Optimal Design of UPFC Based Damping Controller Using Iteration PSO

Amin Safari and Hossein Shayeghi

Abstract—This paper presents a novel approach for tuning unified power flow controller (UPFC) based damping controller in order to enhance the damping of power system low frequency oscillations. The design problem of damping controller is formulated as an optimization problem according to the eigenvalue-based objective function which is solved using iteration particle swarm optimization (IPSO). The effectiveness of the proposed controller is demonstrated through eigenvalue analysis and nonlinear time-domain simulation studies under a wide range of loading conditions. The simulation study shows that the designed controller by IPSO performs better than CPSO in finding the solution. Moreover, the system performance analysis under different operating conditions show that the δ_E based controller is superior to the m_B based controller.

Keywords—UPFC, Optimization Problem, Iteration Particle Swarm Optimization, Damping Controller, Low Frequency Oscillations.

I. INTRODUCTION

IN recent years, flexible AC transmission system (FACTS) devices are one of the most effective ways to improve power system operation controllability and power transfer limits. Through the modulation of bus voltage, phase shift between buses, and transmission line reactance, FACTS devices can cause a substantial increase in power transfer limits during steady-state [1]. Among them, UPFC is effective for damping power system oscillations. This is achieved by regulating the controllable parameters of the system, line impedance, voltage magnitude and phase angle of the UPFC bus. The UPFC consists of two ac/dc converters. One of the two converters is connected to the transmission line via a series transformer and the other in parallel with the line via a shunt transformer. The series and shunt converters are connected via a large DC capacitor. The series branch of the UPFC injects an AC voltage with controllable magnitude and phase angle at the power frequency via an insertion 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 line and the shunt converter. The shunt converter exchanges a current of controllable magnitude and power factor angle with the power system [2, 3].

Amin Safari is with the Young Researchers Club, Islamic Azad University, Ahar branch, Iran. (e-mail: asafari1650@ yahoo.com).

Hossein Shayeghi is with the Department of Technical Eng., University of Mohaghegh Ardabili, Ardabil, Iran.

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 [4]. Wang [5-7] presents the establishment of the linearized Phillips–Heffron model of a power system installed with a UPFC. The papers have not presented a systematic approach for designing the damping controllers.

Recently, global optimization techniques like particle swarm optimization [8, 9] have been applied for controller parameter optimization. The PSO is a novel population based metaheuristic, which utilize the swarm intelligence generated by the cooperation and competition between the particle in a swarm and has emerged as a useful tool for engineering optimization. Unlike the other heuristic techniques, it has a flexible and well-balanced mechanism to enhance the global and local exploration abilities. This algorithm has also been found to be robust in solving problems featuring non-linearing, non-differentiability and high-dimensionality [10-13].

In this paper, to enrich the searching behavior and to avoid being trapped into local optimum, IPSO technique is proposed, which is modified from PSO, is developed to optimize the damping controller parameters. The effectiveness of the proposed controller is demonstrated through nonlinear time simulation studies and eigenvalue analysis to damp low frequency oscillations under different operating conditions. Results evaluation show that the Iteration PSO based tuned damping controller achieves good performance for a wide range of operating conditions and is superior to designed controller using CPSO technique.

II. REVIEW OF CPSO AND IPSO

A. Classical Particle Swarm Optimization

The PSO method is a population-based one and is described by its developers as an optimization paradigm, which models the social behavior of birds flocking or fish schooling for food. Therefore, PSO works with a population of potential solutions rather than with a single individual [11]. Its key concept is that potential solutions are flown through hyperspace and are accelerated towards better or more optimum solutions. Its paradigm can be implemented in simple form of computer codes and is computationally inexpensive in terms of both memory requirements and speed. The higher dimensional space calculations of the PSO concept are performed over a series of time steps. The population is responding to the quality factors of the previous best individual values and the previous best group values. It has also been found to be robust

in solving problem featuring non-linearing, non-differentiability and high-dimensionality [8-9].

The PSO starts with a population of random solutions ''particles'' in a D-dimension space. The ith particle is represented by $X_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$. Each particle keeps track of its coordinates in hyperspace, which are associated with the fittest solution it has achieved so far. The value of the fitness for particle i (pbest) is also stored as $P_i = (p_{i1}, p_{i2}, \ldots, p_{iD})$. The global version of the PSO keeps track of the overall best value (gbest), and its location, obtained thus far by any particle in the population. The PSO consists of, at each step, changing the velocity of each particle toward its pbest and gbest according to Eq. (1). The velocity of particle i is represented as $V_i = (v_{i1}, v_{i2}, \ldots, v_{iD})$. Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward pbest and gbest. The position of the ith particle is then updated according to Eq. (2) [13]:

$$v_{id} = w \times v_{id} + c_1 \times rand(\ ) \times (P_{id} - x_{id})$$
$$+ c_2 \times rand(\ ) \times (P_{gd} - x_{id}) \tag{1}$$

$$x_{id} = x_{id} + cv_{id} \tag{2}$$

Where, P_{id} and P_{gd} are *pbest* and *gbest*. The positive constants c_1 and c_2 are the cognitive and social components that are the acceleration constants responsible for varying the particle velocity towards *pbest* and *gbest*, respectively. Variables r_1 and r_2 are two random functions based on uniform probability distribution functions in the range [0, 1]. The use of variable w is responsible for dynamically adjusting the velocity of the particles, so it is responsible for balancing between local and global searches, hence requiring less iteration for the algorithm to converge [12]. The following weighting function w is used in Eq. (1):

$$w = w_{max} - \frac{w_{max} - w_{min}}{iter\_max} iteration \tag{3}$$

Where, *iter_max* is the maximum number of iterations and *iteration* is the current number of iteration. The Eq. (3) presents how the inertia weight is updated, considering w_{max} and w_{min} are the initial and final weights, respectively [12].

B. Iteration Particle Swarm Optimization

In this paper, a new index named, Iteration Best, is incorporated in Eq. (1) to enrich the searching behavior, solution quality and to avoid being trapped into local optimum, IPSO technique is proposed, Eq. (4) shows the new form of Eq. (1):

$$v_{id} = w \times v_{id} + c_1 \times rand(\ ) \times (P_{id} - x_{id})$$
$$+ c_2 \times rand(\ ) \times (P_{gd} - x_{id}) + c_3 \times rand() \times (I_b - x_{id}) \tag{4}$$

Where, I_b is the best value of the fitness function that has been obtained by any particle in any iteration and c_3 shows the weighting of the stochastic acceleration terms that pull each particle toward I_b [14]. Figure 1 shows the flowchart of the proposed IPSO algorithm.
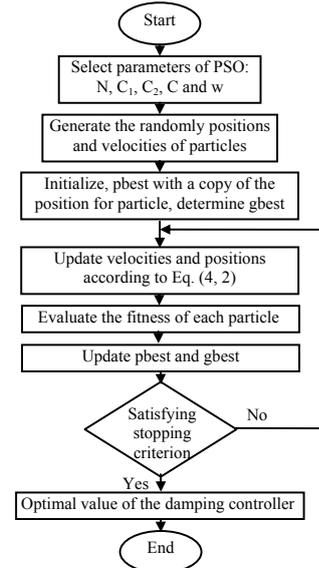

Fig. 1 Flowchart of the proposed IPSO technique

III. POWER SYSTEM MODEL

Fig. 2 shows a 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 system data is given in the Appendix. 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 [1, 8].
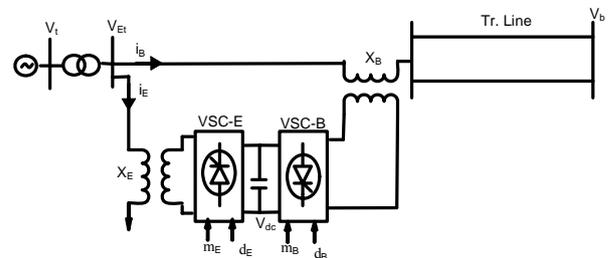

Fig. 2 SMIB power system equipped with UPFC

In order to study the effect of the UPFC for enhancing the small signal stability of the power system dynamic model of the UPFC is required. Therefore, the UPFC can be modeled as [5-7]:

$$\begin{bmatrix} v_{Etd} \\ v_{Etq} \end{bmatrix} = \begin{bmatrix} 0 & -x_E \\ x_E & 0 \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_E \cos \delta_E v_{dc}}{2} \\ \dfrac{m_E \sin \delta_E v_{dc}}{2} \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} v_{Btd} \\ v_{Btq} \end{bmatrix} = \begin{bmatrix} 0 & -x_B \\ x_B & 0 \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_B \cos \delta_B v_{dc}}{2} \\ \dfrac{m_B \sin \delta_B v_{dc}}{2} \end{bmatrix} \tag{6}$$

$$\dot{v}_{dc} = \frac{3m_E}{4C_{dc}} [\cos \delta_E \quad \sin \delta_E] \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \frac{3m_B}{4C_{dc}} [\cos \delta_B \quad \sin \delta_B] \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} \tag{7}$$

Where, 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. The nonlinear model of the SMIB system is described by [8, 9]:

$$\dot{\delta} = \omega_0(\omega - 1) \tag{8}$$

$$\dot{\omega} = (P_m - P_e - D\Delta\omega)/M \tag{9}$$

$$\dot{E}'_q = (-E_q + E_{fd})/T'_{do} \tag{10}$$

$$\dot{E}_{fd} = (-E_{fd} + K_a(V_{ref} - V_t))/T_a \tag{11}$$

A linear dynamic model is obtained by linearizing the nonlinear model round an operating condition. The linearized model of power system is given as follows:

$$\Delta\dot{\delta} = \omega_0\Delta\omega \tag{12}$$

$$\Delta\dot{\omega} = (-\Delta P_e - D\Delta\omega)/M \tag{13}$$

$$\Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \tag{14}$$

$$\Delta\dot{E}_{fd} = (K_A(\Delta v_{ref} - \Delta v) - \Delta E_{fd})/T_A \tag{15}$$

$$\Delta\dot{v}_{dc} = K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta v_{dc} + K_{ce}\Delta m_E \\ + K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B \tag{16}$$

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{pd}\Delta v_{dc} + K_{pe}\Delta m_E \\ + K_{p\delta e}\Delta\delta_E + K_{pb}\Delta m_B + K_{p\delta b}\Delta\delta_B \tag{17}$$

$$\Delta E'_q = K_4\Delta\delta + K_3\Delta E'_q + K_{qd}\Delta v_{dc} + K_{qe}\Delta m_E \\ + K_{q\delta e}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta b}\Delta\delta_B \tag{18}$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E'_q + K_{vd}\Delta v_{dc} + K_{ve}\Delta m_E \\ + K_{v\delta e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B \tag{19}$$

K_1, K_2...K_9, K_{pu}, K_{qu} and K_{vu} are linearization constants. The block diagram of the linearized dynamic model of the SMIB power system with UPFC is shown in Fig. 3.
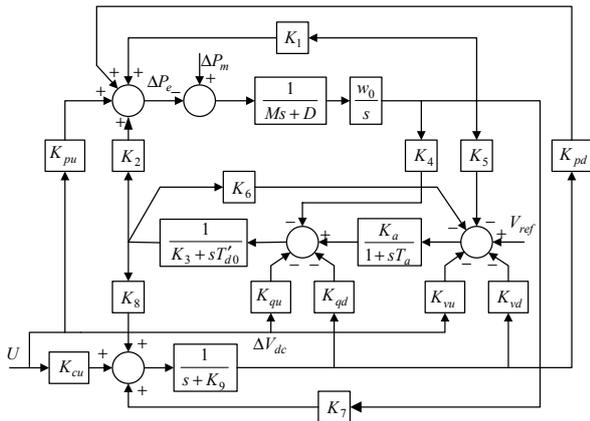

Fig. 3. Modified Heffron–Phillips transfer function model.

IV. UPFC BASED DAMPING CONTROLLER DESIGN

The damping controller is designed to produce an electrical torque in phase with the speed deviation according to phase compensation method. In this paper δ_E and m_B are 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 damping controller is shown in Fig. 4. This controller may be considered as a lead-lag compensator [3]. However, an electrical torque in phase with the speed deviation is to be produced in order to improve damping of the system oscillations. It comprises gain block, signal-washout block and lead-lag compensator. To acquire an optimal combination, this paper employs IPSO [14] to improve optimization synthesis and find the global optimum value of fitness function. To increase the system damping to electromechanical modes, an eigenvalue-based objective function is considered as follows:

$$J = \max(real(\lambda)) \tag{20}$$

Where, real (λ_i) is the real part of the ith electromechanical mode eigenvalue, respectively. In the optimization process, it is aimed to minimize J in order to shift the poorly damped eigenvalues to the left in s-plane.
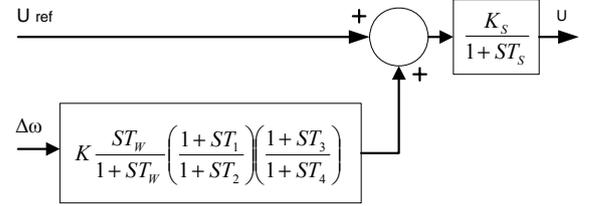

Fig. 4. UPFC with lead-lag controller

The design problem can be formulated as the following constrained optimization problem, where the constraints are the controller parameters bounds [1]:

Minimize J Subject to:

$$K^{min} \leq K \leq K^{max}$$
$$T_1^{min} \leq T_1 \leq T_1^{max}$$
$$T_2^{min} \leq T_2 \leq T_2^{max} \tag{21}$$
$$T_3^{min} \leq T_3 \leq T_3^{max}$$
$$T_4^{min} \leq T_4 \leq T_4^{max}$$

Typical ranges of the optimized parameters are [0.01-100] for K and [0.01-1] for T_1, T_2, T_3 and T_4. The proposed approach employs IPSO and CPSO to solve this optimization problem and search for an optimal set of controller parameters. In this work, in order to acquire better performance, number of particle, particle size, number of iteration, c_1, c_2, and c is chosen as 20, 5, 50, 2, 2 and 1, respectively. Also, the inertia weight, w, is linearly decreasing from 0.9 to 0.4. The final values of the optimized parameters are given in Table I.

TABLE I
OPTIMAL PARAMETERS OF THE CONTROLLER

Controller parameters	δ_E based controller		m_B based controller	
	IPSO	CPSO	IPSO	CPSO
K	96.11	84.21	93.56	89.00
T_1	0.4988	0.0661	0.1721	0.3275
T_2	0.5652	0.0177	0.2111	0.1465
T_3	0.6661	0.2609	0.7566	0.9457
T_4	0.5348	0.1998	0.2423	0.5003

V. SIMULATION RESULTS

A. Eigenvalue Analysis

The system eigenvalues with and without the proposed controllers at nominal condition are given in Table II. 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.

TABLE II
SYSTEM EIGENVALUES WITH AND WITHOUT CONTROLLER
(NOMINAL CONDITION)

Type of Algorithm	Without controller	δ_E based controller	m_B based controller
CPSO	**0.16615 ± i4.5031** -3.2531, -96.582	-1.0024 ± i3.205 -3.3757, -2.7444, -95.5 -76.731, -6.8716	-1.4908 ± i2.3581 -6.6615 ± i2.4349 -2.1011, -3.168, -96.976
IPSO	**0.16615 ± i4.5031** -3.2531, -96.582	-1.7172 ± i2.7264 -1.7946 ± i0.11839 -2.5852, -6.7389, -96.5	-1.4816 ± i1.9317 -4.2656 ± i5.275 -5.460, -2.3978, -96.847

B. Nonlinear Time Domain Simulation

In any power system, the operating load varies over a wide range. It is extremely important to investigate the variation of the loading condition on the dynamic performance of the system. The operating conditions are considered as:

- P = 0.80pu, Q = 0.114 pu   (Nominal loading)
- P = 0.2 pu, Q = 0.01   (Light loading)
- P = 1.20 pu, Q = 0.4   (Heavy loading)

To investigate the performance of the proposed controller under transient conditions is verified by applying a 6-cycle three-phase fault at $t = 1$ sec, at the middle of the one transmission line. The performance of the controllers when the iteration PSO is used in the design is compared to that of the controllers designed using the classical PSO. The simulation results at nominal, light and heavy loading conditions due to designed controller based on the δ_E and m_B are shown in Figs. 5-8. It can be seen that the IPSO based UPFC controller achieves good robust performance, provides superior damping in comparison with the CPSO based UPFC controller and enhance greatly the dynamic stability of power system. From the above conducted tests, it can be concluded that the δ_E controller is superior to the m_B controller.
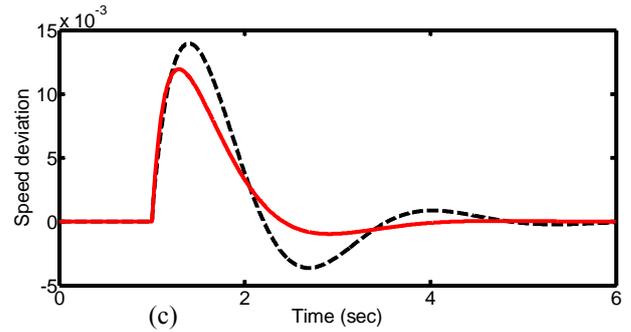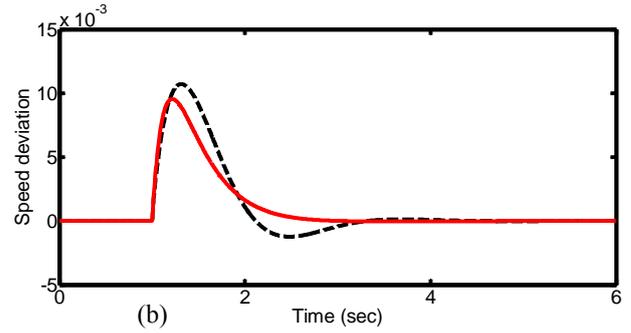

Fig. 5 Dynamic responses for $\Delta\omega$ at (a) nominal (b) light (c) heavy loading conditions; Solid (IPSO *based δ_E controller*) and Dashed (PSO *based δ_E controller*).
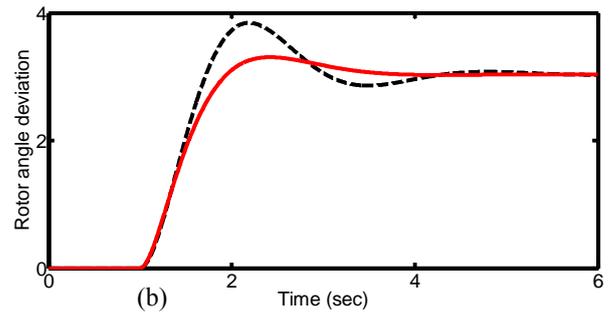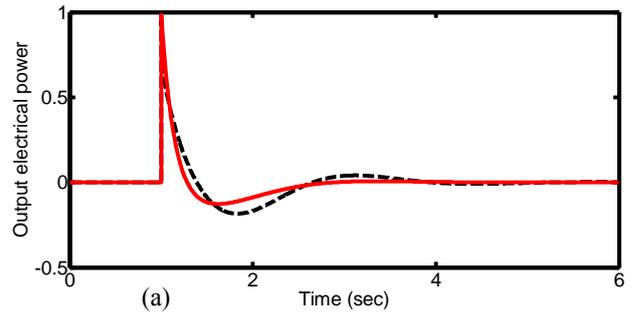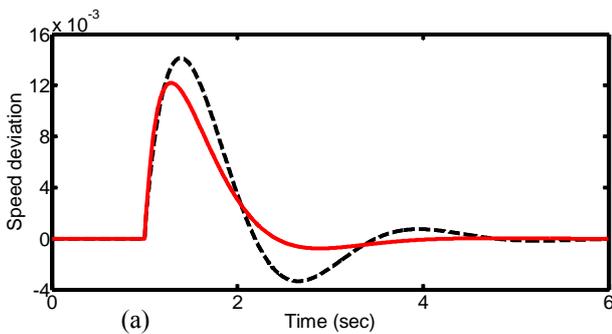

Fig. 6 Dynamic responses at nominal loading (a) ΔP_e and (b) ($\Delta\delta$); Solid (IPSO *based δ_E controller*) and Dashed (PSO *based δ_E controller*).
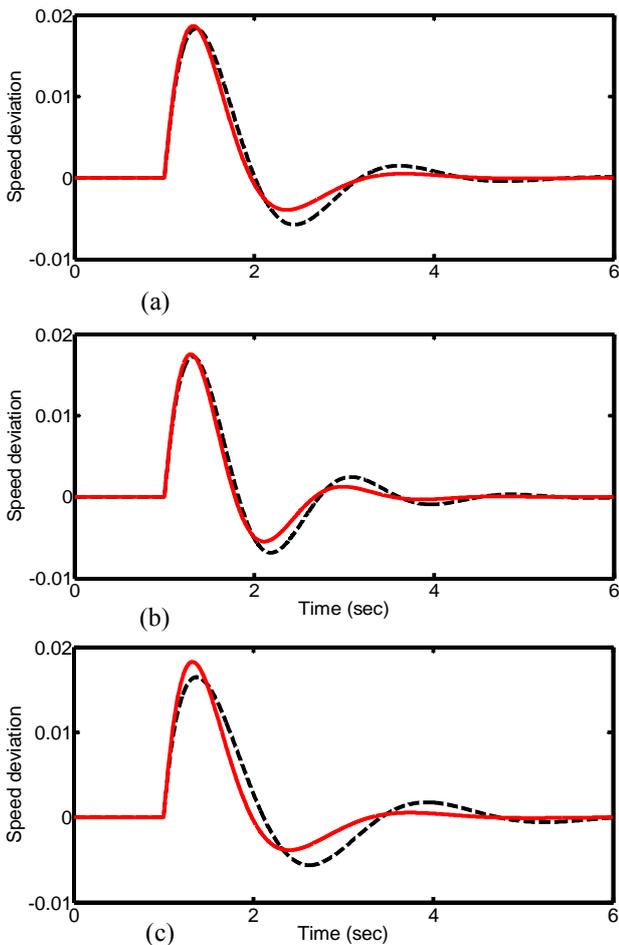
Fig. 7 Dynamic responses for Δω at (a) nominal (b) light (c) heavy loading conditions; Solid (IPSO *based m_B controller*) and Dashed (PSO *based m_B controller*).
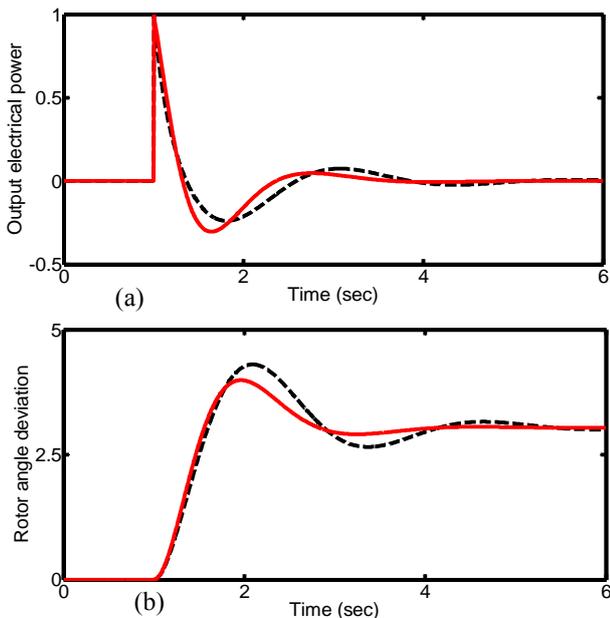

Fig. 8 Dynamic responses at nominal loading (a) ΔPₑ and (b) (Δδ); Solid (IPSO *based m_B controller*) and Dashed (PSO *based m_B controller*).

VI.   CONCLUSIONS

The iteration particle swarm optimization algorithm has been successfully applied to the optimal design of UPFC based damping controllers. The design problem of the selecting controller parameters is converted into an optimization problem which is solved by a IPSO technique with the eigenvalue-based objective function. The effectiveness of the proposed UPFC controllers for improving transient stability performance of a power system are demonstrated by a weakly connected example system subjected to severe disturbance. The eigenvalue analysis and non-linear time domain simulation results show the effectiveness of the proposed controller and their ability to provide good damping of low frequency oscillations.

APPENDIX

The nominal parameters of the system are listed in Table III.

TABLE III
SYSTEM PARAMETERS

Generator	$M = 8$ MJ/MVA	$T'_{do} = 5.044$ s	$X_d = 1$pu
	$X_q = 0.6$p.u	$X'_d = 0.3$pu	$D = 0$
Excitation system		$K_a = 25$	$T_a = 0.05$s
Transformers		$X_T = 0.1 pu$	$X_{SDT} = 0.1 pu$
DC link parameter		$V_{DC} = 1 pu$	$C_{DC} = 1 pu$
STATCOM parameter		$C = 0.25$	$\varphi = 52°$
		$K_s = 1$	$T_s = 0.05$

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