# IPSO Based UPFC Robust Output Feedback Controllers for Damping of Low Frequency Oscillations

A. Safari, H. Shayeghi, H. A. Shayanfar

***Abstract*—**On the basis of the linearized Phillips-Herffron model of a single-machine power system, a novel method for designing unified power flow controller (UPFC) based output feedback controller is presented. The design problem of output feedback controller for UPFC is formulated as an optimization problem according to with the time domain-based objective function which is solved by iteration particle swarm optimization (IPSO) that has a strong ability to find the most optimistic results. To ensure the robustness of the proposed damping controller, the design process takes into account a wide range of operating conditions and system configurations. The simulation results prove the effectiveness and robustness of the proposed method in terms of a high performance power system. The simulation study shows that the designed controller by Iteration PSO performs better than Classical PSO in finding the solution.

***Keywords*--** UPFC, IPSO, output feedback Controller.

**Nomenclature**

| | |
|---|---|
| BT | boosting transformer |
| D | Machine damping coefficient |
| DC | Direct current |
| $E'_q$ | internal voltage behind transient reactance |
| $E_{fd}$ | equivalent excitation voltage |
| ET | excitation transformer |
| FACTS | flexible alternating current transmission systems |
| GTO | gate turn off thyristor |
| IPSO | Iteration particle swarm optimization |
| ITAE | time multiplied absolute value of the error |
| K | proportional gain of the controller |
| $K_A$ | regulator gain |
| M | Machine inertia coefficient |
| $m_E$ | excitation amplitude modulation ration |
| $m_B$ | boosting amplitude modulation ration |
| $P_e$ | electrical output power |
| PI | proportional integral |
| $P_m$ | mechanical input power |
| PSO | particle swarm optimization |
| SMIB | single machine infinite |
| SVC | static var compensator |
| $T_A$ | regulator time constant |
| $T'_{do}$ | time constant of excitation circuit |
| $T_e$ | electric torque |
| UPFC | unified power flow controller |
| V | terminal voltage |
| $v_{ref}$ | reference voltage |
| VSC | voltage source converter |
| $\omega$ | rotor speed |
| $\delta$ | rotor angle |
| $\delta_B$ | boosting phase angle |
| $\delta_E$ | excitation phase angle |
| $\Delta P_e$ | electrical power deviation |
| $\Delta V_{dc}$ | DC voltage deviation |

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## I. INTRODUCTION

DAMPING of low frequency oscillations in a power system is one of the important applications of a unified power flow controller (UPFC). These oscillations can occur in a system as a result of a number of contingencies including sudden load changes or power system faults. The UPFC has the ability to control of the power flow in the transmission line, improve the transient stability, mitigate system oscillation and provide voltage support. It performs this through the control of the in-phase voltage, quadrate voltage and shunts compensation due to its mains control strategy [1, 2]. 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 shunt converter exchanges a current of controllable magnitude and power factor angle with the power system [3].

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. 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 [5-7] presents the establishment of the linearized Phillips–Heffron model of a power system installed with a UPFC. The paper 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.

Recently, global optimization techniques like particle swarm optimization [8] 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 [9-14].

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 output feedback controller parameters. The problem of robust output feedback controller design is formulated as an optimization problem and PSO 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 ($\Delta\omega$ and $\Delta V_t$) 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 nonlinear time simulation studies 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. Iteration Particle Swarm Optimization

### *A. Classical PSO*

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 [10]. As in evolutionary computation paradigms, the concept of fitness is employed and candidate solutions to the problem are termed particles or sometimes individuals, each of which adjusts its flying based on the flying experiences of both itself and its companion. Its key concept is that potential solutions are flown through hyperspace and are accelerated towards better or more optimum solutions [14]. 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].

The PSO starts with a population of random solutions ‘‘particles’’ in a D-dimension space. The *i*th 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 (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 *i*th particle is then updated according to (2) [12]:

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

$$x_{id} = x_{id} + cv_{id} \quad (2)$$

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 [11].

### *B. Iteration PSO*

In this paper, a new index named, Iteration Best, is incorporated in (1) to enrich the searching behavior, solution quality and to avoid being trapped into local optimum, IPSO technique is proposed, (3) shows the new form of (1):

$$v_{id} = w \times v_{id} + c_1 \times rand(\,) \times (P_{id} - x_{id}) + c_2 \times rand(\,) \times (P_{gd} - x_{id}) + c_3 \times rand() \times (I_b - x_{id}) \quad (3)$$

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 $I_b$ [13]. Figure 1 shows the flowchart of the proposed IPSO algorithm.

## III. Linear Model of Power System

A single machine infinite bus power system equipped with a UPFC is shown in Fig 2. 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 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 [5-8]:

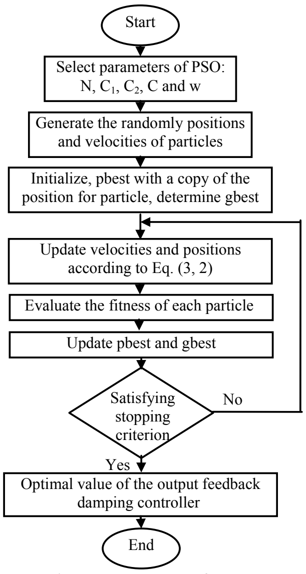



Fig. 1 Structure of IPSO

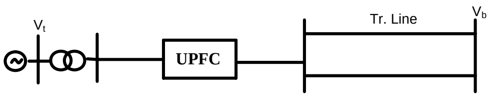



Fig. 2 SMIB power system equipped with UPFC

$$\begin{bmatrix} v_{Etd} \\ v_{Etq} \end{bmatrix} = \begin{bmatrix} 0 & -x_E \\ x_E & 0 \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_E \cos\delta_E v_{dc}}{2} \\ \dfrac{m_E \sin\delta_E v_{dc}}{2} \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} v_{Btd} \\ v_{Btq} \end{bmatrix} = \begin{bmatrix} 0 & -x_B \\ x_B & 0 \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_B \cos\delta_B v_{dc}}{2} \\ \dfrac{m_B \sin\delta_B v_{dc}}{2} \end{bmatrix} \quad (5)$$

$$\dot{v}_{dc} = \frac{3m_E}{4C_{dc}}[\cos\delta_E \quad \sin\delta_E]\begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \frac{3m_B}{4C_{dc}}[\cos\delta_B \quad \sin\delta_B]\begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} \quad (6)$$

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]:

$$\dot{\delta} = \omega_0(\omega - 1) \quad (7)$$

$$\dot{\omega} = (P_m - P_e - D\Delta\omega)/M \quad (8)$$

$$\dot{E}'_q = (-E_q + E_{fd})/T'_{do} \quad (9)$$

$$\dot{E}_{fd} = (-E_{fd} + K_a(V_{ref} - V_t))/T_a \quad (10)$$

A linear dynamic model is obtained by linearizing the nonlinear model round an operating condition. The linearized model of power system is given in Ref [5].

## IV. Output Feedback Controller Design Using IPSO

A power system can be described by a linear time invariant state space model as follows [8]:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \quad (11)$$

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. An output feedback controller has the following structures:

$$u = -Ky \quad (12)$$

Substituting (12) into (11) the resulting state equation is:

$$\dot{x} = A_C x \quad (13)$$

Where, $A_c$ is the closed-loop state matrix and is given by:

$$A_C = A - BKC \quad (14)$$

Only the local and available state variables Δω and $\Delta V_t$ are taken as the input signals of each controller, so the implementation of the designed stabilizers becomes more feasible. By properly choosing the feedback gain *K*, the eigenvalues of closed-loop matrix $A_c$ are moved to the left-hand side of the complex plane and the desired performance of controller can be achieved. Once the output feedback signals are selected, only the selected signals are used in forming (11). Thus, the remaining problem in the design of output feedback controller is the selection of *K* to achieve the required objectives. In this paper, $\delta_E$ and $m_B$ are 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. To acquire an optimal combination, this paper employs IPSO [13] to improve optimization synthesis and find the global optimum value of objective function. Since the operating conditions in power systems are often varied, a performance index for a wide range of operating points is defined as follows [8]:

$$J = \sum_{i=1}^{Np} \int_0^{tsim} t|\Delta\omega_i|dt \quad (15)$$

Where, the $t_{sim}$ is the time range of simulation and $N_P$ is the total number of operating points for which the optimization is carried out. It is aimed to minimize this objective function in order to improve the system response in terms of the settling time and overshoots. The design problem can be formulated as the following constrained optimization problem, where the constraints are the controller parameters bounds:

Minimize J Subject to:

$$\begin{aligned} K_1^{min} &\le K_1 \le K_1^{max} \\ K_2^{min} &\le K_2 \le K_2^{max} \end{aligned} \quad (16)$$

Typical ranges of the optimized parameters are [0.01-150] for $K_1$ and [0.01-10] for $K_2$. The proposed approach employs IPSO to solve this optimization problem and search for an optimal set of output feedback controller parameters. The optimization of UPFC controller parameters is carried out by evaluating the objective cost function as given in (15), which considers a multiple of operating conditions. The operating conditions are considered as [8]:

- Base case: P = 0.80pu, Q = 0.114 pu and $X_L$=0.3 pu. (Nominal loading)
- Case 1: P = 0.2 pu, Q = 0.01 and $X_L$=0.3 pu. (Light loading)
- Case 2: P = 1.20 pu, Q = 0.4 and $X_L$=0.3 pu. (Heavy loading)
- Case 3: P = 0.80pu, Q = 0.114 pu and $X_L$=0.6 pu.
- Case 4: P = 1.20 pu, Q = 0.4 and $X_L$=0.6 pu.

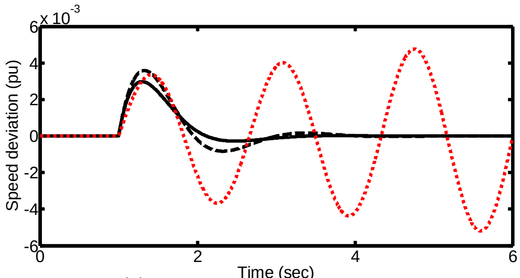
In this work, in order to acquire better performance, number of particle, particle size, number of iteration, $c_1$, $c_2$, and $c$ is chosen as 30, 2, 50, 2, 2 and 1, respectively. Also, the inertia weight, $w$, is linearly decreasing from 0.9 to 0.4. It should be noted that IPSO algorithm is run several times and then optimal set of output feedback gains for the UPFC controllers is selected. The final values of the optimized parameters are given in Table 1.

TABLE I
OPTIMAL PARAMETERS OF THE PROPOSED CONTROLLERS

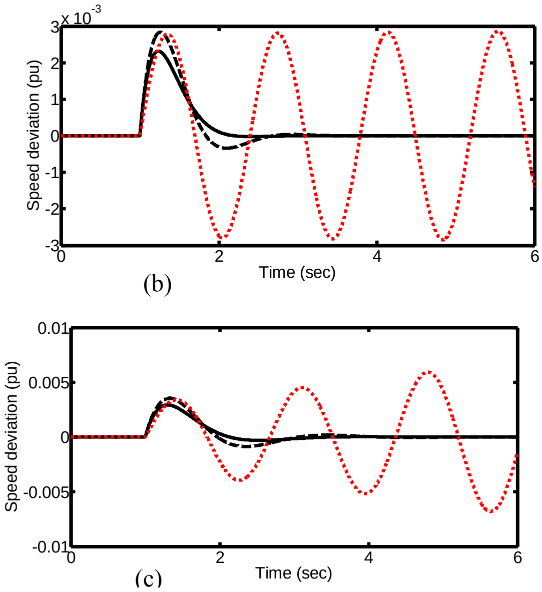
| | $K_1$ | $K_2$ |
|---|---|---|
| $m_B$ based controller | 174.88 | 0.143 |
| $\delta_E$ based controller | 87.32 | 0.742 |

## V. Nonlinear Time Domain Simulation

To assess the effectiveness and robustness of the proposed controllers, 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 fault is cleared by permanent tripping of the faulted line. The speed deviation of generator at nominal, light and heavy loading conditions due to designed controller based on the $\delta_E$ and $m_B$ are shown in Figs. 3 and 4. The performance of the proposed method is compared to that of the classical PSO given in [8]. It can be seen that the IPSO based designed controller achieves good robust performance, provides superior damping in comparison with the classical method.

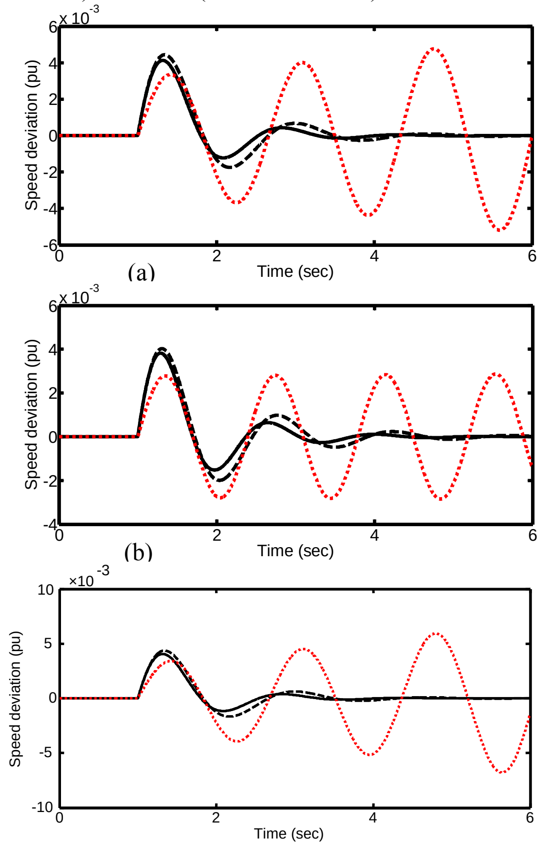


(a)



(b)
(c)

Fig. 3. Dynamic responses for Δω at (a) Nominal (b) Light (c) Heavy loading; Solid (IPSO *based* $\delta_E$ *controller*), Dashed (CPSO [8] *based* $\delta_E$ *controller*) and Dotted (Without controller).



(a)
(b)
(c)

Fig. 4. Dynamic responses for Δω at (a) Nominal (b) Light (c) Heavy loading; Solid (IPSO *based* $m_B$ *controller*) and Dashed (CPSO [8] *based* $m_B$ *controller*) and Dotted (Without controller).

## VI. CONCLUSIONS

In this paper, improvement of the power systems low frequency oscillations using a UPFC based output feedback controller has been investigated. The design problem of the output feedback controller is converted into an optimization problem which is solved by a IPSO technique that has a strong ability to find the most optimistic results. The effectiveness of the proposed controllers for improving transient stability performance are demonstrated by a weakly connected example power system subjected to different operating conditions. The nonlinear time domain simulation results show the robustness of the proposed controller and their ability to provide good damping of low frequency oscillations. Moreover, the $\delta_E$ -based stabilizer provides better damping characteristics and enhances greatly the first swing stability compared to the $m_B$-based stabilizer.

## APPENDIX

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

TABLE II
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 | | $K_a = 10$ | $T_a = 0.05$s |
| Transformers | | $X_T = 0.1pu$ | $X_E = 0.1pu$ |
| | | $X_B = 0.1pu$ | |
| Transmission line | | $X_L = 1$pu | |
| Operating condition | | $P = 0.8pu$ | $V_b = 1.0pu$ |
| | | $V_t = 1.0pu$ | |
| DC link parameter | | $V_{DC} = 2pu$ | $C_{DC} = 1pu$ |
| UPFC parameter | | $m_B = 0.08$ | $\delta_B = -78.21°$ |
| | | $\delta_E = -85.35°$ | $m_E = 0.4$ |
| | | $K_s = 1$ | $T_s = 0.05$ |

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