International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online)) Volume 2, Issue 2, February 2014)

Tuning of output feedback UPFC Controller parameters using ICA

M. R. Banaei, Mehdi Mirzaey

[1] *Electrical Engineering Department, Faculty of Engineering, Azarbaijan Shahid Madani University,Tabriz, Iran*
[2] *Electrical Engineering Department, Faculty of Engineering, Azad Malekan University, Tabriz, Iran*

***Abstract*— –In this paper a method for the design of output feedback controller for unified power flow controller (UPFC) to damp low frequency oscillations in a weakly connected system is investigated. The selection of output feedback gains for the UPFC controller is converted to an optimization problem with the Multi objective function which is solved by an imperialist competitive algorithm (ICA) that has a strong ability to find the most optimistic results. The effectiveness and validity of the proposed controller on damping low frequency oscillations is tested through eigenvalue analysis and time domain simulation under three loading conditions and input mechanical torque disturbances. For comparison purposes, a LQR controller is designed. The simulation results carried out by MATLAB/SIMULINK software show that the tuned ICA based output feedback controller has an excellent capability in damping low frequency oscillations and enhance greatly the dynamic stability of the power systems.**

***Keywords* — UPFC, low frequency oscillation damping, ICA.**

I. INTRODUCTION

Power transfer in an integrated power system, is constrained by transient stability, voltage stability and small signal stability. These constraints limit a full utilization of available transmission corridors. The flexible AC transmission system (FACTS) is the technology that provides the needed corrections of the transmission functionality in order to fully utilize the existing transmission facilities and hence, minimizing the gap between the stability limit and thermal limit [1]. Unified power flow controller (UPFC) is one of the FACTS devices which can control power system parameters such as terminal voltage, line impedance and phase angle [2].

Several trials have been reported in the literature to dynamic models of UPFC in order to design suitable controllers for power flow, voltage and damping controls [3]. Nabavi-Niaki and Iravani [4] developed a steady-state model, a small-signal linearized dynamic model, and a state-space large-signal model of a UPFC. Wang [1, 5-6] presents the establishment of the linearized Phillips–Heffron model of a power system installed with a UPFC. Wang has not presented a systematic approach for designing the damping controllers. Further, no effort seems to have been made to identify the most suitable UPFC control parameter, in order to arrive at a robust damping controller. 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 highly nonlinear and stochastic operating nature. Consequently, a fixed-parameter controller based on the classical control theory is not certainly suitable for the UPFC damping control design. Thus, it is required that a flexible controller be developed. Some authors suggested neural networks method [7] and robust control methodologies [8, 9] to cope with system uncertainties to enhance the system damping performance using the UPFC. However, the parameters adjustments of these controllers need some trial and error. Also, although using the robust control methods, the uncertainties are directly 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 feasible because of the computational economical difficulties in implementing. Moreover in [10] authors developed an adaptive UPFC controller to damp low frequency oscillations.

In general, for the simplicity of practical implementation of the controllers, decentralized output feedback control with feedback signals available at the location of the each controlled device is most favorable. Methods for the selection of the TCSC installation locations and the output feedback signals have been developed and reported in [11, 12]. In this paper, Imperialist Competitive Algorithm technique is used for optimal tuning of output feedback gains for the UPFC controllers to improve optimization synthesis and the speed of algorithm convergence. ICA is a new algorithm for global optimization which is inspired by imperialistic competition [13]. All the countries are divided into two types: imperialist states and colonies.

Imperialistic competition is the main part of proposed algorithm and hopefully causes the colonies to converge to the global minimum of the cost function.

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online)) Volume 2, Issue 2, February 2014)

A new approach for the optimal decentralized design of output feedback gains for the UPFC damping controller is investigated in this paper. The problem of robust output feedback controller design is formulated as an optimization problem and ICA technique is used to solve it. The proposed design process for controller with the output feedback scheme is applied to a single-machine infinite-bus power system. Since only local and available states (Δω and ΔVt) are used as the inputs of each controller, the optimal decentralized design of controller can be accomplished. The effectiveness of the proposed controller is demonstrated through eigenvalue analysis and time domain simulation under three loading conditions and input mechanical torque disturbances. Results evaluation show that the proposed output feedback UPFC damping controller achieves good robust performance in damping low frequency oscillations.

II. ICA TECHNIQUE

Imperialist Competitive Algorithm is a new evolutionary optimization method which is inspired by imperialistic competition [13]. Like other evolutionary algorithms, it starts with an initial population which is called country and is divided into two types of colonies and imperialists which together form empires. Imperialistic competition among these empires forms the proposed evolutionary algorithm. During this competition, weak empires collapse and powerful ones take possession of their colonies. Imperialistic competition converges to a state in which there exists only one empire and colonies have the same cost function value as the imperialist.

The pseudo code of Imperialist competitive algorithm is as follows:

1) Select some random points on the function and initialize the empires.
2) Move the colonies toward their relevant imperialist (Assimilation).
3) Randomly change the position of some colonies (Revolution).
4) If there is a colony in an empire which has lower cost than the imperialist, exchange the positions of that colony and the imperialist.
5) Unite the similar empires.
6) Compute the total cost of all empires.
7) Pick the weakest colony (colonies) from the weakest empires and give it (them) to one of the empires (Imperialistic competition).
8) Eliminate the powerless empires.
9) If stop conditions satisfied, stop, if not go to 2.

After dividing all colonies among imperialists and creating the initial empires, these colonies start moving toward their relevant imperialist state which is called assimilation policy [14]. Fig.1 shows the movement of a colony towards the imperialist. In this movement, θ and x are random numbers with uniform distribution as illustrated in (1) and d is the distance between colony and the imperialist.

$$x \approx U(0, \beta \times d), \qquad \theta \approx U(-\gamma, \gamma) \qquad (1)$$

Where, β and γ are parameters that modify the area that colonies randomly search around the imperialist. In ICA, revolution causes a country to suddenly change its socio-political characteristics. That is, instead of being assimilated by an imperialist, the colony randomly changes its position in the socio-political axis. The revolution increases the exploration of the algorithm and prevents the early convergence of countries to local minimums. The total power of an empire depends on both the power of the imperialist country and the power of its colonies which is shown in (2).

T.C.n = Cost (imperialist n) + ζica mean{Cost (colonoes of impire n)} (2)

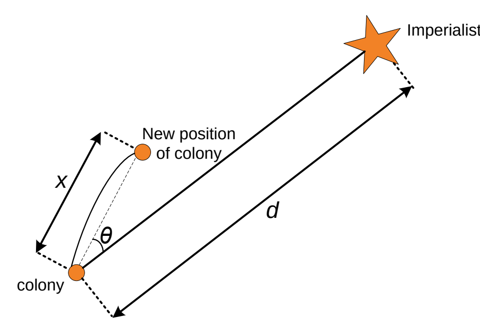

Fig.1. Motion of colonies toward their relevant imperialist

In imperialistic competition, all empires try to take possession of colonies of other empires and control them. This competition gradually brings about a decrease in the power of weaker empires and an increase in the power of more powerful ones. This is modeled by just picking some of the weakest colonies of the weakest empires and making a competition among all empires to possess these colonies.

Fig. 2 shows a big picture of the modeled imperialistic competition. Based on their total power, in this competition, each of the empires will have a likelihood of taking possession of the mentioned colonies. The more powerful an empire, the more likely it will possess the colonies.

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online)) Volume 2, Issue 2, February 2014)

In other words these colonies will not be certainly possessed by the most powerful empires, but these empires will be more likely to possess them. Any empire that is not able to succeed in imperialist competition and cannot increase its power (or at least prevent decreasing its power) will be eliminated.

ICA as a new evolutionary method is used in several applications, such as designing PID controller [15], achieving Nash equilibrium point [16], characterizing materials properties [17], error rate beam forming [18], designing vehicle fuzzy controller [19], etc.

In this paper, ICA is applied to search for the optimal gains of the output feedback controller.

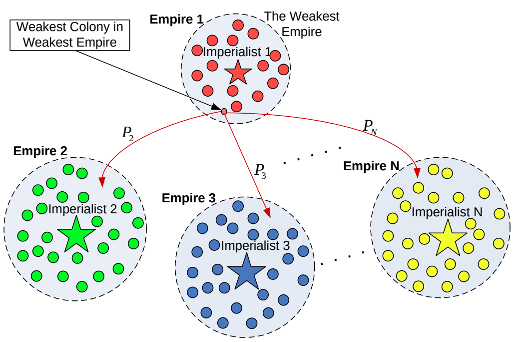

Fig.2. Imperialistic competition

III. Mathematical Modeling

Fig. 3 shows a SMIB power system with a UPFC. The four input control signals of UPFC are mE, mB, δE, and δB. The system data is given in the Appendix.

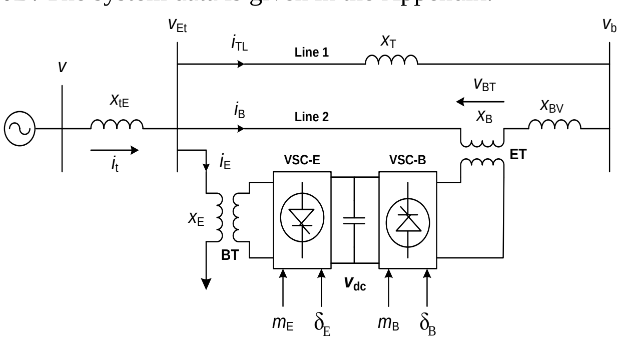

Fig. 3. SMIB Power System Equipped With UPFC

A. Power system non-linear model

The dynamic model of the UPFC is required in order to study the effect of the UPFC for enhancing the small signal stability of the power system. By applying Park's transformation and neglecting the resistance and transients of the ET and BT transformers, the UPFC can be modeled as [1, 4, 20]:

$$\begin{bmatrix} v_{Etd} \\ v_{Etq} \end{bmatrix} = \begin{bmatrix} 0 & -x_E \\ x_E & 0 \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \begin{bmatrix} \frac{m_E \cos\delta_E v_{dc}}{2} \\ \frac{m_E \sin\delta_E v_{dc}}{2} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} v_{Btd} \\ v_{Btq} \end{bmatrix} = \begin{bmatrix} 0 & -x_B \\ x_B & 0 \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \frac{m_B \cos\delta_B v_{dc}}{2} \\ \frac{m_B \sin\delta_B v_{dc}}{2} \end{bmatrix} \quad (4)$$

$$\dot{v}_{dc} = \frac{3m_E}{4C_{dc}} \begin{bmatrix} \cos\delta_E & \sin\delta_E \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \frac{3m_B}{4C_{dc}} \begin{bmatrix} \cos\delta_B & \sin\delta_B \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} \quad (5)$$

where vEt, iE, vBt, and iB are the excitation voltage, excitation current, boosting voltage, and boosting current, respectively; Cdc and vdc are the DC link capacitance and voltage, respectively.

The relations of excitation and boosting transformers parameters and line 2 currents can be written as:

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

$$i_{TLq} = \frac{1}{x_T}\left(x_E i_{Eq} - \frac{m_E \cos\delta_E v_{dc}}{2} + v_b \sin\delta \right) \quad (7)$$

$$i_{Ed} = \frac{x_{BB}}{x_{d2}} E'_q + x_{d7} \frac{m_B \sin\delta_B v_{dc}}{2} + x_{d5} v_b \cos\delta + x_{d6} \frac{m_E \sin\delta_E v_{dc}}{2} \quad (8)$$

$$i_{Eq} = x_{q7} \frac{m_B \cos\delta_B v_{dc}}{2} + x_{q5} v_b \sin\delta + x_{q6} \frac{m_E \cos\delta_E v_{dc}}{2} \quad (9)$$

$$i_{Bd} = \frac{x_E}{x_{d2}} E'_q - \frac{x_{d1}}{x_{d2}} \frac{m_B \sin\delta_B v_{dc}}{2} + x_{d3} v_b \cos\delta + x_{d4} \frac{m_E \sin\delta_E v_{dc}}{2} \quad (10)$$

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online)) Volume 2, Issue 2, February 2014)

$$i_{Bq} = \frac{X_{q1}}{X_{q2}} \frac{m_B \cos \delta_B V_{dc}}{2} + X_{q3} V_b \sin \delta + X_{q4} \frac{m_B \cos \delta_B V_{dc}}{2} \quad (11)$$

Where xE and xB are the ET and BT reactances, respectively; the reactances xqE, xdE, xBB, xd1-xd7 and xq1-xq7 are as shown in [21].

The non-linear model of the SMIB system of Fig. 3 is:

$$\dot{\delta} = \omega_b(\omega - 1) \quad (12)$$

$$\dot{\omega} = (P_m - P_e - D(\omega - 1))/M \quad (13)$$

$$\dot{E}'_q = \left(E_{fd} - \left(x_d - x'_d\right) i_d - E'_q\right)/T'_{d0} \quad (14)$$

$$\dot{E}_{fd} = \left(K_A\left(V_{ref} - v + u_{pss}\right) - E_{fd}\right)/T_A \quad (15)$$

Where,

$$P_e = v_d i_d + v_q i_q \qquad v = \left(v_d^2 + v_q^2\right)^{1/2}$$

$$v_d = x_q i_q \qquad v_q = E'_q - x'_d i_d$$

$$i_d = i_{Ed} + i_{Bd} + i_{TLd} \qquad i_q = i_{Eq} + i_{Bq} + i_{TLq}$$

where Pm and Pe are the input and output power, respectively; M and D the inertia constant and damping coefficient, respectively; ωb 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; xd, x'd, and xq the d-axis reactance, d-axis transient reactance, and q-axis reactance, respectively; KA and TA the exciter gain and time constant, respectively; Vref the reference voltage; and upss the PSS control signal.

B. Power System Linearized Model

The non-linear dynamic equations can be linearized around an operating point condition. The linearized model of power system as shown in Fig. 3 is given as follows:

$$\Delta\dot{\delta} = \omega_b \Delta\omega \quad (16)$$

$$\Delta\dot{\omega} = \frac{1}{M}\left(\Delta P_m - \Delta P_e - D\Delta\omega\right) \quad (17)$$

$$\Delta\dot{E}'_q = \frac{1}{T'_{d0}}\left(-\Delta E'_q + \Delta E_{fd} + (x_d - x'_d)\Delta i_{1d}\right) \quad (18)$$

$$\Delta\dot{E}_{fd} = \frac{1}{T_A}\left(-\Delta E_{fd} + K_A(\Delta V_{tref} - \Delta V_t + \Delta u_{pss})\right) \quad (19)$$

$$\Delta\dot{V}_{dc} = K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta V_{dc} + K_{ce}\Delta m_E + K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B \quad (20)$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E'_q + K_{vd}\Delta V_{dc} + K_{ve}\Delta m_E + K_{v\delta e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B \quad (21)$$

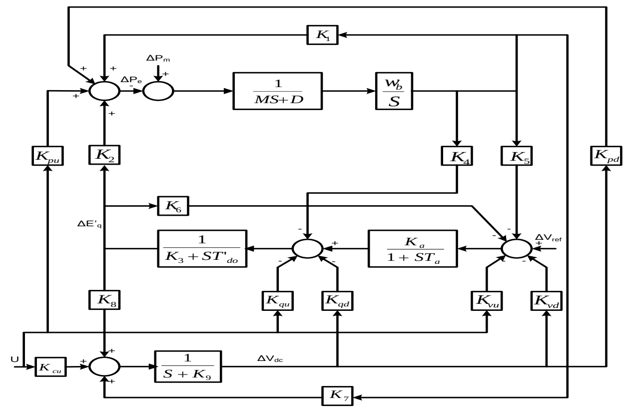

Fig.4. Modified Heffron–Phillips transfer function model.

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

$$\dot{x} = Ax + Bu \quad (22)$$

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

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

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

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

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

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online)) Volume 2, Issue 2, February 2014)

The linearized dynamic model of the state-space representation is shown in Fig. 4.

C. ICA-based output feedback controller design

A power system can be described by a linear time invariant (LTI) state-space model as follows [22]:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{23}$$

where x, y and u denote the system linearized state, output and input variable vectors, respectively. A, B and C are constant matrixes with appropriate dimensions which are dependent on the operating point of the system. The eigenvalues of the state matrix A that are called the system modes define the stability of the system when it is affected by a small interruption. As long as all eigenvalues have negative real parts, the power system is stable when it is subjected to a small disturbance. If one of these modes has a positive real part the system is unstable. In this case, using either the output or the state feedback controller can move the unstable mode to the left hand side of the complex plane in the area of the negative real parts. An output feedback controller has the following structures:

$$u = -Gy \tag{24}$$

Substituting (23) into (22) the resulting state equation

$$\dot{x} = A_c x \tag{25}$$

where Ac is the closed-loop state matrix and is given by:

$$A_c = A - BGC \tag{26}$$

By properly choosing the feedback gain G, the eigenvalues of closed-loop matrix Ac are moved to the left-hand side of the complex plane and the desired performance of controller can be achieved. The output feedback signals can be selected by using mode observability analysis [11, 12]. Once the output feedback signals are selected, only the selected signals are used in forming Eq. (23). Thus, the remaining problem in the design of output feedback controller is the selection of G to achieve the required objectives. The control objective is to increase the damping of the critical modes to the desired level. It should be noted that the four control parameters of the UPFC (mB, mE, δB and δE) can be modulated in order to produce the damping torque. Based on singular value decomposition (SVD) analysis in [10] modulating δE has an excellent capability in damping low frequency oscillations in comparison with other inputs, thus in this paper, δE is modulated in order to damping controller design. The proposed controller must be able to work well under all the operating conditions where the improvement in damping of the critical modes is necessary. Since the selection of the output feedback gains for mentioned UPFC based damping controller is a complex optimization problem. Thus, to acquire an optimal combination, this paper employs ICA to improve optimization synthesis and find the global optimum value of objective function. In this study, the ICA module works offline. Fig. 6 shows the flowchart of the proposed ICA technique.

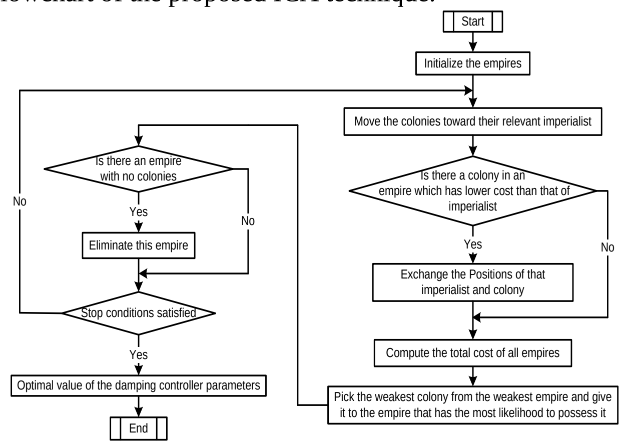

Fig.6. Flowchart of the proposed ICA technique.

For our optimization problem, an eigenvalue based multi objective function reflecting the combination of damping factor and damping ratio is considered as follows [12]:

$$J = J1 + aJ2 \tag{27}$$

Where, $J_1 = \sum_{\sigma_i \geq \sigma_0} (\sigma_0 - \sigma_i)^2$, $J_2 = \sum_{\xi_i \leq \xi_0} (\xi_0 - \xi_i)^2$, σi and ξi are the real part and the damping ratio of the i-th eigenvalue.

In this paper the value of a is chosen at 10. The value of σ0 determines the relative stability in terms of damping factor margin provided for constraining the placement of eigenvalues during the process of optimization. The closed loop eigenvalues are placed in the region to the left of dashed line as shown in Fig. 7-a, if only J1 were to be taken as the objective function. Similarly, if only J2 is considered, then it limits the maximum overshoot of the eigenvalues as shown in Fig. 7-b. In the case of J2, ξ0 is the desired minimum damping ratio which is to be achieved. When optimized with J, the eigenvalues are restricted within a D-shaped area as shown shaded in Fig. 7-c.

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:

$$\begin{aligned} &\text{Minimize } J \\ &\text{Subject to} \\ &G1min \leq G1 \leq G1max \\ &G2min \leq G2 \leq G2max \end{aligned} \tag{28}$$

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online)) Volume 2, Issue 2, February 2014)

Typical ranges of the optimized parameters are [-100 100] for G1 and [-10 10] for G2. The proposed approach employs ICA algorithm to solve this optimization problem and search for an optimal or near optimal set of controller parameters. The optimization of UPFC controller parameters is carried out by evaluating the multiobjective cost function as given in (27).

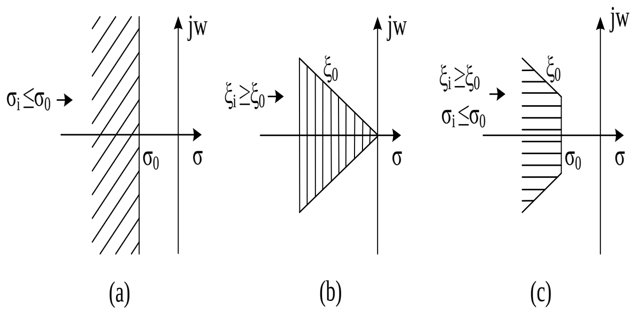

Fig. 7. Region of eigenvalue location for objective functions.

IV. LQR CONTROLLER DESIGN

This method determines the feedback gain matrix that minimizes J, in order to achieve some compromise between the use of control effort, the magnitude, and the speed of response that will guarantee a stable system.

A. *Control Algorithm*

For a given system

$$\dot{x} = Ax + Bu \quad (29)$$

Determine the matrix k of the LQR vector

$$u(t) = -kx(t) \quad (30)$$

So in order to minimize the cost function J, where:

$$J = \int_0^\infty \left(x^T Qx + u^T Ru\right)dt \quad (31)$$

And Q and R are the positive definite or real symmetric matrices. Thus we get a control law as:

$$u(t) = -kx(t) = -R^{-1}B^T Px(t) \quad (32)$$

In which P must be determined to solve the Riccati equation as:

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \quad (33)$$

$$k = [q_1 \quad q_2 \quad \ldots \quad q_n][V_1 \quad V_2 \quad \ldots \quad V_n]^{-1} \quad (34)$$

V. SIMULATION RESULTS

A. *Application of ICA to the design process*

The ICA has been applied to search for the optimal parameter settings of the δE supplementary controller so that the objective function is optimized. In this study, the values of σ0 and ξ0 are taken as -2 and 0.5, respectively. In order to acquire better performance, number of countries, number of initial imperialist, number of decades, assimilation coefficient (β), assimilation angle coefficient (γ), and ζica is chosen as 100, 10, 50, 3, 0.3 and 0.2, respectively.

It should be noted that ICA is run several times and then optimal set of UPFC controller parameters is selected. The final values of the optimized parameters with the multi objective function are given in Table 1.

Also, notice that the optimization process has been carried out with the system operating at nominal loading condition given in Table 2.

Table 1. Optimal parameters of the proposed controller

G1	G2
43.3230	-2.4225

B. *Time Domain Simulation*

To assess the effectiveness of the proposed stabilizer, three different loading conditions given in Table II were considered with an input mechanical torque disturbance.

Table 2. System Operating Conditions

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

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online)) Volume 2, Issue 2, February 2014)

Table 3.
System eigenvalues and damping ratios with and without controllers at the three loading conditions

	Nominal Loading	Light Loading	Heavy Loading
Without Controller	-15.7670 0.7848±j4.00 65, -0.1922 -5.1875 -1.1339	-15.0467 0.1528±j3.74 20, -0.0408 -5.2749 -0.4855	-15.5630 0.6940±j4.19 85, -0.1631 -5.6580 -0.6817
LQR Controller	-15.7732 - 1.9392±j4.5651, 0.3910 -5.5471 -0.7218	-15.0467 - 0.9820±j3.9135, 0.2434 -5.3511 -0.4143	-15.5544 - 1.7443±j4.5458, 0.3582 -5.7281 -0.5161
ICA Output Feedback Controller	-15.7063 - 2.1581±j2.4515, 0.6608 -5.3437 -2.0145	-14.8513 - 2.1340±j2.7143, 0.6181 -6.6670 -0.6865	-15.4087 - 2.8024±j3.0972, 0.6709 -5.7414 -0.8833

The system eigenvalues with and without the controllers at three different loading conditions are given in Table 3. It is clear that the open loop system is unstable, whereas the proposed controllers stabilize the system. It is obvious that the electromechanical mode eigenvalues have been shifted to the left in s-plane and the system damping with the proposed method greatly improved and enhanced. It could be seen that not all of the eigenvalues are shifted to the left part of σ0 but all the damping factors have been improved dramatically and are greater than ξ0.

The system behavior due to the utilization of the proposed controller has been tested by applying a 10% step increase in mechanical power input at t = 1.0s. For comparison purposes, a LQR controller has been designed using the diagonal elements of Q and R as diag [Q] = [1, 8, 0, 0] and diag [R] = [10, 100, 100, 10]. It can be observed from Figs. 8-9 that the performance of the system is better with the proposed ICA optimized output feedback damping controller compared to the LQR controller.

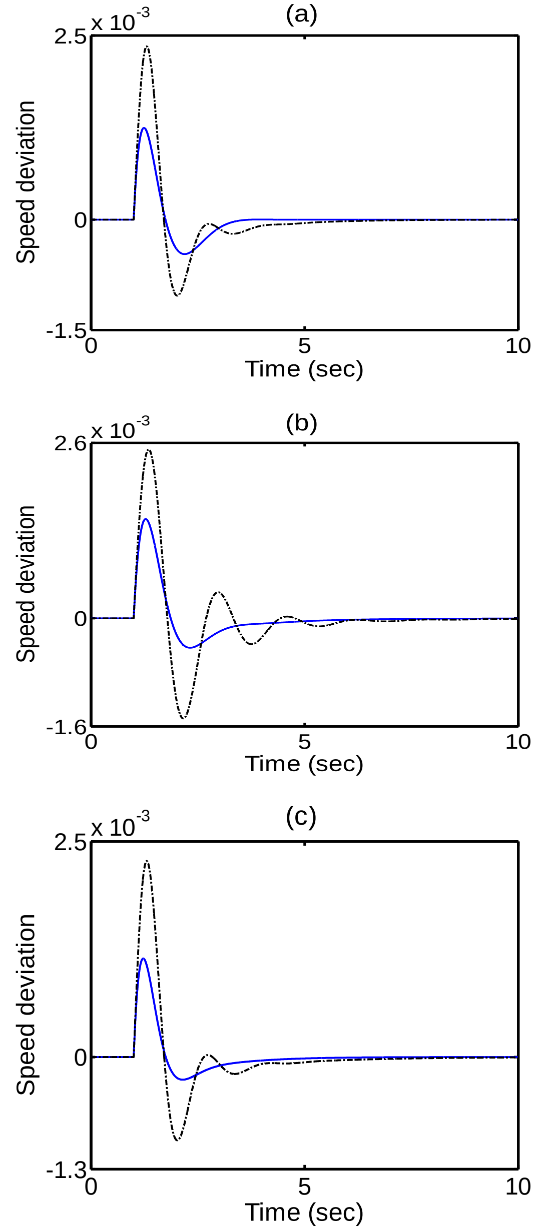

Fig. 8. Dynamic responses to 10% increase in mechanical power for P_e (t=1sec) at (a) nominal (b) light (c) heavy loading conditions; solid (ICA based controller) dash-dotted (LQR based controller).

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online)) Volume 2, Issue 2, February 2014)

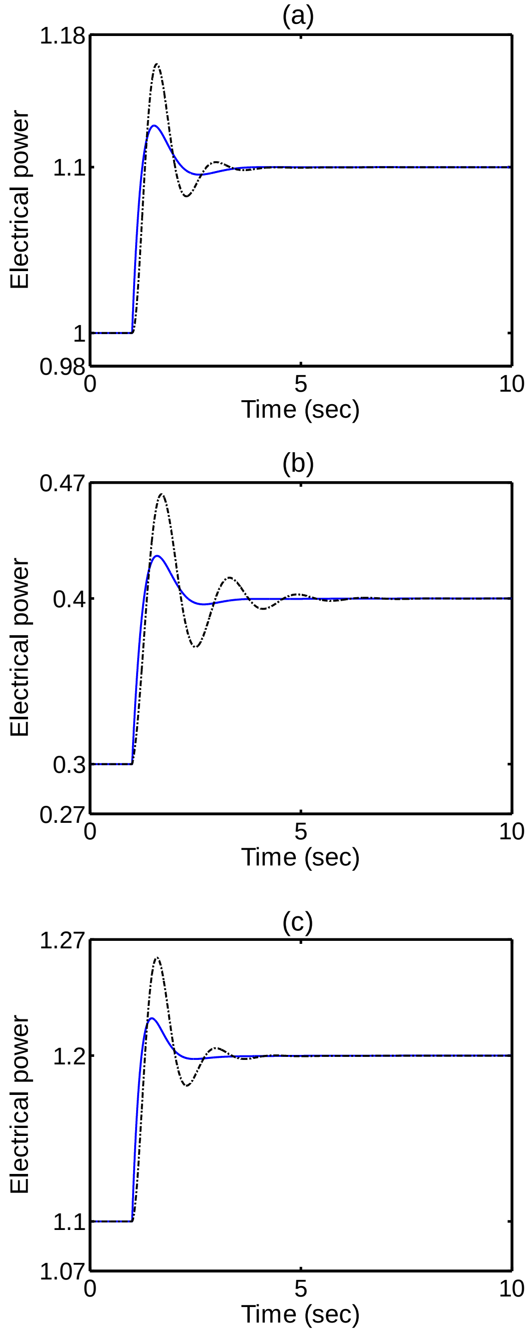

Fig. 9. Dynamic responses to 10% increase in mechanical power for Δω (*t*=1sec) at (a) nominal (b) light (c) heavy loading conditions; solid (ICA based controller) dash-dotted (LQR based controller).

VI. Conclusion

The imperialist competitive algorithm has been successfully applied to the design of robust output feedback UPFC based damping controller. The design problem of the robustly selecting output feedback controller parameters is converted into an optimization problem which is solved by an ICA technique with the multiobjective function. Only the local and available state variables Δω and ΔVt are taken as the input signals of each controller, so the implementation of the designed stabilizers becomes more feasible. The effectiveness of the proposed UPFC controller for improving low frequency oscillation damping of a power system was demonstrated by a weakly connected example power system subjected to mechanical input torque disturbances under different operating conditions. For comparison purposes, a LQR controller has been designed. The eigenvalue analysis and time domain simulation results show the effectiveness of the proposed controller in comparison with LQR based controller.

VII. Appendix

A. The nominal parameters of the system are listed in Table 4.

Table 4. test system parameters

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 = 0.6 pu 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} = 1 pu

References

[1] H. F. Wang, "Damping Function of Unified Power Flow Controller," IEEE Transaction Proceeding-Generation Transmission Distribution, Vol. 146, No. 1, pp. 81-87, January 1999.

[2] Chuan Qin, Wen Juan Du, H.F. Wang, Qun Xu and Ping Ju, "Controllable Parameter Region and Variable-Parameter Design of Decoupling Unified Power Flow Controller," Transmission and Distribution Conference and Exhibition: Asia and Pacific, IEEE/PES, Dalian, China, 2005.

[3] Song YH, Johns AT, Flexible AC Transmission Systems (FACTS). UK: IEE Press; 1999.

[4] Nabavi-Niaki, A. Iravani MR, "Steady-State and Dynamic Models of Unified Power Flow Controller (UPFC) for Power System Studies," IEEE Transaction on Power Systems, 1996, Vol. 11, No. 4, pp. 1937–1943.

[5] H. F. Wang, "A Unified Model for the Analysis of FACTS Devices in Damping Power System Oscillations – part III: Unified Power Flow Controller," IEEE Transaction on Power Delivery, 2000, vol. 15, No. 3, pp. 978–983.

[6] H. F. Wang, "Application of Modeling UPFC into Multi-Machine Power Systems," IEE Proceeding-Generation Transmission Distribution, Vol. 146, No. 3, pp. 306-312, 1999.

[7] Dash PK, Mishra S, Panda G., "A Radial Basis Function Neural Network Controller for UPFC," IEEE Transaction on Power System, 2000, Vol. 15, No. 4, pp. 1293–1299.

[8] Vilathgamuwa M, Zhu X, Choi SS., "A Robust Control Method to Improve the Performance of a Unified Power Flow Controller," Electric Power System Research, 2000, Vol. 55, pp. 103–111.

[9] Pal BC, "Robust Damping of Inter-area Oscillations with Unified Power Flow Controller," IEE Proceeding-Generation Transmission Distribution, Vol. 149, No. 6, pp. 733-738, 2002.

[10] M. R. Banaei, A. Hashemi, "An Adaptive UPFC Based Stabilizer for Damping of Low Frequency Oscillation," Journal of Electrical Engineering & Technology, Vol. 5, No. 2, pp. 197-208, 2010.

[11] Chen XR, Pahalawaththa NC, Annakkage UD, Cumble CS, "Design of Decentralized Output Feedback TCSC Damping Controllers by Using Simulated Annealing," IEE Proceeding-Generation Transmission Distribution, Vol. 145, No. 5, pp. 553-558, 1998.

[12] Chen XR, Pahalawaththa NC, Annakkage UD, Cumble CS, "Output Feedback TCSC Controllers to Improve Damping of Meshed Multimachine Power Systems," IEE Proceeding-Generation Transmission Distribution, Vol. 144, No. 3, pp. 243-248, 1997.

[13] E. Atashpaz-Gargari, C. Lucas, "Imperialist competitive algorithm: An algorithm for optimization inspired by imperialistic competition", IEEE Congress on Evolutionary Computation, 2007.

[14] I. Tsoulos, D. Gavrilis, E. Glavas, "Neural network construction and training using grammatical evolution", Science Direct Neurocomputing Journal, Vol.72, Issues 1-3, December 2008, pp. 269-277.

[15] E. Atashpaz, F. Hashemzadeh, R. Rajabioun, C. Lucas, "Colonial competitive algorithm: a novel approach for PID controller design in MIMO distillation column process", Intl. Journal of Intelligent Computing and Cybernetics, Vol.1, Issue 3, 2008, pp.337 – 355.

[16] Ramin Rajabioun, E. Atashpaz, C. Lucas, "Colonial Competitive Algorithm as a Tool for Nash Equilibrium Point Achievement", Lecture Notes In Computer Science; Vol. 5073, Proc. of the Intl. conf. on Computational Science and Its Applications, Part II, 2008, pp.680-695.

[17] B. Oskouyi, E. Atashpaz-Gargari, N. Soltani, C. Lucas, "Application of Imperialist Competitive Algorithm for Materials Property Characterization from Sharp Indentation Test", International Journal of Engineering Simulation, 2009; pages:9.

[18] A. Khabbazi, E. Atashpaz and C. Lucas, "Imperialist Competitive Algorithm for Minimum Bit Error Rate Beam forming", International Journal of Bio-Inspired Computation (IJBIC),2009; pages:9.

[19] A. M. Jasour, E. Atashpaz, C. Lucas, "Vehicle Fuzzy Controller Design Using Imperialist Competitive Algorithm", Second Iranian Joint Congress on Fuzzy and Intelligent Systems, Tehran, Iran, 2008.

[20] H. shayeghi, H. A. shayanfar, S. jalilzadeh, A. safari, "A PSO Based Unified Power Flow Controller for Damping of Power System Oscillations", Energy conversion and management, 2009, vol. 50, p.p. 2583-2592.

[21] Abido M.A., Al-Awami A.T., Abdel-Magid Y.L. "Power system stability enhancement using simultaneous design of damping controllers and internal controllers of a unified power flow controller," IEEE PES General Meeting, June 2006; pages:8.

[22] Lee S. "Optimal Decentralized Design for Output-Feedback Power System Stabilizers," IEE Proceeding-Generation Transmission Distribution, Vol. 152, No. 4, pp. 494-502, 2005.