power flow control function of the SSSC so as to enhance low frequency oscillations damping and power system dynamical stability [8].

The applications of SSSC for power oscillation damping, dynamical stability improvement and frequency stabilization can be found in several references [6-9]. In some researches a comparative study between SSSC and other FACTs devices is carried out [10-12]. Some authors suggested active and reactive power flow control using SSSC and other FACTS devices in [13] and [14], respectively. Based on re-

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sults in [15] SSSC's performance is better than static compensator (STATCOM) in damping oscillations. In [16] a novel design of a fuzzy coordinated SSSC controller for integrated power system is used. Recently optimization methods for obtaining parameters of controller are used. Uses of genetic algorithm (GA) and PSO for SSSC-based controller design are investigated in [17-19].

The COA algorithm is a new and very strong method for optimization and has emerged as a useful tool for engineering optimization. So it is used in multiple applications, such as PID controller designing [20] or optimal placement and sizing of distributed generation (DG) [21]. In this study SSSC damping controller design using COA to find the optimal parameters of lead-lag controller is presented. To show effectiveness of the COA method, it is compared with PSO technique [22]. SSSC based damping controller is considered as an optimization problem and both, COA and PSO techniques are used for searching optimized parameters. The effectiveness and robustness of the proposed controller are demonstrated through time-domain simulation and some performance indices studying the damping of low frequency oscillations under various loading conditions and large disturbances. Results shows that the COA based tuned damping controller, achieves good performance for a wide range of operating conditions and is superior to the controller designed using PSO technique. The advantages of the proposed controller are simplicity and feasibility.

The rest of the paper is organized as follows: Section 2 describes proposed COA and PSO methods. Modeling of the case study power system, proposed controller structure and simulation problem have been presented in Section 3. The time domain simulation results and conclusions are described in section 4 and section 5, respectively.

2. DESCRIPTION OF THE OPTIMIZATION METHODS

2.1 PROPOSED COA METHOD

The COA is a new heuristic algorithm for global optimization searches. This optimization algorithm is inspired by the life of a bird family, called Cuckoo. Particular lifestyle of these birds and their specifications in egg laying and breeding has been the basic motivation for expansion of this new evolutionary optimization algorithm. COA similar to other heuristic algorithms such as PSO, GA, imperialist competitive algorithm (ICA), etc, starts with an initial population. The cuckoo population, in different societies, is divided into 2 types, mature cuckoos and eggs. These initial cuckoos grow and they have some eggs to lay in some host birds' nests. Among them, each cuckoo starts laying eggs randomly in some other host birds' nests within her egg laying radius (ELR) [20].Some of these eggs which are more like to the host bird's eggs have the opportunity to grow up and become a mature cuckoo. Other eggs are detected by host birds and are destroyed. The grown eggs disclose the suitability of the nests in that area. The more eggs survive in an area, the more benefit is gained in the area. So the location in which more eggs survive will be the term that COA is going to optimize. Then they immigrate into this best habitat. Each cuckoo only flies $\lambda\%$ of all distance toward final destination (goal habitat) and also has a deviation of ϕradians. These two parameters, λ and ϕ, assistance cuckoos search much more positions in all environment. For each cuckoo, λ and $\phi$are defined as follows:

$$\lambda \sim U(0,1), \phi \sim U(-\omega, \omega) \tag{1}$$

Where $\lambda \sim U(0,1)$ means that λ is a random number that uniformly distributed between 0 and 1. ω is a parameter that inflicts the deviation from goal habitat. When all cuckoos immigrated toward final destination and new habitats were specified, each mature cuckoo is given some eggs. Then considering the number of eggs allocated to each bird, an ELR is calculated for each cuckoo. Then new egg laying process restarts [20]. The pseudo-code of COA is as follows:

1. Initialize cuckoo habitats with some random points on the fitness function
2. Dedicate some eggs to each cuckoo
3. Define ELR for each cuckoo
4. Let cuckoos to lay eggs inside their corresponding ELR
5. Kill those eggs that are recognized by host birds
6. Let eggs hatch and chicks grow
7. Evaluate the habitat of each newly grown cuckoo
8. Limit cuckoos maximum number in environment and kill those who live in worst habitats
9. Cluster cuckoos and find the best group and select goal habitat
10. Let new cuckoo population immigrate toward goal habitat
11. If stop condition is satisfied stop, if not go to 2

2.2 PSO ALGORITHM

A novel population based optimization approach, called PSO approach, was introduced first in [22]. Defining the principle of PSO is out of this papers scope and the complete review is given in several papers for instance in [22] and [23].

3. CASE STUDY SYSTEM

3.1 POWER SYSTEM MODEL WITH SSSC

Fig. 1 shows a single machine infinite bus (SMIB) power system equipped with a SSSC. The SSSC consists of a boosting transformer with a leakage reactance X_{SCT}, a three-phase gate turn off thyristor (GTO) based voltage source converter (V_{INV}), and a DC capacitor (C_{DC}). X_{TS} and X_{SB} are transmission line reactances before and after of SSSC, respectively.

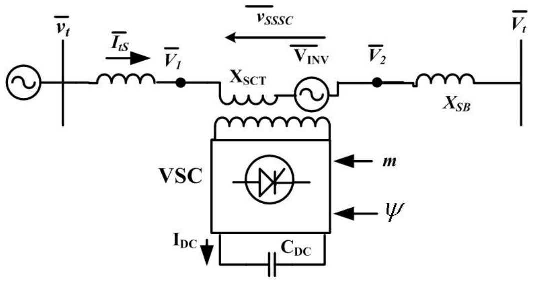


Fig.1: *SSSC installed on a SMIB system.*

The two input control signals to the SSSC are m and ψ . Signal m is the amplitude modulation ratio of the pulse width modulation (PWM) based voltage source converter (VSC). Also, signal ψ is the phase of the injected voltage and is kept in quadrature with the line current (inverter losses are ignored). Therefore, the compensation level of the SSSC can be controlled dynamically by changing the magnitude of the injected voltage. Hence, if the SSSC is equipped with a damping controller, it can be effective in enhancing power system dynamical stability.

3.2 NONLINEAR POWER SYSTEM MODEL WITH SSSC

The dynamic model of the SSSC is required in order to study the effect of the SSSC for increasing the small signal dynamical stability of the power system. The system data is given in the Appendix. By applying Park's transformation and neglecting the resistance and transients of the transformer, nonlinear dynamic model of the system with SSSC is given as [9]:

$$\bar{I}_{ts} = I_{tsd} + jI_{tsq} = I_{TS}\angle\varphi \tag{2}$$

$$\begin{aligned} &\bar{V}_{INV} = mkV_{DC}(\cos\psi + j\sin\psi) = mkV_{DC}\angle\psi \\ &\psi = \varphi \pm 90 \end{aligned} \tag{3}$$

$$\dot{V}_{DC} = \frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} \tag{4}$$

$$\dot{V}_{DC} = \frac{mk}{C_{DC}}(I_{tsd}\cos\psi + jI_{tsq}\sin\psi) \tag{5}$$

Where, k is the ratio between AC and DC voltages and is dependent on the inverter structure. The nonlinear model of the SMIB system as shown in Fig. 1 has been introduced by following equations [9]:

$$\dot{\delta} = \omega_b \omega i \tag{6}$$

$$\dot{\omega} = (P_m - P_e - D\omega)/M \tag{7}$$

$$\dot{E}_q' = (E_{fd} - E_q)/T_{d0}' \tag{8}$$

$$\dot{E}_{fd} = (k_A(v_{to} - v_t) - E_{fd})/T_A \tag{9}$$

Where,

$P_e = E_q' I_{tsq} + (X_q - X_d')I_{tsd}I_{tsq}$

$E_q = E_q' + (X_d - X_d')I_{tsd}$

$V_t = \sqrt{(E_q' - X_d' I_{tsd})^2 + (X_q I_{tsq})^2}$

3.3 LINEARIZED POWER SYSTEM MODEL

Linearizing by applying linearization process Eq. (2)-(9),around operation point of case study system, state space model of the system can be achieved, as follow [9]:

$$\Delta\dot{\delta} = \omega_b \Delta\omega \tag{10}$$

$$\Delta\dot{\omega} = -\frac{1}{M}(\Delta P_e + D\Delta\omega) \tag{11}$$

$$\Delta\dot{E}_q' = \frac{1}{T_{d0}'}(\Delta E_{fd} - \Delta E_q) \tag{12}$$

$$\Delta\dot{E}_{fd} = -\frac{1}{T_A}(\Delta E_{fd} + k_A \Delta v_t) \tag{13}$$

$$\begin{aligned} \Delta\dot{v}_{DC} = &k_7'\Delta\delta + k_8'\Delta E_q' + k_9'\Delta v_{DC} \\ &+ k_{dm}'\Delta m + k_{d\psi}'\Delta\psi \end{aligned} \tag{14}$$

Where,

$\Delta P_e = k_1'\Delta\delta + k_2'\Delta E_q' + k_{pDC}'\Delta v_{DC} + k_{pm}'\Delta m + k_{p\psi}'\Delta\psi$

$\Delta E_q = k_4'\Delta\delta + k_3'\Delta E_q' + k_{qDC}'\Delta v_{DC} + k_{qm}'\Delta m + k_{q\psi}'\Delta\psi$

$\Delta V_t = k_5'\Delta\delta + k_6'\Delta E_q' + k_{vDC}'\Delta v_{DC} + k_{vm}'\Delta m + k_{v\psi}'\Delta\psi$

K_1', K_2'...K_9', K_{pu}', K_{qu}' and K_{vu}' are linearization constants and are dependent on system parameters and the operating condition. The state space model of power system is given by:

$$\dot{x} = Ax + Bu \tag{15}$$

Where x and u are state vector and control vector, respectively. The variables x, u, A and B are:

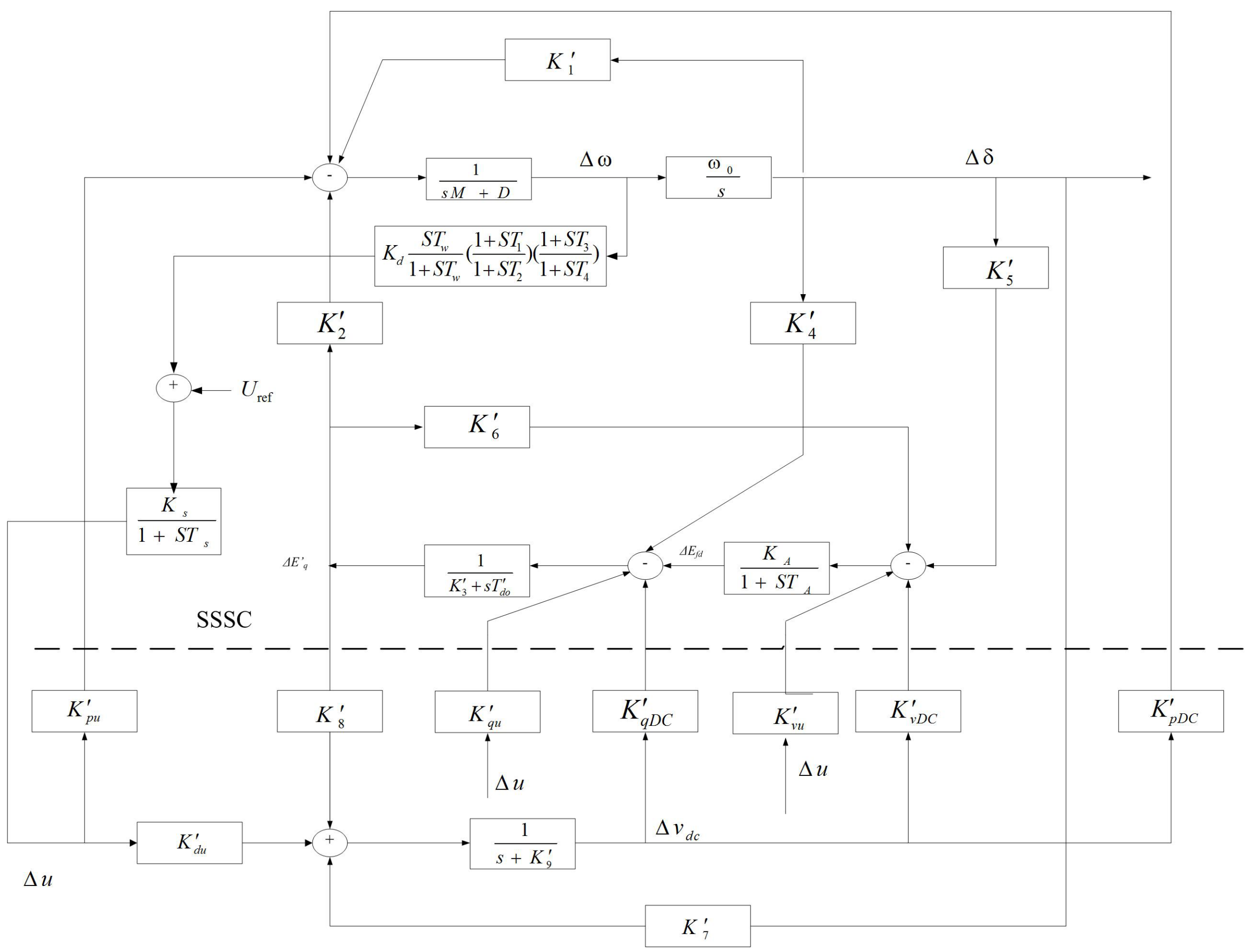


Fig.2: *Modified Phillips-Heffron model of a SMIB system equipped with SSSC and supplementary controller.*

$x = [\ \Delta\delta \quad \Delta\omega \quad \Delta E'_q \quad \Delta E_{fd} \quad \Delta V_{DC}\ ]^T$

$x = [\ \Delta m \quad \Delta\psi\ ]^T$

$$A = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{k'_1}{M} & -\frac{D}{M} & -\frac{k'_2}{M} & 0 & -\frac{k'_{pDC}}{M} \\ -\frac{k'_4}{T'_{do}} & 0 & -\frac{k'_3}{T'_{do}} & \frac{1}{T'_{do}} & -\frac{k'_{qDC}}{T'_{do}} \\ -\frac{k_A k'_5}{T_A} & 0 & -\frac{k_A k'_6}{T_A} & -\frac{1}{T_A} & -\frac{k_A k'_{vDC}}{T_A} \\ k'_7 & 0 & k'_8 & 0 & k'_9 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ -\frac{k'_{pm}}{M} & -\frac{k'_{p\psi}}{M} \\ -\frac{k'_{qm}}{T'_{do}} & -\frac{k'_{q\psi}}{T'_{do}} \\ -\frac{k_A k'_{vm}}{T_A} & -\frac{k_A k'_{v\psi}}{T_A} \\ k'_{dm} & k'_{d\psi} \end{bmatrix}$$

The block diagram of the linearized dynamic model of the SMIB power system installed SSSC is shown in Fig. 2.

3.4 SSSC BASED PROPOSED CONTROLLER STRUCTURE

The SSSC damping controller structure is embedded in Fig. 2, where u can be m or ψ. It comprises gain block, signal-washout block and lead-lag compensator [5].

3.5 OPTIMIZATION PROBLEM

In the proposed method, we must tune the SSSC controller parameters optimally to improve overall system dynamic stability in a robust way under different operating conditions. For our optimization problem, an eigenvalue based multi objective function reflecting the combination of damping factor and damping ratio is considered as follows:

$$J = \sum_{i=1}^{N_p} (\sigma_0 - \sigma_i)^2 + a \sum_{i=1}^{N_p} (\xi_0 - \xi_i)^2 \qquad (16)$$

are the real part and the damping ratio of the ith eigenvalue, respectively. The value of σ_0 determines the relative stability in terms of damping factor margin provided for constraining the placement of eigenvalues during the process of optimization and ξ_0 is the desired minimum damping ratio which is to be achieved. The closed loop eigenvalues are placed in the region to the left of dashed line as shown in Fig. 3. It is necessary to mention here that only the unstable or lightly damped electromechanical modes of oscillations are relocated. The design problem can be formulated as the following constrained optimiza-

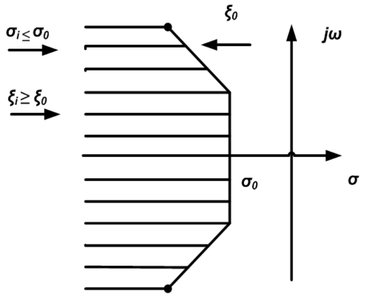


Fig.3: *Region of eigenvalue location for objective function.*

tion problem, where the constraints are the controller parameters bounds:

$$\begin{aligned}
&Minimize J\\
&For\ the\ lead-lag\ controller\ subject\ to\\
&{K_d}^{min} \le K_d \le {K_d}^{max}\\
&{T_1}^{min} \le T_1 \le {T_1}^{max}\\
&{T_2}^{min} \le T_2 \le {T_2}^{max}\\
&{T_3}^{min} \le T_3 \le {T_3}^{max}\\
&{T_4}^{min} \le T_4 \le {T_4}^{max}
\end{aligned} \quad (17)$$

Typical ranges of the five parameters of lead-lag controller are [-100,100] for K_d and [0.01,1.5] for T_1, T_2, T_3 and T_4. The proposed approach employs COA to solve this optimization problem and search for an optimal or near optimal set of controller parameters. The optimization of SSSC controller parameters is carried out by evaluating the objective cost function as given in Eq. (16), for the lead-lag controller.

4. SIMULATION RESULTS

4.1 APPLICATION OF THE COA AND PSO TO THE DESIGN PROCESS

Based on singular value decomposition (SVD) analysis in [15] modulating ψ has an excellent capability in damping low frequency oscillations in comparison to other inputs of SSSC, thus in this paper, ψ is modulated in order to damping controller design. In this paper, the values of σ_0,ξ_0 and a are taken as -2, 0.5 and 10, respectively. In order to acquire better performances of COA and PSO, proper parameters are given in Table 1. The COA and PSO were applied to search for the optimal parameter settings of the ψ supplementary controller so that the objective function is optimized. The both algorithms are run 1 and 10 times and the best solution based on the minimum cost function Eq. (16) is selected. Table 2 shows the optimal controller parameters with 1 and average of 10 runs. Fig. 4 shows the cost of COA and PSO controller with the same objective function when the program is run once and 10 times. As it can be seen from this figure, for the same objective function, COA cost value is less than PSO. Also, its performance in 10 times run is the same as in 1 time run.

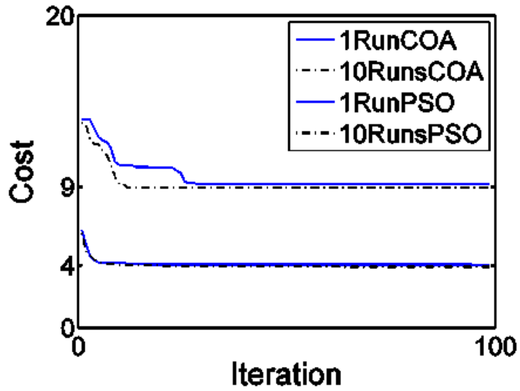


Fig.4: *The convergence for objective function minimization using the COA and PSO techniques.*

4.2 TIME DOMAIN SIMULATION

Notice that the optimization process for both optimization methods has been carried out with the system operating at nominal loading conditions given in Table 3. Also, to evaluate the effectiveness of the proposed controllers, 4 different loading conditions given in Table 3 were considered with an input mechanical torque disturbance.

Eigenvalues, damping factor and frequency of the electromechanical modes with COA and PSO controllers at 4 different loading conditions are given in Table 4. By using objective function in Eq. (16), the electromechanical mode eigenvalues have been shifted to the left in s-plane and the system damping with the proposed methods greatly improved and increased. The system behaviour due to the utilization of the proposed controllers has been tested by applying 10% step increase in mechanical power input at t=1s. The system response to this disturbance under 4 different loading conditions for speed deviation, rotor angle deviation and power deviation with Ψ based controller, as well as, with and without controllers, are shown in Figs. 5-8. It is obvious that the open loop system is unstable, where as the proposed COA and PSO controllers stabilize the system. It can be observed from Figs. 5-8 that the performance of the system is better with the proposed COA optimized lead-lag controller compared to the PSO optimized lead-lag controller. Also, simulation results clearly illustrate, proposed objective function-based optimized SSSC controller with COA, has good performance in damping low-frequency oscillations and stabilizes the system quickly in comparison to the PSO method.

Table 1: *Algorithms proper parameters.*

PSO Method		COA Method	
Article size	5 variables as (17)	Cuckoo size	5 variables as (17)
C1	1	initial population	20
C2	1	minimum and maximum number of eggs for each cuckoo	2 and 4
W_{MAX}	0.9	number of clusters	2
W_{MIN}	0.4	maximum number of cuckoos	30
Iteration	100	Iteration	100

Table 2: *The optimal parameter settings of the PSO and proposed COA controller with 1 and average of 10 runs based on the objective function.*

Controller Parameters		K_d	T_1	T_2	T_3	T_4	Cost
PSO	1-run	-76.0000	1.0500	0.1589	1.5000	0.1580	9.3073
	10-runs	-62.0000	1.0510	0.1638	1.4800	0.1638	8.9583
COA	1-run	-99.8400	1.4799	0.3810	0.9893	0.1335	4.2611
	10-runs	86.5962	1.2303	0.2419	1.1841	0.2010	3.9016

Table 3: *System loading Conditions.*

Loading Conditions	P (P.U.)	Q (P.U.)
Case1 (Nominal)	1	0.15
Case2 (Light)	0.3	0.015
Case3 (Heavy)	1.1	0.4
Case4 (Power Factor)	0.7	-0.03

Table 4: *Eigenvalues, damping ratios and frequencies of the electromechanical modes of the system with designed controllers.*

	Case 1			Case 2		
	Eigenvalues	ξ	f	Eigenvalues	ξ	f
PSO controller	-0.04± j4.87 -2.30± j0.18	0.01 0.98	0.77 0.03	-5.4450 ± j10.4979 -0.2790±j5.3214	0.46 0.05	1.67 0.85
COA controller	-4.0982±j8.2950 -1.8648±j4.9493	0.44 0.35	1.32 0.79	-3.7623±j6.5977 -2.8516±j5.0907	0.49 0.49	1.05 0.81
	Case 3			Case 4		
	Eigenvalues	ξ	f	Eigenvalues	ξ	f
PSO controller	-0.0820±j 4.6924	0.02	0.75	-0.03±j5.30 -1.61±j0.07	0.01 0.99	0.84 0.01
COA controller	-3.97±j7.69 -1.87±j4.62	0.46 0.37	1.22 0.73	-3.5588±j7.0450 -2.2043±j5.2405	0.45 0.39	1.12 0.83

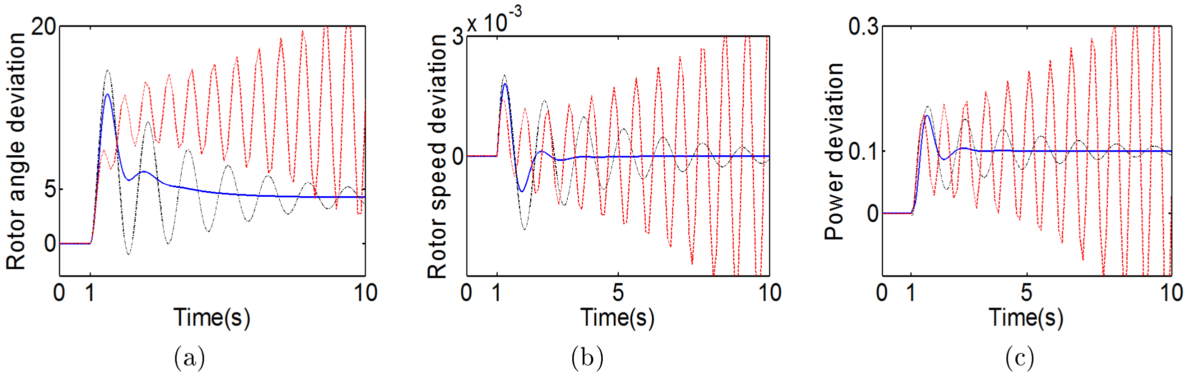
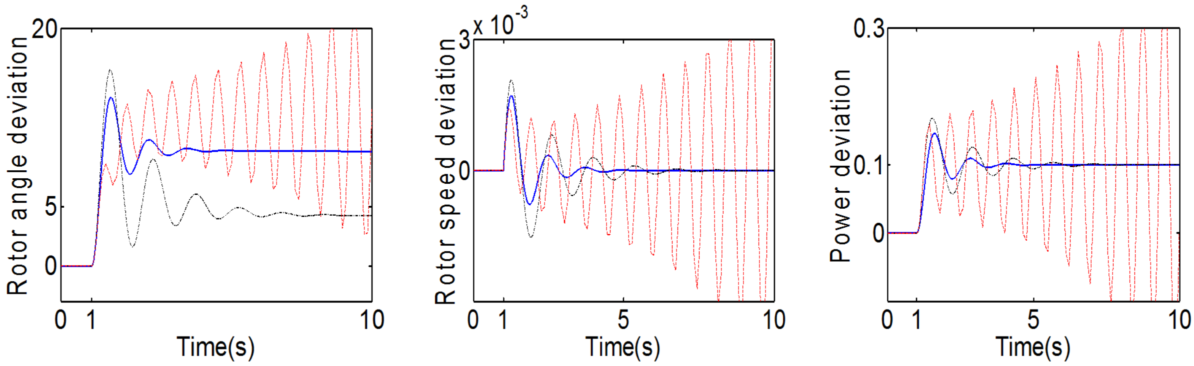
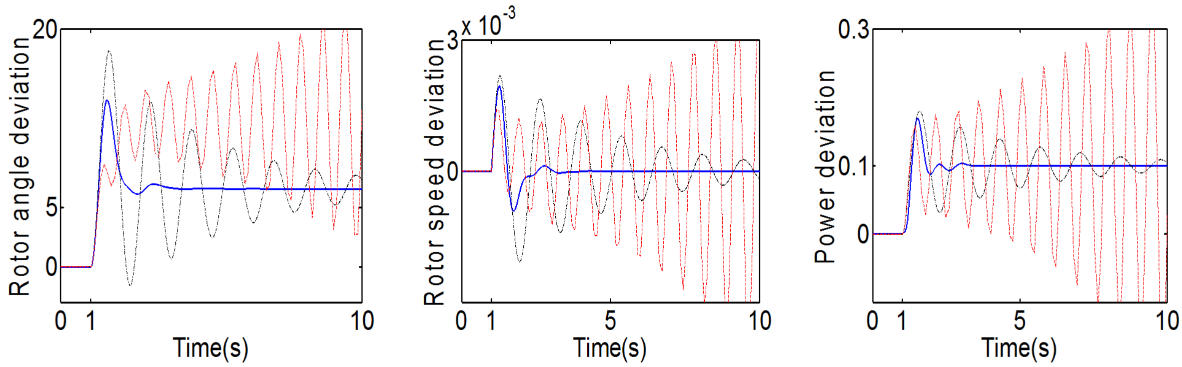


Fig.5: *Dynamic responses for (a) $\Delta\delta$(b) $\Delta\omega$(c)ΔP_e with ψ controller at Case 1 loading condition; solid (proposed COA controller), dash-dotted (PSO controller) and dashed (without controller).*



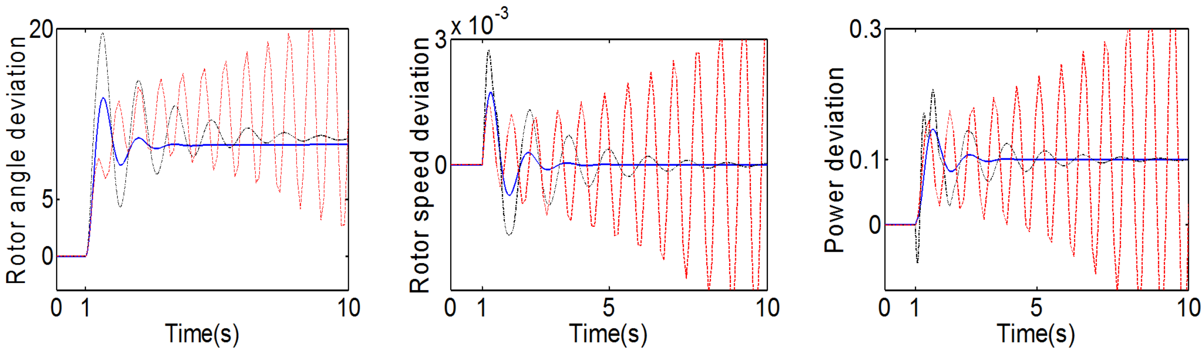
(a) (b) (c)

Fig.6: *Dynamic responses for (a) $\Delta\delta$(b) $\Delta\omega$(c)ΔP_e with ψ controller at Case 2 loading condition; solid (proposed COA controller), dash-dotted (PSO controller) and dashed (without controller).*



(a) (b) (c)

Fig.7: *Dynamic responses for (a)$\Delta\delta$(b) $\Delta\omega$(c)ΔP_e with ψ controller at Case 3 loading condition; solid (proposed COA controller), dash-dotted (PSO controller) and dashed (without controller).*



(a) (b) (c)

Fig.8: *Dynamic responses for (a)$\Delta\delta$(b) $\Delta\omega$(c)ΔP_e with ψ controller at Case 4 loading condition; solid (proposed COA controller), dash-dotted (PSO controller) and dashed (without controller).*

5. CONCLUSIONS

In this paper, COA has been utilized to search for the optimal controller parameters of SSSC. The effectiveness of the proposed SSSC controller for damping of low-frequency oscillations of a power system was demonstrated by a weakly connected example power system subjected to a disturbance; an increase in mechanical power. PSO was compared to COA. In comparison to PSO, the eigenvalue analysis, cost values and time-domain simulation results showed the effectiveness of the proposed COA controller in damping low-frequency oscillations under all of the loading conditions.

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