Damping of Low Frequency Electro-Mechanical Oscillations Using UPFC Based on Cuckoo Optimization Algorithm

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Abstract-In this study alinearized Heffron-Phillipsmodel of a single machine power system installed with a unified power flow controller (UPFC) has been presented. The selection of the output feedback parameters for the UPFC controllers is converted to an optimization problem which is solved by 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 is tested and results compared with imperialist competitive algorithm (ICA).The controllers are tested to variations in system loading. There sulks analysis reveals that COA minimized cost function and improved dynamic stability, better than ICA. In addition, the potential and superiority of the proposed method over the ICA is demonstrated. The simulation results analysis shows that the designed COA based output feedback UPFC damping controller has an excellent capability in damping low frequency oscillations and enhance rapidly and greatly the dynamic stability of the power systems**.**

Keywords: cuckoo optimization algorithm, UPFC, power system oscillations.

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. In addition, interconnection between remotely located power systems gives rise to low frequency oscillations in the range of 0.2–3.0 Hz. If these oscillations are not well damped, these may keep growing in magnitude until loss of synchronism results [1] and [2]. In the past three decades, power system stabilizers (PSSs) have been broadly used to increase the system damping for low frequency oscillations. 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 [1].Some of these were due to the limited capability of PSS, in damping only local and not inter area modes of electro-mechanical oscillations [3].This status has necessitated a review of the traditional power system concepts and practices to achieve a larger stability margin, greater operating flexibility, and better utilization of existing power systems. Flexible AC transmission systems (FACTS) have gained a great interest during the last few years, due to recent advances in power electronic devices. FACTS devices have been extensively used for solving various power system steady state control problems, such as voltage regulation, transfer capability enhancement, power flow control and damping of power system oscillations[4].As supplementary functions, damping the inter area modes and enhancing power system dynamical stability using FACTS controllers have been mainly studied and investigated. Generally, it is not cost-effective to install FACTS devices for the sole purpose of power system stability enhancement[5]. For this reason in recent years, FACTS devices are one of the most useful ways to improve power system operation controllability and power transfer limits.

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Through the modulation of bus voltage, phase shift between buses, and transmission line reactance, FACTS devices can cause a fundamental increase in power transfer limits during steady-state [1] and [6]. Among FACTS devices, UPFC is impressive for damping power system oscillations. This is achieved by adjusting the controllable parameters of the system, line reactance, voltage magnitude and phase angle of the UPFC bus. UPFC consists of two AC/DC converters. One of themes linked to the transmission line via a series transformer and the other one in parallel with the line via a shunt transformer. STATCOM is a shunt controller and SSSC is a series controller. The series and shunt branches of UPFC can produce/absorb reactive power independently and the two branches can exchange real power; therefore, UPFC has three degrees of freedom[7]. In other words, the series and shunt converters are linked via a large DC capacitor. The series branch of the UPFC injects an AC voltage with control label magnitude and phase angle at the power frequency via anisette on transformer. The real power exchanged between the line and the converter is supplied by the shunt converter through the DC link and is equal to the real power exchanged between the transmission line and the shunt converter. STATCOM exchanges a current of controllable magnitude and power factor angle with the power system [8].Recently, researchers have presented dynamic UPFC models in order to design a proper controller for power flow, voltage and damping controls [9] and [10]. Nabavi-Niaki and Iravani[11]developed steady-state model, large-signal model and small-signal lineari zed dynamic model of a UPFC. Wang has introduced a modified linearized Heffron-Phillips model of a power system installed with a UPFC [12] and [13]. Wang has not presented a systematic approach to design the damping controllers of power systems.[14]Tried to design a conventional fixed-parameter lead-lag controller for a UPFC installed in the tie line of a two area system to damp the inter-area mode of oscillations. An industrial process, such as a power system, contains different kinds of uncertainties due to continuous load changes or parameters drift due to power systems extremely nonlinear and stochastic operating nature. As a consequent, a fixed-parameter controller based on the classical control theory is not certainly suitable for the UPFC damping control design. Thus, it is needed that a flexible controller be developed. Some authors suggested neural networks technique [15] and robust control methodologies [16] and [10]to cope with power system uncertainties to increase the system damping performance using the UPFC. However, the parameters adjustments of these lead-lag controllers need some trial and error. Also, although using the robust control methods, the uncertainties are straightly introduced to the synthesis, but due to the large model order of power systems the order resulting controller will be very large in general, which is not conceivable because of the computational economic difficulties in implementing. Some researchers used fuzzy logic based damping control strategy for TCSC, UPFC and SVC in a multi-machine power system[17] and [18].The damping control strategy employs non-optimal fuzzy logic controller that is why the system's response settling time is intolerable. Moreover, the initial parameters adjustment of this kind of controller needs some trial and error. Khon and Lo[19] used a fuzzy damping controller designed by micro Genetic Algorithm (GA) for TCSC and UPFC to improve powers system dynamical stability. Abido has used the PSO technique to design a controller and this method not only is an off-line procedure, but also depends forcefully on the selection of the primary conditions of control systems [20].An adaptive controller is able to control a nonlinear system with fast changing dynamics, like the power system better, since the dynamics of a power system are continuously identified by a model. Advantages of on-line adaptive controllers over conventional controllers are that they are able to adapt to changes in system operating situations automatically, unlike conventional controllers whose efficiency is degraded by such changes and require re-tuning in order to provide the desired efficiency [10].In this study UPFC damping controller design using COA to find the optimal five parameters of lead-lag controller is presented. The COA, as a new evolutionary optimization algorithm, is used in multiple applications, such as PID controller designing [21] or optimal placement and capacity of DG [22]. Recently, Humar Kahramanli modified cuckoo optimization algorithm for engineering optimization[23]. The advantages of the proposed controller are their simplicity and feasibility. In this paper, the COA is used to

obtain the optimal values of the supplementary controller parameters of a UPFC. To show effectiveness of COA method, it is compared with ICA [24] method for various load conditions and large disturbances.

2. Description of Cuckoo Optimization Algorithm

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, ICA, etc, starts with an initial population**.** The cuckoo population, in different societies, is divided into 2 types, mature cuckoos and eggs [21]. 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).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 that area. So the location in which more eggs survive will be the term that COA is going to optimize. Cuckoos search for the most proper area to lay eggs in order to magnify their eggs survival rate. After remained cuckoos eggs grow and turn into a mature cuckoo, they make some societies. Each society has its habitat zone to live in. The best habitat of all societies will be the final destination for the cuckoos in other societies. Then they immigrate into this best habitat. When moving toward goal point, the cuckoos do not fly all the way to the final destination habitat. They only fly a part of the path and also has a deviation. Each cuckoo only flies λ% of all distance toward final destination (goal habitat) and also has a deviation of ϕ radians. These two parameters, λ and ϕ, assistance cuckoos search much more positions in all environment. For each cuckoo, λ and ϕ are defined as follows:

$$\lambda \sim U(0, 1)$$
$$\phi \sim U(-\omega, \omega) \quad (1)$$

Where λ~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. An ω of π/6 (rad) seems to be enough for good convergence of the cuckoo population to global maximum benefit. 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 EL Ris calculated for each cuckoo. Then new egg laying process restarts[21].

3. Mathematical Model of Power System with UPFC

A. Description of case study system

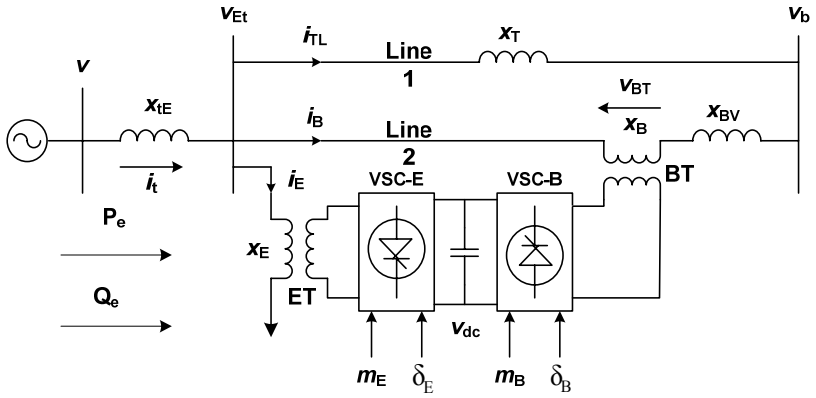


Figure 1**.** UPFC installed in a SMIB system

Figure 1 shows a single-machine infinite-bus (SMIB) power system equipped with a UPFC. The synchronous generator is delivering power to the infinite-bus through a double circuit transmission line and a UPFC. The UPFC consists of an excitation transformer (ET), a boosting transformer (BT), two three-phase GTO based voltage source converters (VSCs), and a DC link capacitors. The four input control signals to the UPFC are m_E, m_B, δ_E, and δ_B, where, m_E is the excitation amplitude modulation ratio, m_B is the boosting amplitude modulation ratio, δ_E is the excitation phase angle and δ_B is the boosting phase angle. As it seen in Figure 1, in this paper, the test power system is a SMIB with 2 parallel lines. The parameters of the test power system are given in the appendix.

B. Power System Nonlinear Model with UPFC

The dynamic model of the UPFC is essential in order to study the effect of the UPFC for increasing the small signal dynamical stability of the power system. By using Park's transformation and disregarding the resistance and transients of the ET and BT transformers, the non-linear dynamic model of the system installed with UPFC is given as [1, 11, 12, 25].

$$\begin{bmatrix} v_{Etd} \\ v_{Etq} \end{bmatrix} = \begin{bmatrix} 0 & -x_E \\ x_E & 0 \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \begin{bmatrix} \frac{m_E \cos\delta_E v_{dc}}{2} \\ \frac{m_E \sin\delta_E v_{dc}}{2} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} v_{Btd} \\ v_{Btq} \end{bmatrix} = \begin{bmatrix} 0 & -x_B \\ x_B & 0 \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \frac{m_B \cos\delta_B v_{dc}}{2} \\ \frac{m_B \sin\delta_B v_{dc}}{2} \end{bmatrix} \tag{3}$$

$$\dot{v}_{dc} = \frac{3m_E}{4C_{dc}} \begin{bmatrix} \cos\delta_E & \sin\delta_E \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \frac{3m_B}{4C_{dc}} \begin{bmatrix} \cos\delta_B & \sin\delta_B \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} \tag{4}$$

In the above equations v_{Et}, i_E, v_{Bt}, and i_B are the excitation voltage, excitation current, boosting voltage, and boosting current, respectively; C_{dc} and v_{dc} are the DC link capacitance and voltage, respectively. The relations of excitation and boosting transformers parameters and line 1 currents can be written as:

$$i_{TLd} = \frac{1}{x_T}\left(x_E i_{Ed} + \frac{m_E \sin\delta_E v_{dc}}{2} - v_b \cos\delta \right) \tag{5}$$

$$i_{TLq} = \frac{1}{x_T}\left(x_E i_{Eq} - \frac{m_E \cos\delta_E v_{dc}}{2} + v_b \sin\delta \right) \tag{6}$$

$$i_{Ed} = \frac{x_{BB}}{x_{d2}} E'_q + x_{d7} \frac{m_B \sin\delta_B v_{dc}}{2} + x_{d5} v_b \cos\delta + x_{d6} \frac{m_E \sin\delta_E v_{dc}}{2} \tag{7}$$

$$i_{Eq} = x_{q7} \frac{m_B \cos\delta_B v_{dc}}{2} + x_{q5} v_b \sin\delta + x_{q6} \frac{m_E \cos\delta_E v_{dc}}{2} \tag{8}$$

$$i_{Bd} = \frac{x_E}{x_{d2}} E'_q - \frac{x_{d1}}{x_{d2}} \frac{m_B \sin\delta_B v_{dc}}{2} + x_{d3} v_b \cos\delta + x_{d4} \frac{m_E \sin\delta_E v_{dc}}{2} \tag{9}$$

$$i_{Bq} = \frac{X_{q1}}{X_{q2}} \frac{m_B \cos\delta_B V_{dc}}{2} + X_{q3} V_b \sin\delta + X_{q4} \frac{m_B \cos\delta_B V_{dc}}{2} \tag{10}$$

Where x_E and x_B are the ET and BT reactance's, respectively; the reactance's $x_{q\,E}$,x_{dE}, x_{BB}, x_{d1}-x_{d7} and x_{q1}-x_{q7} are as shown in [26].The conventional non-linear model of the SMIB system of Figure 1 is:

$$\dot{\delta} = \omega_b(\omega - 1) \tag{11}$$

$$\dot{\omega} = \left(P_m - P_e - D(\omega - 1)\right)/M \tag{12}$$

$$\dot{E}'_q = \left(E_{fd} - \left(x_d - x'_d\right) i_d - E'_q\right)/T'_{d0} \tag{13}$$

$$\dot{E}_{fd} = \left(K_A\left(V_{ref} - v + u_{pss}\right) - E_{fd}\right)/T_A \tag{14}$$

where,

$$P_e = v_d i_d + v_q i_q \qquad v = \left(v_d^2 + v_q^2\right)^{1/2} \qquad v_d = x_q i_q \;\; v_q = E'_q - x'_d i_d$$
$$i_d = i_{Ed} + i_{Bd} + i_{TLd} \qquad i_q = i_{Eq} + i_{Bq} + i_{TLq}$$

where P_m and P_e are the input and output power, respectively; M and D the inertia fixed and damping coefficient, respectively; ω_b the synchronous speed; δ and ω the rotor angle and speed, respectively; E'_q, E'_{fd}, and v the generator internal, field and terminal voltages, respectively; T'_{do} the open circuit field time constant; x_d, x'_d, and x_q the d-axis reactance, d-axis transient reactance, and q-axis reactance, respectively; K_A and T_A the exciter gain and time constant, respectively; V_{ref} the reference voltage; and u_{pss} the PSS control signal.

4. Linear zed Model of the Power System

In this paper, in order to perform a stability evaluation, Eigen value analysis is used. For this reason and to obtain the Eigen values of the system, the nonlinear dynamic equations of power system must be lineari zed around an operating point condition. The linear zed model of power system as shown in Figure 1 is explained by:

$$\Delta\dot{\delta} = \omega_b \Delta\omega \tag{15}$$

$$\Delta\dot{\omega} = \frac{1}{M}\left(\Delta P_m - \Delta P_e - D\Delta\omega\right) \tag{16}$$

$$\Delta\dot{E}'_q = \frac{1}{T'_{d0}}\left(-\Delta E'_q + \Delta E_{fd} + (x_d - x'_d)\Delta i_{ld}\right) \tag{17}$$

$$\Delta\dot{E}_{fd} = \frac{1}{T_A}(-\Delta E_{fd} + K_A(\Delta V_{tref} - \Delta V_t + \Delta u_{pss}) \tag{18}$$

$$\Delta\dot{V}_{dc} = K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta V_{dc} + K_{ce}\Delta m_E + K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B \tag{19}$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E'_q + K_{vd}\Delta V_{dc} + K_{ve}\Delta m_E + K_{v\delta e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B \tag{20}$$

In state-space representation, the power system can be modeled as:

$$\dot{x} = Ax + Bu \tag{21}$$

The lineari zed dynamic model of the state-space representation is shown in figure 2

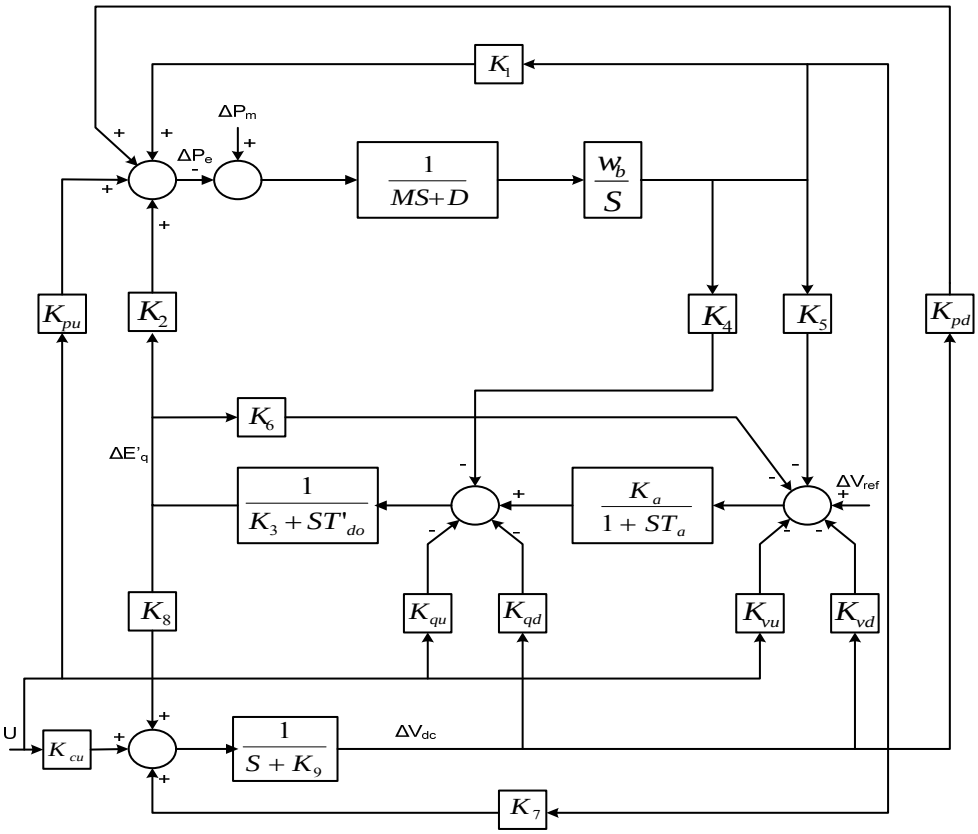


Figure 2. Modified Heffron–Phillips transfer function model

Where, the state vector x, control vector u, state matrix A and input matrix B are:

$$x = \left[\Delta\delta \quad \Delta\omega \quad \Delta E'_q \quad \Delta E_{fd} \quad \Delta v_{dc}\right]^T$$

$$u = \left[\Delta u_{pss} \quad \Delta m_E \quad \Delta\delta_E \quad \Delta m_B \quad \Delta\delta_B\right]^T$$

$$\boldsymbol{A}=\begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{k_1}{M} & -\frac{D}{M} & -\frac{k_2}{M} & 0 & -\frac{k_{pd}}{M} \\ -\frac{k_4}{T'_{do}} & 0 & -\frac{k_3}{T'_{do}} & \frac{1}{T'_{do}} & -\frac{k_{qd}}{T'_{do}} \\ -\frac{k_A k_5}{T_A} & 0 & -\frac{k_A k_6}{T_A} & -\frac{1}{T_A} & -\frac{k_A k_{vd}}{T_A} \\ k_7 & 0 & k_8 & 0 & -k_9 \end{bmatrix}$$

$$\boldsymbol{B}=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{k_{pe}}{M} & -\frac{k_{p\delta e}}{M} & -\frac{k_{pb}}{M} & -\frac{k_{p\delta b}}{M} \\ 0 & -\frac{k_{qe}}{T'_{do}} & -\frac{k_{q\delta e}}{T'_{do}} & -\frac{k_{qb}}{T'_{do}} & -\frac{k_{q\delta b}}{T'_{do}} \\ \frac{k_A}{T_A} & -\frac{k_A k_{ve}}{T_A} & -\frac{k_A k_{v\delta e}}{T_A} & -\frac{k_A k_{vb}}{T_A} & -\frac{k_A k_{v\delta b}}{T_A} \\ 0 & k_{ce} & k_{c\delta e} & k_{cb} & k_{c\delta b} \end{bmatrix}$$

A. UPFC Based Lead-Lag Damping Controller Design

The lead-lag damping controller is designed to produce an electrical torque, according to the phase compensation method, in phase with the speed deviation. To produce the damping torque, the four control parameters of the UPFC (m_E, δ_E, m_B, and δ_B) can be modulated in order to produce the damping torque. Based on singular value decomposition (SVD) analysis in [1] modulating δ_E has an excellent capability in damping low frequency oscillations in comparison with other inputs of UPFC, thus in this paper, δ_E is modulated in order to damping controller design. The speed deviation $\Delta\omega$ is considered as the input to the damping controller. The structure of UPFC based lead-lag damping controller is shown in Figure 3. It comprises signal-washout block, gain block and lead-lag compensator. The five parameters of lead-lag controller are obtained using the COA technique and results compared with ICA.

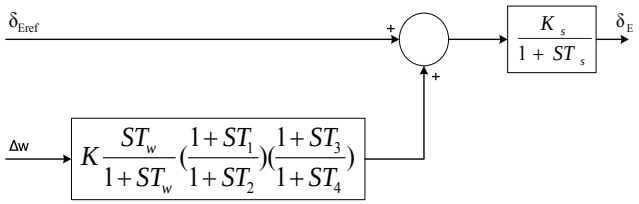


Figure 3. Lead-lag damping controller structure

B. COA-Based Output Feedback Controller Design

In the proposed method, the five parameters (K, T_1, T_2, T_3 and T_4)of lead-lag controller must be tuned optimally to improve overall system dynamic stability. This study employs the COA to improve optimization synthesis and find the global optimum value of the cost function in order to acquire an optimal combination. In this study, the COA module works offline. In other words, the five parameters of UPFC-based controllers are optimized in order to have robust stabilizers over a wide range of operating conditions for several loading conditions, representing nominal, light and heavy, are taken into account. Figure 4, shows the flowchart of the proposed COA technique. Defining the principle of COA and ICA is out of this papers scope and the complete review is given in several papers for instance in [21] and [24].The optimization problem design can be formulated as the constrained problem shown below, where the constraint is the controller parameters bounds. Optimal parameters of the damping

controller are applied to the time-domain simulation. Finally obtained parameters compared with ICA.

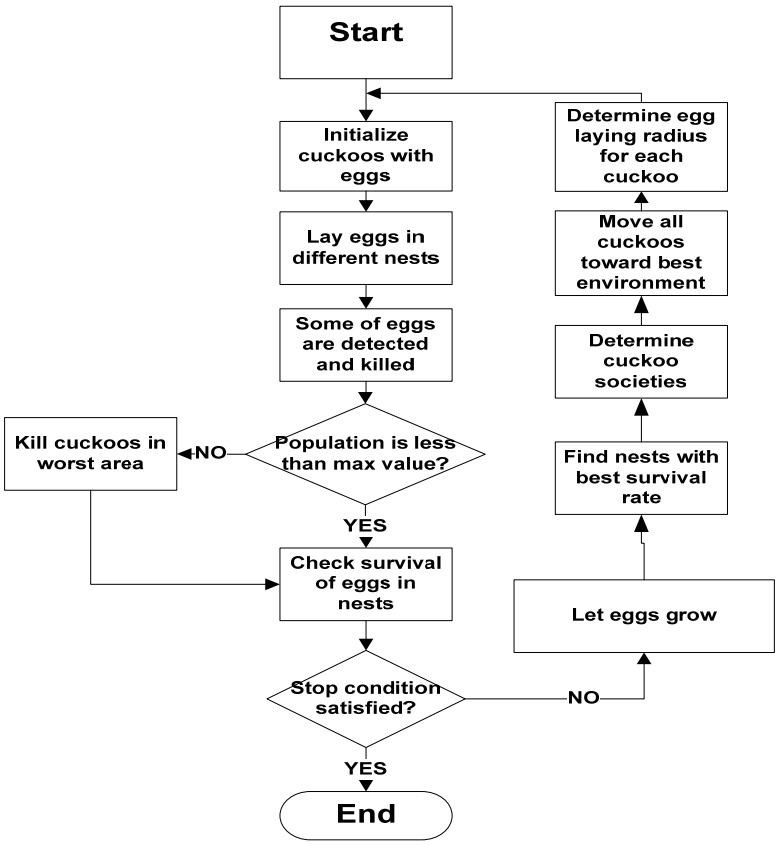


Figure 4. Flowchart of cuckoo optimization algorithm

For our optimization problem, an Eigen value-based objective function is considered as follows:

$$J = \sum_{i=1}^{NP} \left(\sigma_0 - \sigma_i \right)^2 \tag{22}$$

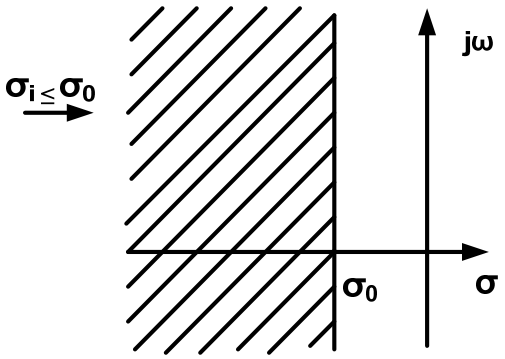


Figure 5. Region of Eigen value location for objective function.

In Eq. (22), σ_i is the real part of the its Eigen value of the its operating point and N_P is the total number of operating points for which the optimization is carried out. The value of σ_0 determines the relative stability in terms of damping factor margin provided for constraining the placement of Eigen values during the process of optimization. The closed loop Eigen values are placed in the region to the left of dashed line as shown in figure 5.

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

Minimize J

For the lead-lag controller subject to

$$\begin{aligned} K^{min} \le K \le K^{max} \\ T_1^{min} \le T_1 \le T_1^{max} \\ T_2^{min} \le T_2 \le T_2^{max} \\ T_3^{min} \le T_3 \le T_3^{max} \\ T_4^{min} \le T_4 \le T_4^{max} \end{aligned} \quad (23)$$

Typical ranges of the optimized five parameters of lead-lag controller are [-100 100] for K, [0.01 1.5] for T_1, T_2, T_3 and T_4. The proposed approach employs COA algorithm to solve these optimization problems and search for an optimal or near optimal set of controller parameters. The optimization of UPFC controller parameters is carried out by evaluating the single-objective cost function as given in Eq. (22), for the lead-lag controller.

5. Simulation results

A. Application of the COA and ICA to the design process

The COA was applied to search for the optimal parameter settings of the δ_E supplementary controller so that the single-objective function is optimized. In this paper, the value of σ_0 is taken as -2. In order to acquire better performance of COA, number of initial population, maximum number of cuckoos that can live at the same time, minimum and maximum number of eggs for each cuckoo, number of clusters that we want to make and maximum iterations of the cuckoo algorithm were chosen as 20, 30, 2,4,2and 300, respectively. Also, in order to acquire better performance of ICA , number of countries, number of initial imperialists, number of decades, assimilation coefficient (β), and ζ_{ica} were chosen as 50, 6, 300, 3, and 0.2, respectively. It should be noted that both the COA and ICA are run for several times, then optimal set of UPFC controller parameters are chosen. The final values of the optimized five parameters with the single-objective function for lead-lag controller are given in Tables1 and 2, respectively. As it is seen in Figure 6, for the same objective function, COA cost value is less than ICA.

Table 1. Optimal parameters of the lead-lag controller for COA

T_3	T_4	cost
0.1876	0.1903	3.2604

Table 2. Optimal parameters of the lead-lag controller for ICA

K	T_1	T_2	T_3	T_4	cost
-37.92	0.4048	0.5816	1.0768	0.8571	4.8914

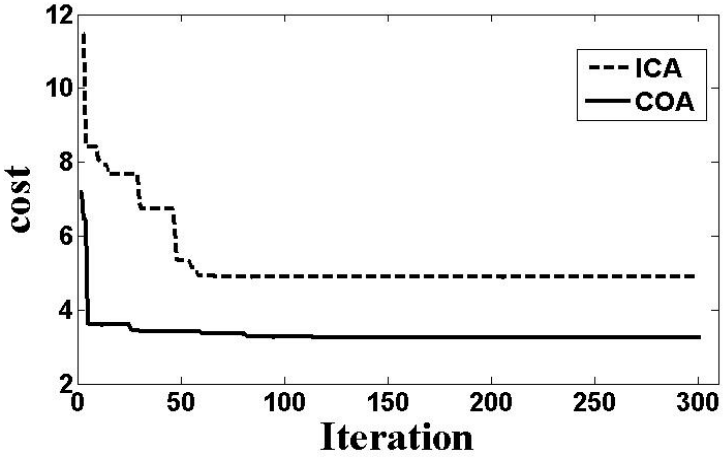


Figure 6**.** The convergence for objective function minimization using the COA and ICA techniques

B. Time Domain Simulation

Notice that the optimization process for both 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, three different loading conditions given in table 3 were considered with an input mechanical torque disturbance.

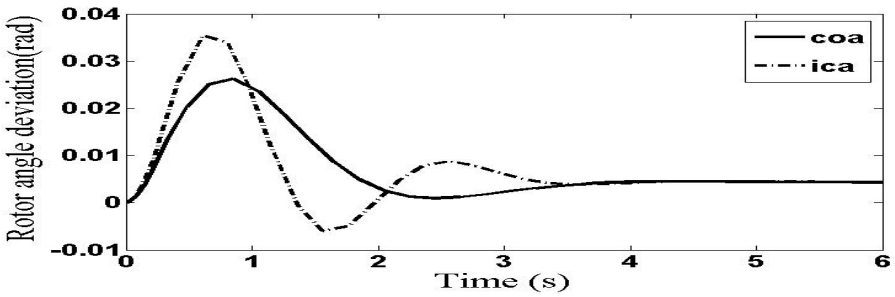
Table 3. System operating conditions

Loading conditions	***Pe***	***Qe***
Nominal	1.000	0.015
Light	0.300	0.015
Heavy	1.100	0.400

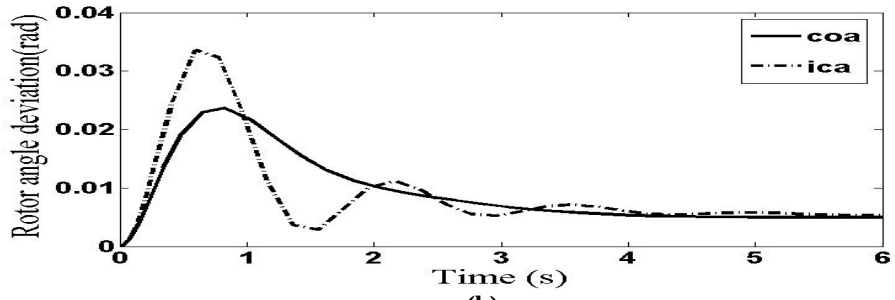
Table 4. System electromechanical modes with and without controllers

	Nominal loading	**Light loading**	**Heavy loading**
Without controller	-15.7666 0.7829 + 4.0025*i* 0.7829 - 4.0025*i* -5.1985 -1.0609	-18.7198 + 0.0174*i* -2.3480 + 6.9683*i* -2.0317 - 6.7508*i* 2.7594 - 0.5147*i* -0.1206 + 0.2830*i*	-15.5627 0.6923 + 4.1968*i* 0.6923 - 4.1968*i* -5.6635 -0.6228
COA controller	-15.9698 -2.0460 + 3.1647*i* -2.0460 - 3.1647*i* -4.5630 -3.3181 -0.1934 -2.0576 + 0.3891*i* -2.0576 - 0.3891*i*	-15.2480 -2.5627 + 3.8890*i* -2.5627 - 3.8890*i* -6.1946 -3.4282 -0.1868 -0.8237 + 0.3134*i* -0.8237 - 0.3134*i*	-15.7682 -2.0955 + 4.0187*i* -2.0955 - 4.0187*i* -5.1338 + 1.3119*i* -5.1338 - 1.3119*i* -0.1917 -1.0092 + 0.3956*i* -1.0092 - 0.3956*i*
ICA controller	-15.7642 -1.0957 + 3.7850*i* -1.0957 - 3.7850*i* -4.5240 -4.2012 -2.4679 -0.1956 -0.6667	-15.0442 -1.7770 + 3.9501*i* -1.7770 - 3.9501*i* -6.0907 -3.5658 -0.1908 -0.6714 -0.6667	-15.5567 -1.2578 + 4.3209*i* -1.2578 - 4.3209*i* -5.1153 + 1.1081*i* -5.1153 - 1.1081*i* -0.9413 -0.1944 -0.6667

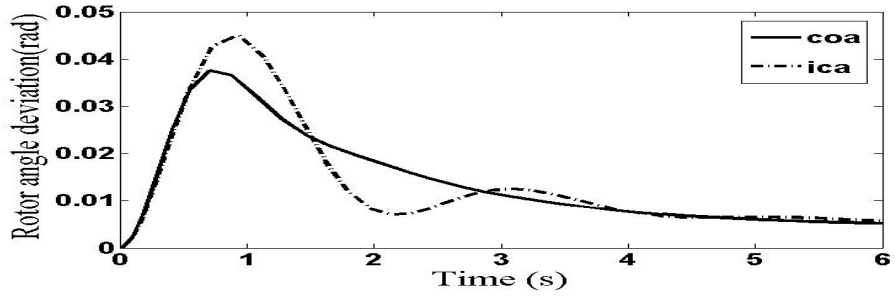
The system eigen values and damping ratios of electromechanical modes with and without controllers at 3 different loading conditions are given in table 4. It is obvious that the open loop system is unstable, whereas the proposed COA and ICA controllers stabilize the system. The electromechanical mode eigen values have been shifted to the left in s-plane and the system damping with the proposed methods greatly improved and in creased. The system behavior due to the utilization of the proposed controllers has been tested by applying 1% and 10% steps increase in mechanical power input at t = 0 s. The system response to these disturbances under 3 different loading conditions for speed deviation and Rotor angle deviation with δ_E based controller, as well as, with controllers, are shown in Figures 7-10.It can be observed from Figs. 7-10 that the performance of the system is better with the proposed COA optimized lead-lag controller compared to the ICA optimized lead-lag controller. Also, simulation results clearly illustrate, proposed objective function-based optimized UPFC controller with COA, has good performance in damping low-frequency oscillations and stabilizes the system quickly in compared to the ICA method.



(a)

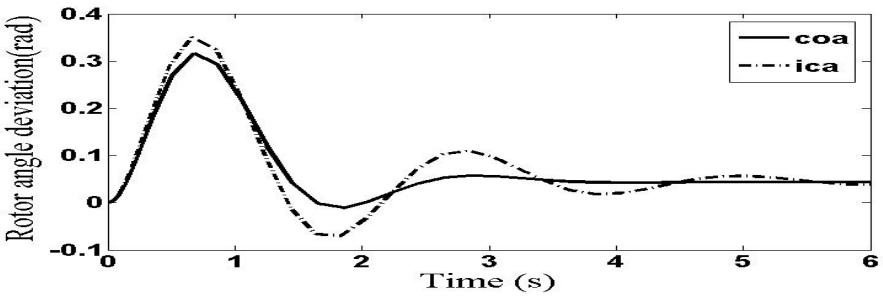


(b)

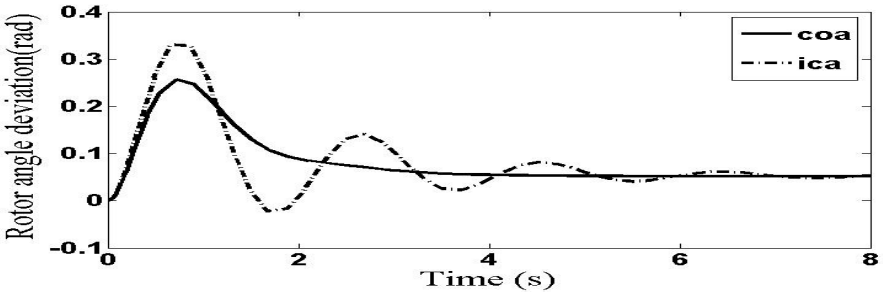


(c)

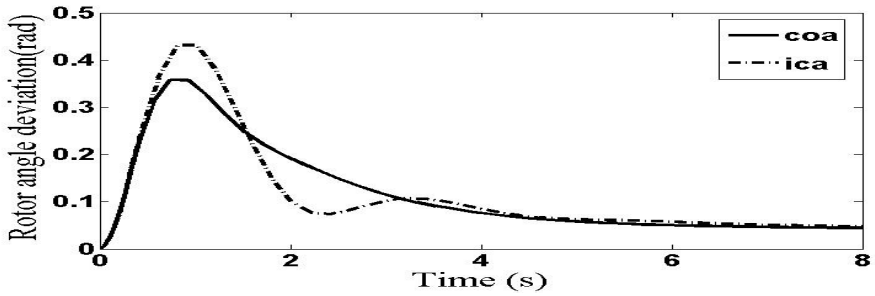
Figure 7. Rotor angle responses for ΔP_m= 0.01(a) Nominal loading (b) Heavy loading (c) Light loading



(a)

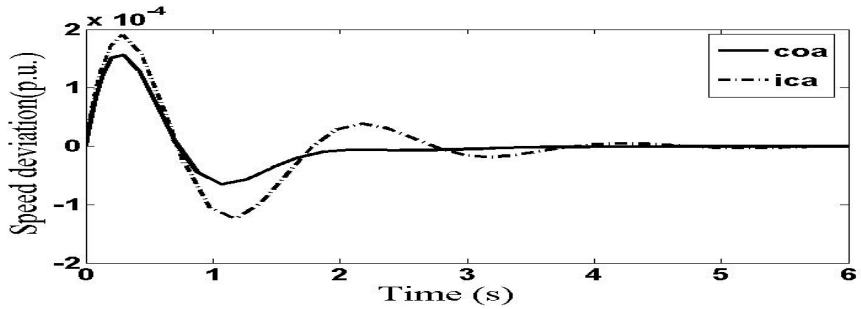


(b)

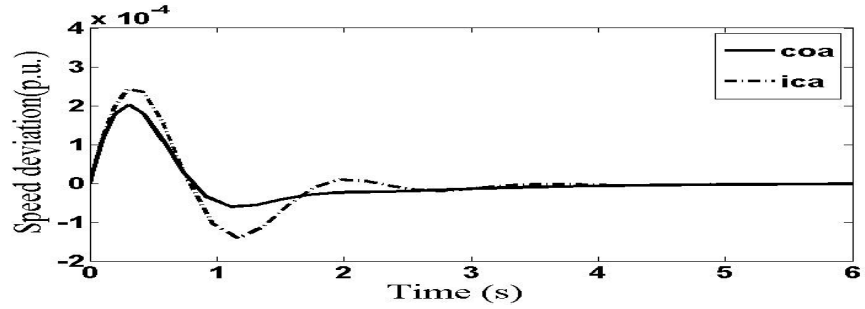


(c)

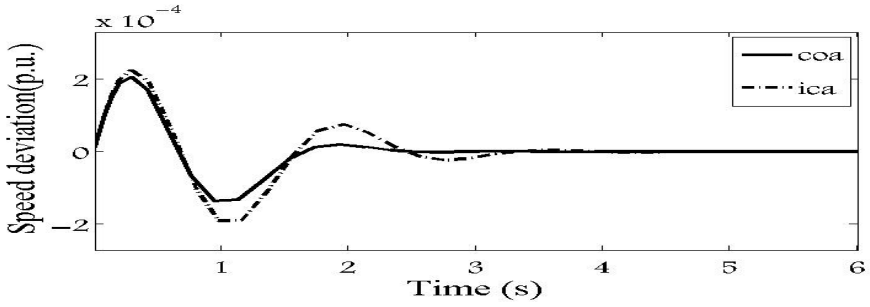
Figure 8. Rotor angle responses for ΔP_m= 0.1(a) Nominal loading (b) Heavy loading (c) Light loading



(a)

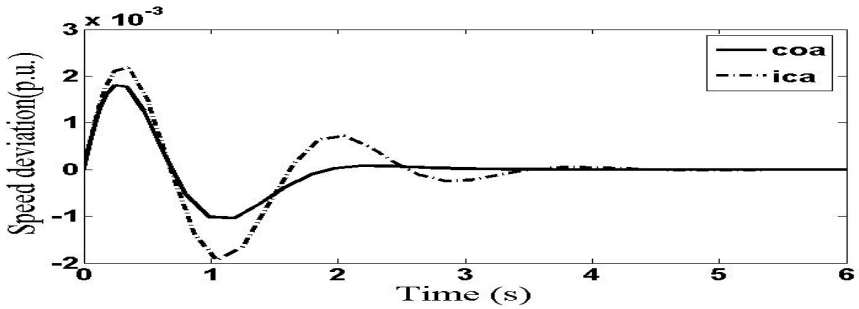


(b)

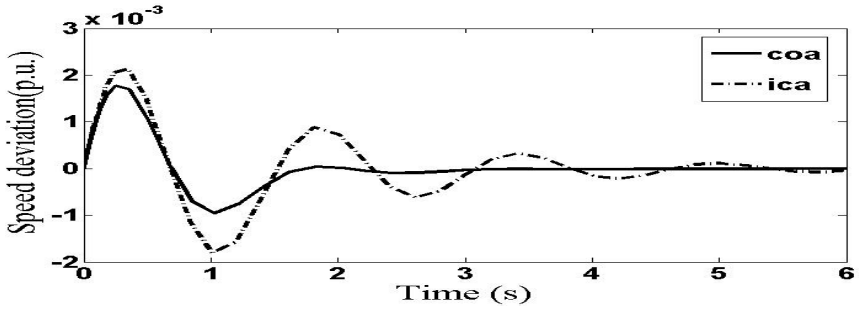


(c)

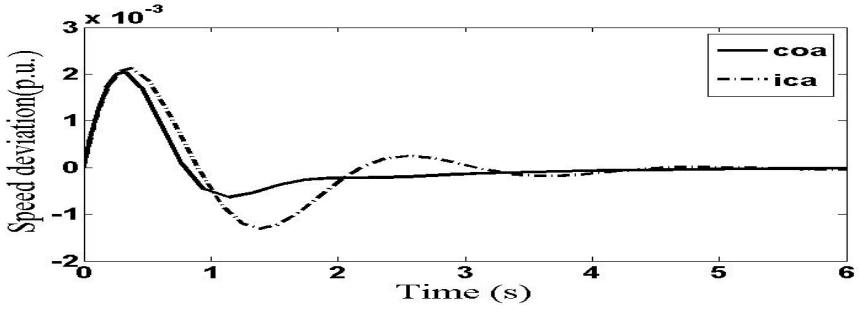
Figure 9. Rotor speed responses for ΔP_m= 0.01(a) Nominal loading (b) Heavy loading (c) Light loading



(a)



(b)



(c)

Figure10. Rotor speed responses for ΔP_m= 0.1(a) Nominal loading (b) Heavy loading (c) Light loading

6. Conclusions

In this paper, an optimization technique has been proposed to design the UPFC controller. COA has been utilized to search for the optimal controller parameters setting that optimizes the nonlinear time domain objective function. The controller parameters design was converted into an optimization problem, which was solved using the COA technique with the eigenv alue-based single-objective function. The effectiveness of the proposed UPFC controller for damping low-frequency oscillations of a power system were demonstrated by a weakly connected example power system subjected to a disturbance, an increasing mechanical power. The designed COA and ICA controllers are applied to the system and their responses are compared with each other. The eigen value analysis, cost values and time-domain simulation results showed the effectiveness of the proposed COA controller in damping low-frequency oscillations under all of load conditions. Simulation results operated by MATLAB/SIMULINK confirm that COA method has an excellent capability in power system oscillations damping and power system stability enhancement under small disturbances in compare to ICA method.

7. Appendix

The nominal parameters and operating condition of the system are:
Generator
M=8.0MJ/MVA, D = 0.0, T'_{do}=5.044s, f = 60 Hz
v = 1.05 pu, x_d= 1.0 pu, x_q= 0.6pu, x'_d = 0.3 pu
Excitation System
K_A= 100, T_A= 0.01s
Transformer
x_{tE}= 0.1 pu
Transmission Line
x_{BV}= 0.6 pu, x_T = 0.6 pu
UPFC
x_E= 0.1 pu, x_B= 0.1 pu, K_s = 1.0, T_s = 0.05s
T_w= 5.0s, V_{dc}= 2 pu, C_{dc} = 1pu

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