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Improvement of Low Frequency Oscillations Damping Model in Presence of UPFC by Cuckoo Optimization Algorithm

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Abstract

Low frequency oscillation (LFO) is a negative phenomenon in the power systems, which increases the risk of instability. Low frequency oscillations in power systems due to lack of damping torque to overcome the power system disorders, occurs when mechanical input power changes. In recent years, power system stabilizer (PSS) for damping low frequency oscillations has been used; but nowadays with using of FACTS devices such as unified power flow controller (UPFC), we can also control network power flow and increase transient stability. Therefore, UPFC with low frequency oscillation damping capability can be used instead of PSS. In this paper, a single linear Heffron-Philips model of synchronous machine connected to an infinite bus in the presence of UPFC is used to improve low frequency oscillation damping. The selection of output feedback parameters for the UPFC controllers is converted to an optimization problem that is solved by cuckoo optimization algorithm (COA). COA, as a new evolutionary optimization algorithm, is usually used in multiple applications. This optimization algorithm has a strong ability to find the most optimistic results for dynamic stability improvement. Simulation of UPFC controller and damping of LFO in MATLAB software environment is planned and tested. The simulation was performed for variety kinds of loads in various levels. Also, more effective results of electromechanical oscillation damping in UPFC controller with COA is compared to the results of the other algorithms.

***Keywords**: Low Frequency Oscillations (LFO), Unified Power Flow Controller (UPFC), Single Machine-Infinite Bus (SMIB), Cuckoo optimization algorithm (COA).*

1. Introduction

The Benefits of Flexible AC Transmission Systems (FACTS) usages to improve power systems stability are well known [1, 2]. The growth of the demand for electrical energy leads to loading the transmission system near to their limits. Thus, the occurrence of the Low Frequency Oscillation (LFO) has increased. FACTS controllers have some capabilities to control network conditions quickly and this feature of FACTS can be used to improve power system stability. The UPFC is a FACTS device that can be used to control LFO. The primarily and fundamental usage of UPFC is controlling of power flow in power systems. The UPFC consists of two voltage source converters (VSC), each of them has two control parameters namely me, δe, mb and δb. The UPFC usually is used to power flow control, enhancement of transient stability, mitigation of system oscillations and voltage regulation [3]. A comprehensive and systematic approach for mathematical modeling of UPFC for steady-state and small signal dynamic studies has been proposed in [4, 7]. The other modified linearized Heffron-Philips model of a power system equipped with UPFC is presented in [8] and [9]. For networks without power system stabilizer (PSS), an excellent damping can be achieved through a proper design for UPFC controller parameters. In another word, by designing a suitable UPFC controller, an effective damping can be achieved. It is usual that Heffron-Philips model is used in power system to study small signal stability concepts. This model has been used for many years providing reliable results [10].

In this study, To show performance of the designed adaptive Lead-lag controller, a conventional lead-lag controller that is designed in [11] is used and the simulation results for the power system including these two controllers are compared together.

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The damping control strategy employs non-optimal fuzzy logic controller that is why the system response settling time is intolerable. Moreover, the initial parameters adjustment of this kind of controller needs a trial and error procurer. Khon and Lo [17] used a fuzzy damping controller designed by micro Genetic Algorithm (GA) for TCSC and UPFC to improve power 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 strictly 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 capability, like the power system, 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 some 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 [18].

In this paper, an UPFC damping lead-lag controller is planned using COA to find the optimal values of the five parameters of this controller. Also The COA is used to obtain the optimal values of the supplementary controller parameters of a the UPFC. To show effectiveness of COA method, it is compared for various load conditions and large disturbances.

2.2. Power System Modeling In Presence of UPFC

UPFC is one of FACTS devices that can be used to improve power system stability. Figure 1 indicates a Heffron-Philips model for a single machine, connected to an infinite bus system in presence of UPFC. This figure also shows m_e, m_b and δ_e, δ_b values of UPFC input control signals, the amplitude ratio and phase nominal voltage of the voltage source converter.

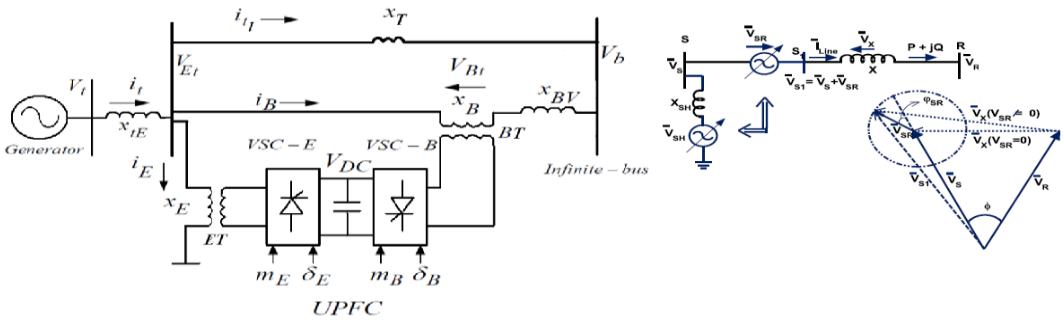

Figure 1. Heffron-Philips Model of a Power System Equipped with UPFC [2]

A general linear model used in the study of power system dynamic. UPFC dynamic model for low frequency oscillation damping UPFC in effect, have been used. In this model, transient resistance and transformer of UPFC can be ignored. Dynamic equations of system are as follows [7]:

$$\dot{\delta}_i = \omega_i - \omega_0 \tag{1}$$

$$\dot{\omega}_i = \frac{1}{M_i}(P_{mi} - P_{ei} - D_i(\omega_i - \omega_0)/\omega_0) \tag{2}$$

$$\dot{E}''_{qi} = \frac{1}{T''_{doi}}[-E_{fdi} - (X'_{di} - X''_{di})I_{di} - E''_{qi} + E'_{qi}] + \dot{E}'_{qi} \tag{3}$$

$$\dot{E}_{fdi} = \frac{1}{T_{Ai}}(-E_{fdi} + K_{Ai}(V_{refi} - V_{Ti})) \tag{4}$$

$$E_d = -r_a I_d + \frac{\dot{E}_{qi}^{''}}{\omega_0} + E_d^{''} + X_q^{''} I_q \tag{5}$$

$$E_q = -r_a I_q + \frac{\dot{E}_{di}^{''}}{\omega_0} + E_q^{''} + X_d^{''} I_d \tag{6}$$

$$T_e = E_d^{''} I_d + E_q^{''} I_q + (X_q^{''} - X_d^{''}) I_d I_q \tag{7}$$

There are several models for UPFC depending on several study cases. The following equations describe the dynamic behavior of an UPFC [7]. series and shunt voltage ratio of UPFC are expressed as follows:

$$\begin{cases} V_{SH} = \dfrac{m_{SH} V_{dc}}{2\sqrt{2} V_B} \\ V_{SR} = \dfrac{m_{SR} V_{dc}}{2\sqrt{2} V_B} \end{cases} \tag{8}$$

Series and shunt voltage angle of UPFC are as:

$$\begin{cases} \phi_{SH} = \angle(\phi_S - \varphi_{SH}) \\ \phi_{SR} = \angle(\phi_S - \varphi_{SR}) \end{cases} \tag{9}$$

Series and shunt power of UPFC:

$$\begin{cases} P_{SH} = R_e(\overline{V}_{SH} \overline{I}_{SH}^{*}) = R_e(\overline{V}_{SH} (\dfrac{\overline{V}_S - \overline{V}_{SH}}{jX_{SH}})^{*}) \\ P_{SR} = R_e(\overline{V}_{SR} \overline{I}_{L}^{*}) = R_e(\overline{V}_{SR} (\dfrac{\overline{V}_S + \overline{V}_{SR} - \overline{V}_R}{j(X_{SR} + X_L)})^{*}) \end{cases} \tag{10}$$

Series and shunt voltage term of UPFC with ingratiate, angle and amplitude inputs, capasitor votage UPFC terms are indicated as [22]:

$$\begin{pmatrix} V_{SHd} \\ V_{SHq} \\ V_{SRd} \\ V_{SRq} \end{pmatrix} = \begin{pmatrix} 0 & -X_{SH} & 0 & 0 \\ X_{SH} & 0 & 0 & 0 \\ 0 & 0 & 0 & -X_{SR} \\ 0 & 0 & X_{SR} & 0 \end{pmatrix} \begin{pmatrix} I_{SHd} \\ I_{SHq} \\ I_{SRd} \\ I_{SRq} \end{pmatrix} + \begin{pmatrix} m_{SH} V_{dc} \cos(\varphi_{SH}) \ /2 \\ m_{SH} V_{dc} \sin(\varphi_{SH}) \ /2 \\ m_{SR} V_{dc} \cos(\varphi_{SR}) \ /2 \\ m_{SR} V_{dc} \sin(\varphi_{SR}) \ /2 \end{pmatrix} \tag{11}$$

$$I_{SHd} = \frac{X_{SRL} E_q^{'}}{X_{DT}} - \frac{X_{SRLTd}}{X_{DT}} \frac{m_{SH} V_{dc} \sin(\varphi_{SH})}{2} + \frac{X_{Td}}{X_{DT}} V_I \cos(\delta) + \frac{X_{Td}}{X_{DT}} \frac{m_{SR} V_{dc} \sin(\varphi_{SR})}{2} \tag{12}$$

$$I_{SHq}=\frac{X_{SRLTq}}{X_{QT}}\frac{m_{SH}V_{dc}\cos(\varphi_{SH})}{2}-\frac{X_{Tq}}{X_{QT}}V_I\sin(\delta)\ -\frac{X_{Tq}}{X_{QT}}\frac{m_{SR}V_{dc}\cos(\varphi_{SR})}{2} \tag{13}$$

$$I_{SRd}=\frac{X_{SH}E_q'}{X_{DT}}+\frac{X_{Td}}{X_{DT}}\frac{m_{SH}V_{dc}\sin(\varphi_{SH})}{2}\ -\frac{X_{TSHd}}{X_{DT}}V_I\cos(\delta)-\frac{X_{TSHd}}{X_{DT}}\frac{m_{SR}V_{dc}\sin(\varphi_{SR})}{2} \tag{14}$$

$$I_{SRq}=\frac{X_{TSHq}}{X_{QT}}\frac{m_{SR}V_{dc}\cos(\varphi_{SR})}{2}+\frac{X_{TSHq}}{X_{QT}}V_I\sin(\delta)\ -\frac{X_{Tq}}{X_{QT}}\frac{m_{SH}V_{dc}\cos(\varphi_{SH})}{2} \tag{15}$$

$$\begin{bmatrix}v_{Etd}\\ v_{Etq}\end{bmatrix}=\begin{bmatrix}0 & -x_E\\ x_E & 0\end{bmatrix}\begin{bmatrix}i_{Ed}\\ i_{Eq}\end{bmatrix}+\begin{bmatrix}\frac{m_E v_{dc}\cos\delta_E}{2}\\ \frac{m_E v_{dc}\sin\delta_E}{2}\end{bmatrix} \tag{16}$$

$$\begin{bmatrix}v_{Btd}\\ v_{Btq}\end{bmatrix}=\begin{bmatrix}0 & -x_B\\ x_B & 0\end{bmatrix}\begin{bmatrix}i_{Bd}\\ i_{Bq}\end{bmatrix}+\begin{bmatrix}\frac{m_B v_{dc}\cos\delta_B}{2}\\ \frac{m_B v_{dc}\sin\delta_B}{2}\end{bmatrix} \tag{17}$$

$$\frac{dv_{dc}}{dt}=\frac{3m_E}{4C_{dc}}\begin{bmatrix}\cos\delta_E & \sin\delta_E\end{bmatrix}\begin{bmatrix}i_{Ed}\\ i_{Eq}\end{bmatrix}+\frac{3m_B}{4C_{dc}}\begin{bmatrix}\cos\delta_B & \sin\delta_B\end{bmatrix}\begin{bmatrix}i_{Bd}\\ i_{Bq}\end{bmatrix} \tag{18}$$

Now, Calculation of K_1-K_9 for Lead_lag controller [17]:

$$K_1=\frac{V_s}{X_d'}e_{q_0}Cos\theta_0+\left(\frac{X_d'-X_q}{X_d'X_q}\right)V_s^2\ Cos2\theta$$
(19)

$$K_2=\frac{V_s}{X_d'}Sin\theta_0$$
(20)

$$K_3=\frac{X_d'}{X_d}$$
(21)

$$K_4=\frac{X_d-X_d'}{X_d'}V_sSin\theta_0$$
(22)

$$K_5=\frac{V_{tqo}}{V_{to}}\left(\frac{X_q-X_e}{X_q}\right)V_sCos\theta+\left(\frac{X_d'-X_e}{X_d}\right)V_sSin\theta_0$$
(23)

By combining the above linear dynamic equations. The state equations expressed as follows [6]:

$$K_6 = \frac{\partial V_{dc}}{\partial m_{SH}} = \frac{V_{tqo}}{V_{to}}\left(\frac{X_e}{X_d'}\right)$$
(24)

$$K_7 = \frac{\partial V_{dc}}{\partial \varphi_{SH}}$$
(25)

$$K_8 = \frac{\partial V_{dc}}{\partial m_{SR}}$$
(26)

$$K_9 = \frac{\partial V_{dc}}{\partial \varphi_{SR}}$$
(27)

$$\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{Bu}$$
(28)

Where the matrixces [6]:

$$\boldsymbol{u} = \begin{bmatrix} \Delta \boldsymbol{u}_{pss} & \Delta \boldsymbol{m}_E & \Delta \delta_E & \Delta \boldsymbol{m}_B & \Delta \delta_B \end{bmatrix}^T$$
$$\boldsymbol{x} = \begin{bmatrix} \Delta \delta & \Delta \omega & \Delta \boldsymbol{E}_q' & \Delta \boldsymbol{E}_{fd} & \Delta \boldsymbol{v}_{dc} \end{bmatrix}^T$$
(29)

By combining and linearizing Equation (1) to (4), UPFC and single machine infinite bus power system (24), the state variable equations of the power system equipped with the UPFC can be represented as follows [22].

$$\dot{V}_{dc} = \frac{3m_{SH}}{4C_{dc}}[\cos(\varphi_{SH})I_{SHd} + \sin(\varphi_{SH})I_{SHq}] + \frac{3m_{SR}}{4C_{dc}}[\cos(\varphi_{SR})I_{SRd} + \sin(\varphi_{SR})I_{SRq}] \quad (30)$$

$$\Delta \dot{\boldsymbol{V}}_{dc} = \boldsymbol{K}_7 \Delta \delta + \boldsymbol{K}_8 \Delta \boldsymbol{E}_q' - \boldsymbol{K}_9 \Delta \boldsymbol{V}_{dc} + \boldsymbol{K}_{ce} \Delta \boldsymbol{m}_E + \boldsymbol{K}_{c\delta e} \Delta \delta_E + \boldsymbol{K}_{cb} \Delta \boldsymbol{m}_B + \boldsymbol{K}_{c\delta b} \Delta \delta_B \quad (31)$$

$$\begin{bmatrix} \Delta \overset{o}{\delta} \\ \Delta \overset{o}{\omega} \\ \Delta \overset{o}{E_q'} \\ \Delta \overset{o}{E}_{qe} \end{bmatrix} = \begin{bmatrix} 0 & \omega_o & 0 & 0 \\ -\frac{K1}{M} & -\frac{D}{M} & -\frac{K2}{M} & 0 \\ -\frac{K_4}{T_{do}'} & 0 & \frac{K_3}{T_{do}'} & \frac{1}{T_{do}'} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta \omega \\ \Delta E_q' \\ \Delta E_{qe} \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{K_{pd}}{M} \\ -\frac{K_{qd}}{T_{do}'} \\ -\frac{K_A K_{vd}}{T_A} \end{bmatrix} \Delta V_{dc}$$
$$+ \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\frac{K_{Pe}}{M} & -\frac{K_{p\delta e}}{M} & -\frac{K_{pb}}{M} & -\frac{K_{p\delta b}}{M} \\ -\frac{K_{qe}}{T_{do}'} & -\frac{K_{q\delta e}}{T_{do}'} & -\frac{K_{qb}}{T_{do}'} & -\frac{K_{q\delta b}}{T_{do}'} \\ -\frac{K_A K_{ve}}{T_A} & -\frac{K_A K_{v\delta e}}{T_A} & -\frac{K_A K_{vb}}{T_A} & -\frac{K_A K_{v\delta b}}{T_A} \end{bmatrix} \begin{bmatrix} \Delta m_E \\ \Delta \delta_E \\ \Delta m_B \\ \Delta \delta_B \end{bmatrix} \quad (32)$$

Where Δm_e, $\Delta\delta_e$, Δm_b and, $\Delta\delta_b$ are the variations of UPFC control parameters considered as the inputs of state space model. The active power equation in series and shunt convertor of UPFC can be evaluated as follows [21-23]:

$$\mathrm{Re}(V_B I_B^* - V_E I_E^*) = 0 \tag{33}$$

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E_q' + K_{pd}\Delta v_{dc} + K_{pe}\Delta m_E + K_{p\delta e}\Delta\delta_E + K_{pb}\Delta m_B + K_{p\delta b}\Delta\delta_B \tag{34}$$

$$\Delta E_q' = K_4\Delta\delta + K_3\Delta E_q' + K_{qd}\Delta v_{dc} + K_{qe}\Delta m_E + K_{q\delta e}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta b}\Delta\delta_B \tag{35}$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E_q' + K_{vd}\Delta V_{dc} + K_{ve}\Delta m_E + K_{v\delta e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B \tag{36}$$

See A and B matrix in bottom [20]:

$$A = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{k_1}{M} & -\frac{D}{M} & -\frac{k_2}{M} & 0 & -\frac{k_{pd}}{M} \\ -\frac{k_4}{T_{do}'} & 0 & -\frac{k_3}{T_{do}'} & \frac{1}{T_{do}'} & -\frac{k_{qd}}{T_{do}'} \\ -\frac{k_A k_5}{T_A} & 0 & -\frac{k_A k_6}{T_A} & -\frac{1}{T_A} & -\frac{k_A k_{vd}}{T_A} \\ k_7 & 0 & k_8 & 0 & -k_9 \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{k_{pe}}{M} & -\frac{k_{p\delta e}}{M} & -\frac{k_{pb}}{M} & -\frac{k_{p\delta b}}{M} \\ 0 & -\frac{k_{qe}}{T_{do}'} & -\frac{k_{q\delta e}}{T_{do}'} & -\frac{k_{qb}}{T_{do}'} & -\frac{k_{q\delta b}}{T_{do}'} \\ \frac{k_A}{T_A} & -\frac{k_A k_{ve}}{T_A} & -\frac{k_A k_{v\delta e}}{T_A} & -\frac{k_A k_{vb}}{T_A} & -\frac{k_A k_{v\delta b}}{T_A} \\ 0 & k_{ce} & k_{c\delta e} & k_{cb} & k_{c\delta b} \end{bmatrix} \tag{37}$$

3. Proposed Lead-lag Damping Controller

As mentioned before, in this paper two different controllers have been used to damp LFO. The first one is conventional lead-lag controller that consists a gain block, washout block and lead-lag compensator block. The washout block is considered as a high-pass filter with time constant TW. Without this block steady changes in input would modify the output. The value of TW is not critical and may be in the range of 1 to 20 seconds. In this study, the parameters obtained from lead-lag controller design as presented in [11], have been used.

To adapt the controller gains in real time, it is necessary to determine a proper set of values for the related weights. The process of reaching to the related weights is normally carried out off-line and is usually referred to the training process. In the training process, we first compile a set of training patterns and store them in the training set. Each training pattern comprises a set of input data and corresponding output data [16]. The input are $\Delta\delta$ and $\Delta\omega$ and desired output is the function of f € { $\Delta\delta_B$, $\Delta\delta_E$, m_B, Δm_E }.

The reducing method to obtain data has the following procure [16]:

$$\Delta f = [\Delta v_{dc} \quad \Delta m_E \quad \Delta\delta_E \quad \Delta m_B \quad \Delta\delta_B] \tag{38}$$

$$Kp = \begin{bmatrix} \frac{K_{pd}}{M} & \frac{K_{pe}}{M} & \frac{Kp_{\delta e}}{M} & \frac{K_{pb}}{M} & \frac{K_{p\delta b}}{M} \end{bmatrix} \tag{39}$$

$$Kq = \begin{bmatrix} \frac{K_{qd}}{T_{do}'} & \frac{K_{qe}}{T_{do}'} & \frac{K_{q\delta e}}{T_{do}'} & \frac{K_{qb}}{T_{do}'} & \frac{K_{q\delta b}}{T_{do}'} \end{bmatrix}^T \tag{40}$$

(41)

$$Kv = \begin{bmatrix} \frac{K_A K_{vd}}{T_A} & \frac{K_A K_{ve}}{T_A} & \frac{K_A K_{v\delta e}}{T_A} & \frac{K_A K_{vb}}{T_A} & \frac{K_A K_{v\delta b}}{T_A} \end{bmatrix}^T$$

$$Kpu = \begin{bmatrix} K_{pe} & K_{p\delta e} & K_{pb} & K_{p\delta b} \end{bmatrix} \quad (42)$$

$$Kqu = \begin{bmatrix} K_{qe} & K_{q\delta e} & K_{qb} & K_{q\delta b} \end{bmatrix} \quad (43)$$

$$Kvu = \begin{bmatrix} K_{ve} & K_{v\delta e} & K_{vb} & K_{v\delta b} \end{bmatrix} \quad (44)$$

$$Kcu = \begin{bmatrix} K_{ce} & K_{c\delta e} & K_{cb} & K_{c\delta b} \end{bmatrix} \quad (45)$$

Now, the block diagrams of damper in two controller are as folows:

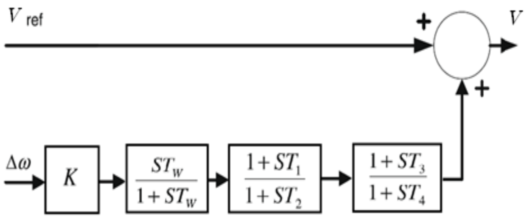

Figure 3. Block Diagram of PSS Controller [11]

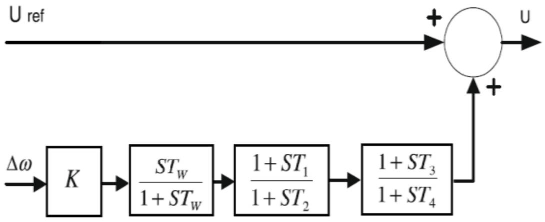

Figure 4. Block Diagram of the Proposed Lead-Lag Damping Controller

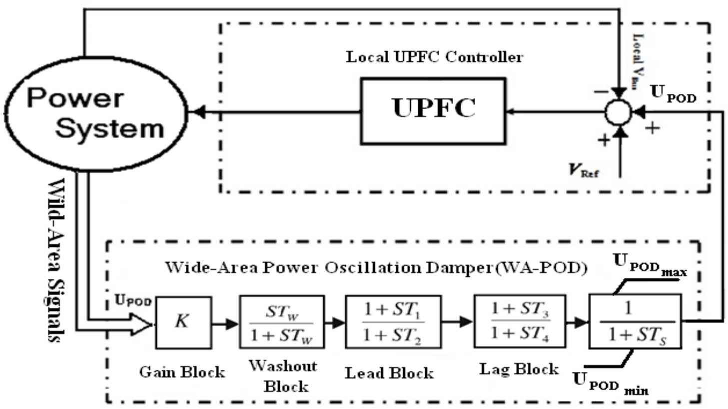

Figure 5. Setting UPFC for Damping LFO in Power System [22]

4. 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 GA, ICA, PSO, etc, starts with an initial population. The cuckoo population, in different societies, is divided into 2 types, mature cuckoos and eggs [19].

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 [19]:

$$\begin{aligned} &\lambda \sim U(0, 1) \\ &\phi \sim U(-\omega, \omega) \end{aligned} \tag{46}$$

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 ELR is calculated for each cuckoo. Then new egg laying process restarts [19].

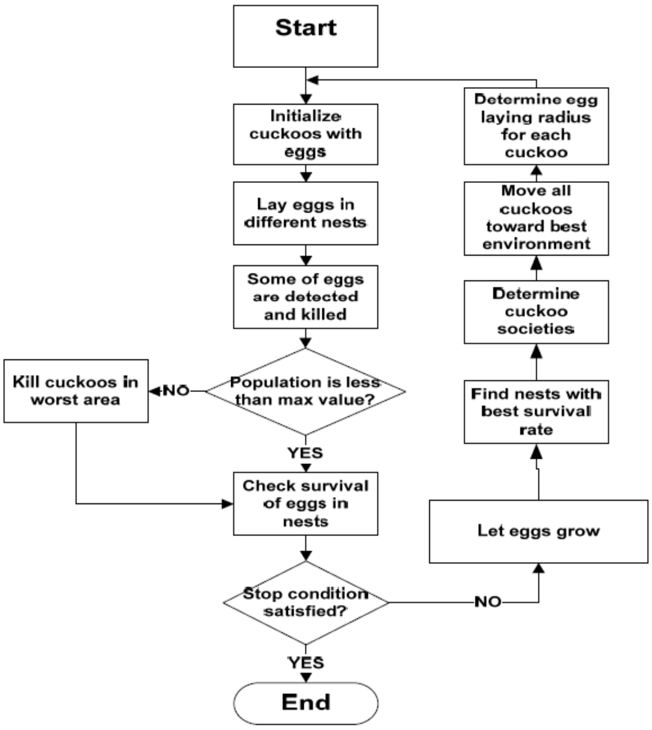

Figure 6. Flowchart of Cuckoo Optimization Algorithm [20] and [21]

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 7, shows the flowchart of the proposed COA technique. Defining the principle of COA and PSO is out of this papers scope and the complete review is given in several papers for instance in [20] and [21].

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 PSO.

For our optimization problem, an Eigen value-based objective function is considered as follows [21-23]:

$$J = \sum_{i=1}^{NP} \left(\sigma_0 - \sigma_i\right)^2 \tag{47}$$

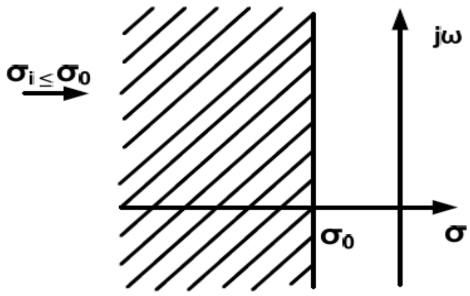

Figure 7. Region of Eigen Value Location for Objective Function [21-23]

In Equation (48), σi is the real part of the its Eigen value of the its operating point and NP 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 8.

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 [21-23]:

Minimize J For the lead-lag controller subject to:

$$\begin{aligned} &K^{\min} \le K \le K^{\max} \\ &T_1^{\min} \le T_1 \le T_1^{\max} \\ &T_2^{\min} \le T_2 \le T_2^{\max} \\ &T_3^{\min} \le T_3 \le T_3^{\max} \\ &T_4^{\min} \le T_4 \le T_4^{\max} \end{aligned} \tag{48}$$

Typical ranges of the optimized five parameters of lead-lag controller are [0, 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 Equation (48), for the lead-lag controller.

Table 1. Optimal Parameters of the Lead-Lag Controller for COA and PSO

	K	T_1	T_2	T_3	T_{4cost}
COA	37.92	01876	0.1903	0.1876	0.1903
PSO	K	T_1	T_2	T_3	T_{4cost}
	37.92	0.4048	0.5816	1.0768	0.8571

5. Simulation Results

In this research, two different cases are studied. In the first case mechanical power and in the second case reference voltage has step change and deviation in ω (Δω) and deviation in rotor angle δ (Δδ) is observed. The parameter values of system are gathered in Appendix. In first case, step change in mechanical input power is studied. 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, 2,4,2 and 300, respectively. Also, in order to acquire better performance of PSO, number of countries, number of initial imperialists, number of decades, assimilation coefficient (β), and ζ were chosen as 50, 6, 300, 3, and 0.2, respectively. It should be noted that both the COA and PSO 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 Table 1 and Table 2, respectively.

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 = 1 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 Figure 8-13. It can be observed from Figure 8-13 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 UPFC controller with COA, has good performance in damping low-frequency oscillations and stabilizes the system quickly in compared to the PSO method.

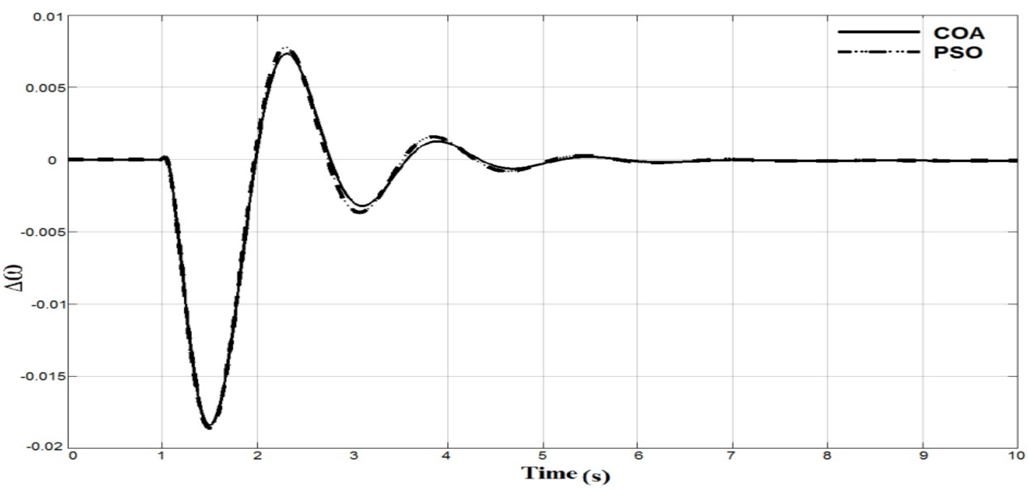

Figure 8. Comparison Out Put Δω for SMB when be UPFC+ PSO Damper Controller and UPFC + COA Damper Controller and Pm=0.1

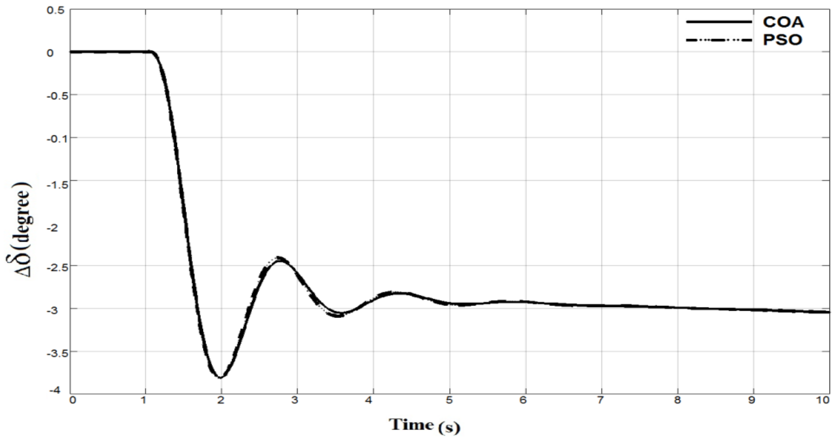

Figure 9. Comparison Δδ for SMB when be UPFC+ PSO Damper Controller and UPFC + COA Damper Controller and Pm=0.1

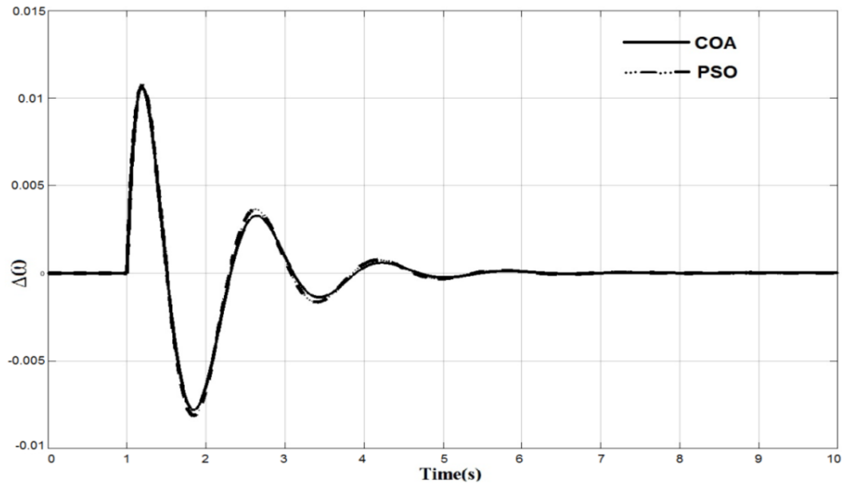

Figure 10. Comparison Out put Δω for SMB when be UPFC+ PSO Damper Controller and UPFC + COA Damper Controller and Pm=1

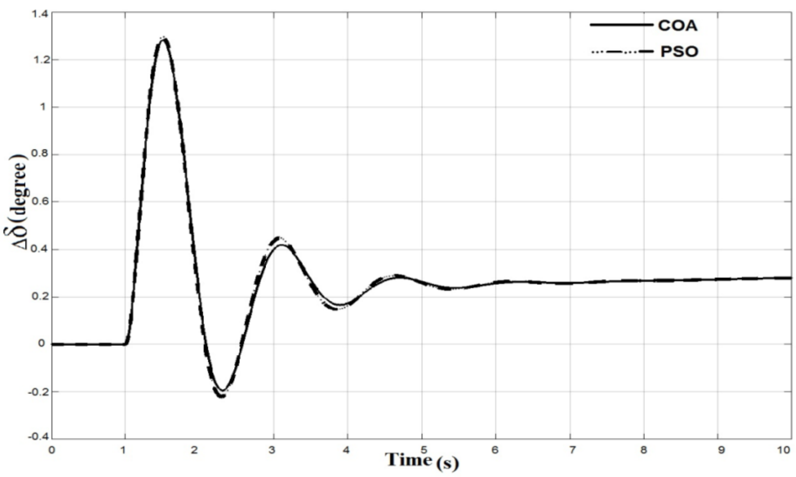

Figure 11. Comparison Δδ for SMB when be UPFC+ PSO Damper Controller and UPFC + COA Damper Controller and Pm=1

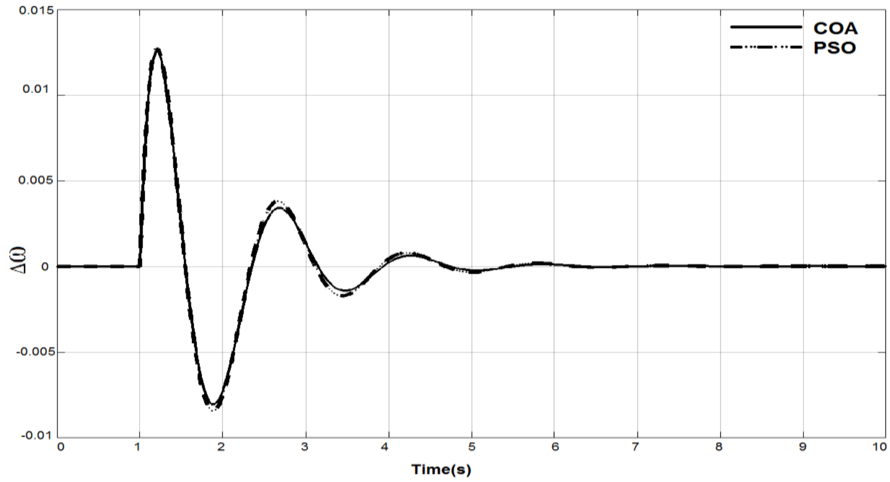

Figure 12. Comparison Out put Δω for SMB when be UPFC+ PSO Damper Controller and UPFC + COA Damper Controller and Pm=1.1

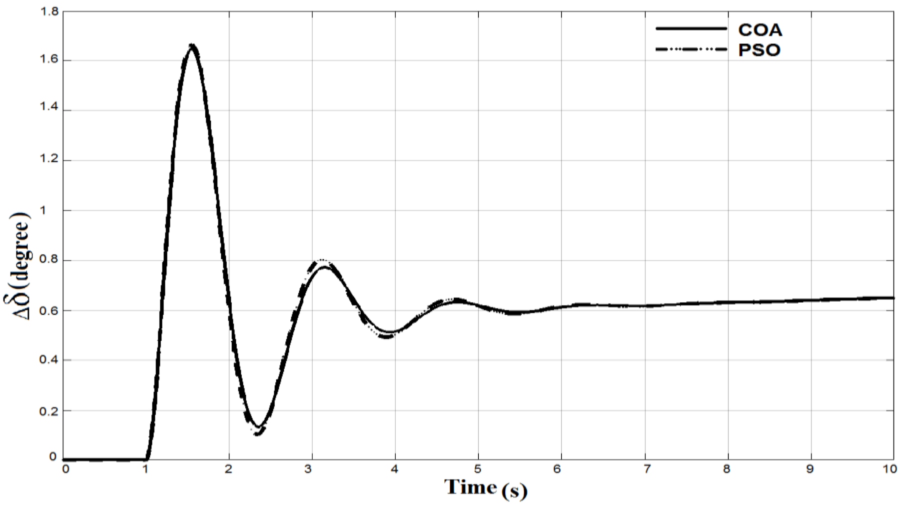

Figure 13. Comparison Δδ for SMB when be UPFC+ PSO Damper Controller and UPFC + COA Damper Controller and Pm=1.1

6. Conclusion

With regard to UPFC capability in transient stability improvement and damping LFO of power systems, an adaptive Lead-lag damping controller for UPFC was presented in this paper. The controller was designed for a single machine infinite bus system. Then simulation results for the system including Lead-lag damping controller were compared with simulation results for the system including conventional lead-lag controller. Simulations were performed for different kinds of loads. Comparison showed that the proposed adaptive Lead-lag damping controller has good ability to reduce settling time and reduce amplitude of LFO. 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 eigen valuebased 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 PSO 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 PSO method.

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