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ROBUST DESIGN OF POWER OSCILLATION DAMPING CONTROLLER FOR IPFC USING PARTICLE SWARM OPTIMIZATION

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Abstract- This paper uses the Particle Swarm Optimization (PSO) technique to investigate the damping control function of an Interline Power Flow Controller (IPFC) installed in a power system. For this purpose, the linearized Herffron-Phillips model of a Single-Machine Infinite Bus (SMIB) system is established and a performance index which is defined based on the system dynamics is applied as an objective function to evaluate the potential of various IPFC control signals upon the power system's different operating conditions. The results in time-domain simulation analysis reveals that the designed PSO based IPFC controller tuned by the proposed objective function has an excellent capability in damping power system low frequency oscillations and enhance greatly the dynamic stability of the power systems. Moreover, the system performance analysis under different operating conditions show that the m_1 (magnitude of injected voltage) based controller is superior to the other based controller.

Keywords: Power Oscillation Damping, Interline Power Flow Controller, Particle Swarm Optimization, Optimal Damping Controller Design.

I. INTRODUCTION

Modern power systems consist of a large number of solitaire elements. Connection of the single elements together and coin a large system which is able to generate, transmit and distribute the electrical energy in a wide geographical region. Moreover, power systems are interconnected large nonlinear systems that have electromechanical oscillatory modes with light damping. Low Frequency Oscillation (LFO) is a one of the phenomena that may threat the dynamic stability of power systems. LFOs commonly defined as the oscillations of the generator rotor angle which might be different due to the location of occurrence and the way of engendering. Inadequate damping torque of some generators produce the LFOs in order of 0.2 to 3 Hz. Traditionally, extension of stability ranges of power systems is exerted by Power System Stabilizers (PSSs). PSSs provide the supplementary control signals for AVR and the turbine regulatory system. However, PSSs suffer a drawback of being liable to cause great variations in the voltage profile and they may even result in leading power factor operation and losing system stability under severe disturbances, especially those three-phase faults which may occur at the generator terminals [1].

In recent years, considering the fast development in power-electronics, FACTS devices meet this opportunity to be applied in power systems for improving the power system controllability limits. The Interline Power Flow Controller (IPFC) is one of the FACTS devices which can be employed for regulating power flow between parallel lines or in the transmission hallways, nevertheless, giving the abilities like improving the voltage profile, dynamic and transient stability make IPFC to be recognized as a versatile controller. When the IPFC is applied to the interconnected power systems, it can also provide significant damping effect on tie line power oscillations through its supplementary control. The basic performance of IPFC is similar to Static Synchronous Series Compensator (SSSC). SSSC consists of a series Voltage Source Converter (VSC) which can inject a series voltage into the transmission line. As such, the series VSC makes SSSC exchange the reactive power with the inserted line. If the DC side of the two VSC is connected together, then the active power as well as the reactive power can transfer in a bilateral and absolute way through the common DC link. The above structure is known as the IPFC. In the view of controllability, this means that the IPFC can control the magnitude and phase of series injected voltages, independently [2].

The basic theory and the operating characteristics of the IPFC is first introduced by Gyugyi et al [2] proposing the IPFC as a new concept for the compensation and the effective power flow management of a multi-line transmission system. Vasquez-Arnez et al [3] used a d-q orthogonal coordinates, to present a practical and direct method to assess the steady-state response of the IPFC controllers as well as to investigate the main operational constraints. A novel power injection model of IPFC for power flow analysis is presented by Yankui Zhang et al [4]. However this novel model because of its parameter numbers is complex and thus it is not proper for dynamic studies.

Recent publication on the modeling of IPFC in Newton power flow calculation and the application of the IPFC to the Optimal Power Flow (OPF) control due to its constraints have greatly deepened people's understanding of the performance of the IPFC in the steady-state analysis. However, although the capability of the IPFC in improving the dynamic and transient stability of power system has been implied by some open literature, detailed and quantities research on this topic is still not sufficient.

Ref. [5] uses the linearized Heffron-Phillips model of a single machine infinite bus power system and phase compensation method, to design the IPFC's lead-lag damping controller parameters. Kazemi et al [6] proposed a PI based damping controller for the IPFC, however it is not a detailed model for identifying the most suitable control parameter.

Recently, PSO technique such as other evolutionary computational techniques based on swarm intelligence like Ant Colony Optimization (ACO) is exerted in power system analysis to improve the stability problem of power system due to the complex and multi-agent constraints. The PSO is a novel population based metaheuristic, which has been found to be robust in solving problems featuring non-linearing, non-differentiability and high-dimensionality [7].

In this paper, the optimal decentralized design of a supplementary lead-lag controller of the IPFC is investigated. The problem of the robust controller design is formulated as an optimization problem and PSO technique is used to solve it. A performance index is defined based on the system dynamics after an impulse disturbance alternately occurs in system and it is organized for a wide range of operating conditions and used to form the objective function of the design problem. The effectiveness of the designed controller is demonstrated through the nonlinear time simulation studies and some performance indices to damp the low frequency oscillations under different operating conditions.

In this study, we also compare IPFC's different control parameters in order to determine the most effective control signal for damping power system oscillations better. Results show the good robustness of this design using PSO and the superiority of the m_1 based controller compare to the other three based controllers due to different operating conditions.

In the following sections, the PSO approach is explained in section II, problem formulation is presented in section III, simulation results are demonstrated in section IV. Finally, the conclusions of the paper are summarized in section V.

II. REVIEW OF PSO TECHNIQUE

PSO is the search method to improve the speed of the convergence and find the global optimum value of the fitness function. PSO is a computational intelligence-based technique that is not largely affected by the size and nonlinearity of the problem, and can converge to the optimal solution in many problems where most analytical methods fail to converge. This optimization technique can be used to solve many of the same kinds of problems as GA, and does not suffer from some of the GAs difficulties. The most important features of the optimization algorithm are easy implementation, fewer adjustable parameters, suitable for the nature of the problem, efficiency in maintaining the diversity of the swarm for improvement of the particle information and easy to coded. The PSO is initialized with a group of random particles and searches for the optimal point by updating generations.

In each iteration, particles are updated by the best values of itself and the group's. The *i*th particle is represented by $X_i = (x_{i1}, x_{i2}, ..., x_{iD})$. 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 $P_i = (p_{i1}, p_{i2}, ..., p_{iD})$. 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 Equation (1). The velocity of particle i is represented as $V_i = (v_{i1}, v_{i2}, ..., v_{iD})$ [7].

$$\begin{aligned} v_{id} &= w.v_{id} + c_1.\text{rand}(\,).(P_{id} - x_{id}) + \\ &+ c_2.\text{rand}(\,).(P_{gd} - x_{id}) \qquad (1) \\ x_{id} &= x_{id} + cv_{id} \end{aligned}$$

where, P_{id} and P_{gd} are *pbest* and *gbest*. In the PSO, the trade off between the local and global exploration abilities is mainly controlled by inertia weights (ω). The inertia weight which is formulated as in Equation (2) varies linearly from 0.4 to 0.9 during the run [7].

$$\omega = \omega_{\max} - \left[\frac{\omega_{\max} - \omega_{\min}}{iter_{\max}} \right].iter \qquad (2)$$

where, $\omega_{\max}$ is the initial value of the inertia weight, $\omega_{\min}$ is the final value of the inertia weight, $iter_{\max}$ is the maximum iteration number and $iter$ is the current iteration number. Figure 1 shows the flowchart of the PSO algorithm.

III. PROBLEM FORMULATION

A. Dynamic model of power system with IPFC

The IPFC consists of two series coupled transformers to each transmission lines, two three-phase GTO based Voltage Source Converters (VSCs), and a DC link capacitor. The control parameters of each IPFC's branch are the magnitude and the angle of series injected voltage, i.e., m_1, m_2, δ_1, and δ_2, respectively [5]. Consequently, by changing these parameters other system parameters such as bus voltages, active and reactive power flows, could be controlled. According to the independence of the magnitude of the series-injected voltages generating by VSCs of the magnitude of the bus voltage, in an IPFC with 2 branches, 3 parameters can be independently controlled as one parameter control the active power balance in IPFC.

$$P_{se1} + P_{se2} = 0 \qquad (3)$$

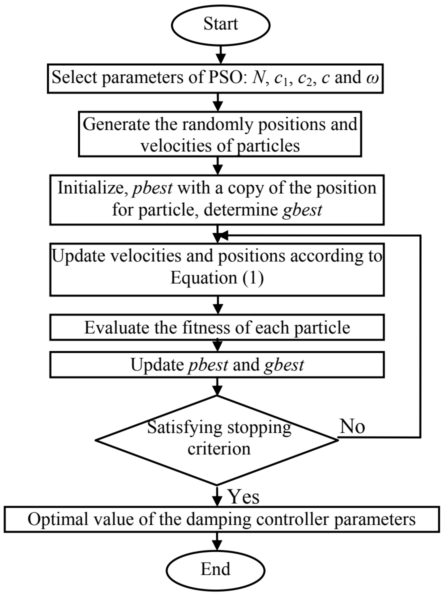

Figure 1. Flowchart of the proposed PSO technique

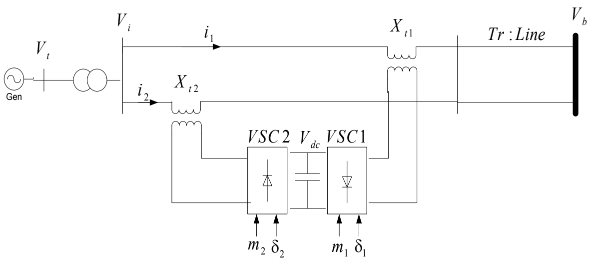

Figure 2. SMIB power system equipped with IPFC

Figure 1 shows a SMIB power system equipped with an IPFC. The synchronous generator is delivering power to the infinite-bus through a double circuit transmission line and an IPFC. By applying the Park's transformation and neglecting the resistance and transients of the transformers, the IPFC's dynamic model in order to study the small-signal stability of a power system can be modeled as following [6]:

$$\begin{bmatrix} v_{inj1d} \\ v_{inj1q} \end{bmatrix} = \begin{bmatrix} 0 & x_{t1} \\ -x_{t1} & 0 \end{bmatrix} \begin{bmatrix} i_{1d} \\ i_{1q} \end{bmatrix} + \begin{bmatrix} \dfrac{m_1 v_{dc} \cos\delta_1}{2} \\ \dfrac{m_1 v_{dc} \sin\delta_1}{2} \end{bmatrix}$$

$$\begin{bmatrix} v_{inj2d} \\ v_{inj2q} \end{bmatrix} = \begin{bmatrix} 0 & x_{t2} \\ -x_{t2} & 0 \end{bmatrix} \begin{bmatrix} i_{2d} \\ i_{2q} \end{bmatrix} + \begin{bmatrix} \dfrac{m_2 v_{dc} \cos\delta_2}{2} \\ \dfrac{m_2 v_{dc} \sin\delta_2}{2} \end{bmatrix} \tag{4}$$

$$\dot v_{dc} = \frac{3m_1}{4C_{dc}} [\cos\delta_1 \quad \sin\delta_1] \begin{bmatrix} i_{1d} \\ i_{1q} \end{bmatrix} + \frac{3m_2}{4C_{dc}} [\cos\delta_2 \quad \sin\delta_2] \begin{bmatrix} i_{2d} \\ i_{2q} \end{bmatrix}$$

where, v_{inj1}, i_1, v_{inj2}, and i_2 are the voltage of the transformer of line 1, current of line 1, voltage of the transformer of line 2 and the current of line 2, respectively; C_{dc} and v_{dc} are the DC link capacitance and voltage. The nonlinear model of the SMIB system as shown in Figure 2 is described by [5]:

$$\begin{aligned} &\dot\delta = \omega_0(\omega - 1) \\ &\dot\omega = (P_m - P_e - D\Delta\omega)/M \\ &\dot E'_q = (-E_q + E_{fd})/T'_{do} \\ &\dot E_{fd} = (-E_{fd} + K_a(V_{ref} - V_t))/T_a \end{aligned} \tag{5}$$

From Figure 2, it can be written that:

$$V_{sei}^{\min} \le V_{sei} \le V_{sei}^{\max}; -\pi \le \delta_i \le \pi \tag{6}$$

where, i = 1, 2; and $V_{sei}^{\min}$, $V_{sei}^{\max}$ are the minimal and maximal voltage limits of V_{sei}, respectively. The series-injected voltages by VSCs and the corresponding currents in the branches in d-q coordinates are obtained as follows:

$$\begin{aligned} &V_{se1d} = -x_{t1}I_{1q} + \frac{V_{dc}}{2} m_1 \cos\delta_1, V_{se1q} = x_{t1}I_{1d} + \frac{V_{dc}}{2} m_1 \sin\delta_1 \\ &V_{se2d} = -x_{t2}I_{2q} + \frac{V_{dc}}{2} m_2 \cos\delta_2, V_{se2q} = -x_{t2}I_{2d} + \frac{V_{dc}}{2} m_2 \sin\delta_2 \\ &I_{1d} = x_{11d}E'_q + \frac{1}{2}(x_{12d} - x_{11d})V_{dc}m_2 \sin\delta_2 - \frac{1}{2}x_{12d}V_{dc}m_1 \sin\delta_1 \\ &-x_{11d}V_b \cos\delta \\ &I_{2d} = x_{21d}E'_q + \frac{1}{2}(x_{22d} - x_{21d})V_{dc}m_2 \sin\delta_2 - \frac{1}{2}x_{22d}V_{dc}m_1 \sin\delta_1 \\ &-x_{21d}V_b \cos\delta \\ &I_{1q} = \frac{1}{2}(x_{11q} + x_{12q})V_{dc}m_2 \cos\delta_2 - \frac{1}{2}x_{12q}V_{dc}m_1 \cos\delta_1 \\ &+x_{11q}V_b \sin\delta \\ &I_{2q} = \frac{1}{2}(x_{21q} + x_{22q})V_{dc}m_2 \cos\delta_2 - \frac{1}{2}x_{22q}V_{dc}m_1 \cos\delta_1 \\ &+x_{21q}V_b \sin\delta \end{aligned} \tag{7}$$

where

$$\begin{aligned} &x_{BB} = -\{(x'_d + x_t)(x_{t2} + x_{L2}) + (x_{t1} + x_{L1})(x'_d + x_t + x_{t2} + x_{L2})\} \\ &x_{PP} = -\{(x_d + x_t)(x_{t2} + x_{L2}) + (x_{t1} + x_{L1})(x_d + x_t + x_{t2} + x_{L2})\} \\ &x_{11d} = \frac{-1}{x_{BB}}(x_{t2} + x_{L2}); x_{12d} = \frac{-1}{x_{BB}}(x'_d + x_t + x_{t2} + x_{L2}) \\ &x_{21d} = \frac{-1}{x_{BB}}(x_{t1} + x_{L1}); x_{22d} = \frac{1}{x_{BB}}(x'_d + x_t) \\ &x_{11q} = \frac{1}{x_{PP}}(x_{t2} + x_{L2}); x_{12q} = \frac{-1}{x_{PP}}(x_d + x_t + x_{t2} + x_{L2}) \\ &x_{21q} = \frac{1}{x_{PP}}(x_{t1} + x_{L1}); x_{22q} = \frac{1}{x_{PP}}(x_d + x_t) \end{aligned} \tag{8}$$

$$P_e = V_{td}I_{td} + V_{tq}I_{tq}; E_q = E'_q + (X_d - X'_d)I_{td}; V_t = V_{td} + jV_{tq}$$

$$V_{td} = X_q I_{tq}; V_{tq} = E'_q - X'_d I_{td}; I_{td} = I_{1d} + I_{2d}; I_{tq} = I_{1q} + I_{2q}$$

and i_t and v_b, are the armature current and infinite bus voltage, respectively. From the above equations, we can obtain: the x_t, x_{t1}, x_{t2}, x_d, x'_d and x_q which are the power transformer reactance's, the inserting transformers 1 and 2 reactance's, d-axis reactance, d-axis transient reactance, and q-axis reactance, respectively.

B. Power system linearized Heffron-Phillips model

The linearized Heffron-Phillips model of power system as shown in Figure 2 is given as follows:

$$\begin{aligned}
&\Delta\dot{\delta} = \omega_0 \Delta\omega \\
&\Delta\dot{\omega} = (-\Delta P_e - D\Delta\omega)/M \\
&\Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \\
&\Delta\dot{E}_{fd} = (K_A(\Delta v_{ref} - \Delta v) - \Delta E_{fd})/T_A \\
&\Delta\dot{v}_{dc} = K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta v_{dc} + K_{cm1}\Delta m_1 + K_{c\delta 1}\Delta\delta_1 + \\
&+K_{cm2}\Delta m_2 + K_{c\delta 2}\Delta\delta_2 \qquad (9)\\
&\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{pd}\Delta v_{dc} + K_{pm1}\Delta m_1 + K_{p\delta 1}\Delta\delta_1 + \\
&+K_{pm2}\Delta m_2 + K_{p\delta 2}\Delta\delta_2 \\
&\Delta E'_q = K_4\Delta\delta + K_3\Delta E'_q + K_{qd}\Delta v_{dc} + K_{qm1}\Delta m_1 + K_{q\delta 1}\Delta\delta_1 + \\
&+K_{qm2}\Delta m_2 + K_{q\delta 2}\Delta\delta_2 \\
&\Delta V_t = K_5\Delta\delta + K_6\Delta E'_q + K_{pv}\Delta v_{dc} + K_{vm1}\Delta m_1 + K_{v\delta 1}\Delta\delta_1 + \\
&+K_{vm2}\Delta m_2 + K_{v\delta 2}\Delta\delta_2
\end{aligned}$$

where, K_1, K_2, …, K_9, K_p, K_q, K_v, K_c, K_{pv}, K_{qv} and K_{vv} are the linearization constants.

$K_p = [K_{pm1}\ K_{p\delta 1}\ K_{pm2}\ K_{p\delta 2}]; K_q = [K_{qm1}\ K_{q\delta 1}\ K_{qm2}\ K_{q\delta 2}];$

$K_v = [K_{vm1}\ K_{v\delta 1}\ K_{vm2}\ K_{v\delta 2}]; K_c = [K_{cm1}\ K_{c\delta 1}\ K_{cm2}\ K_{c\delta 2}];$

The block diagram of the linearized dynamic model of the SMIB power system with IPFC is shown in Figure 3.

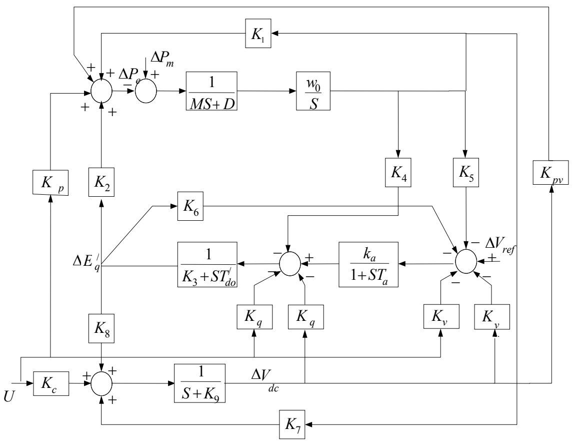

Figure 3. Modified Heffron-Phillips transfer function model for IPFC

C. Design of IPFC based Damping Controller using PSO Algorithm

In order to improve damping low frequency oscillations, the task of damping controller is producing in-phase electrical torque, with the speed deviation $\Delta\omega$, as the input for the damping controller. In this paper, the four control parameters of the IPFC (m_1, m_2, δ_1 and δ_2) are modulated in order to produce the damping torque. The parameters of the damping controller are obtained using PSO algorithm. This controller's structure which comprising gain block, signal-washout block and lead-lag compensator is shown in Figure 4.

To design the IPFC's lead-lag damping controller, we employed PSO algorithm to determine the optimal parameters of the controller and use a performance index based on the system dynamics after an occurred impules disturbance in power system to form an objective function of the designed problem. In this paper, the objective function is an Integral of Time multiplied Absolute value of the Error (ITAE) and is defined as follows [8].

$$J = \sum_{i=1}^{N_P} \int_0^{t_{sim}} t\left|\Delta\omega_i\right| dt \qquad (10)$$

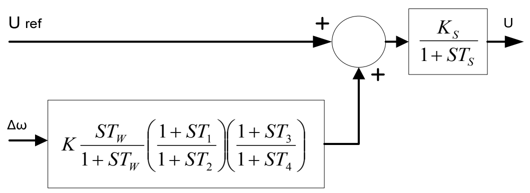

Figure 4. IPFC with lead-lag damping controller

In Equation (10), N_P is the total number of operating points to carry out the optimization, t_{sim} is the time range of simulation and $\Delta\omega$ is the deviation of the rotor speed of the generator in SMIB. The optimization purpose is minimizing the objective function bounded to following constraints.

Minimize J Subject to:

$$\begin{aligned}
&K^{\min} \le K \le K^{\max} \\
&T_1^{\min} \le T_1 \le T_1^{\max},\ T_2^{\min} \le T_2 \le T_2^{\max} \qquad (11)\\
&T_3^{\min} \le T_3 \le T_3^{\max},\ T_4^{\min} \le T_4 \le T_4^{\max}
\end{aligned}$$

The PSO algorithm searches for an optimal or near optimal set of controller parameters, with typical ranges are [0.01-100] for K and [0.01-1] for T_1, T_2, T_3 and T_4 of the optimized parameters. Using the time domain simulation model of the power system on the simulation period, the objective function is calculated and by considering the multiple operating conditions, the optimal parameters of the controller is carried out. The operating conditions are considered as:

- Base case: P = 0.7 pu, Q = 0.15 pu and X_{L1}=0.4 pu. (Nominal loading)
- Case 1: P = 1.25 pu, Q = 0.25 and X_{L1}=0.4 pu. (Heavy loading)
- Case 2: P = 0.2 pu, Q = 0.02 and X_{L1}=0.4 pu. (Light loading)
- Case 3: P = 0.7 pu, Q = 0.15 pu and X_{L1}=0.5 pu.
- (25% increase in the line reactance)

In this work, the value of N_P is 4 corresponding to the above four cases and the simulation run-time equals to 10 sec. In order to acquire better performance, number of particle, particle size, number of iteration, c_1, c_2 and c are chosen as 40, 5, 50, 2, 2 and 1, respectively. It should be noted that the PSO algorithm is run several times and then the optimal set of IPFC controller parameters is selected. The final values of the optimized parameters with the objective functions, J are given in the Table 1.

Table 1. The optimal parameter settings of the proposed controllers based on the different control signals

Controller parameters		K	T_1	T_2	T_3	T_4
Control signal	δ_1	85.9247	0.9751	0.7352	0.5546	0.4954
	m_1	69.7543	1	0.5560	0.5756	0.3609
	δ_2	57.2835	0.6123	0.4310	0.4411	0.3752
	m_2	90.3362	0.9636	0.7848	0.6525	0.6721

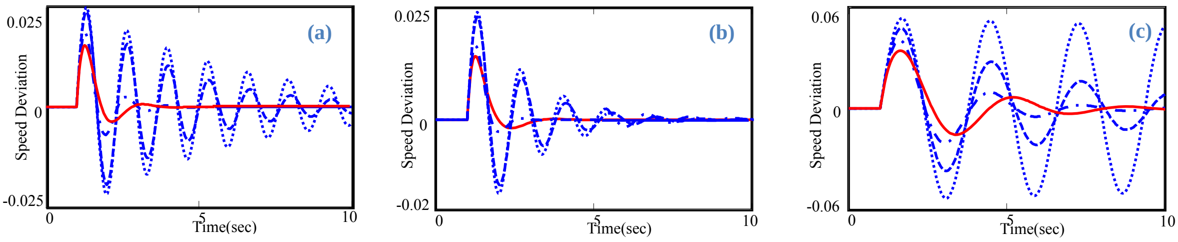

Figure 5. Dynamic responses for $\Delta\omega$ with controller at (a) Base case (b) Case 1 (c) Case 2 loading: Solid (m_1), Dot-Dashed (m_2), Dashed (δ_1) and Dotted (δ_2)

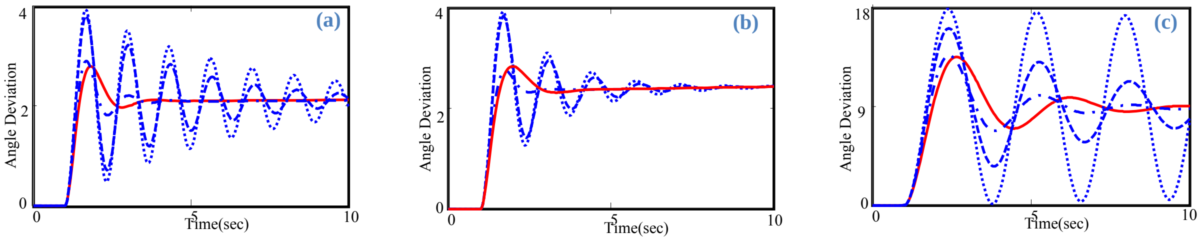

Figure 6. Dynamic responses for $\Delta\delta$ with controller at (a) Base case (b) Case 1 (c) Case 2 loading: Solid (m_1), Dot-Dashed (m_2), Dashed (δ_1) and Dotted (δ_2)

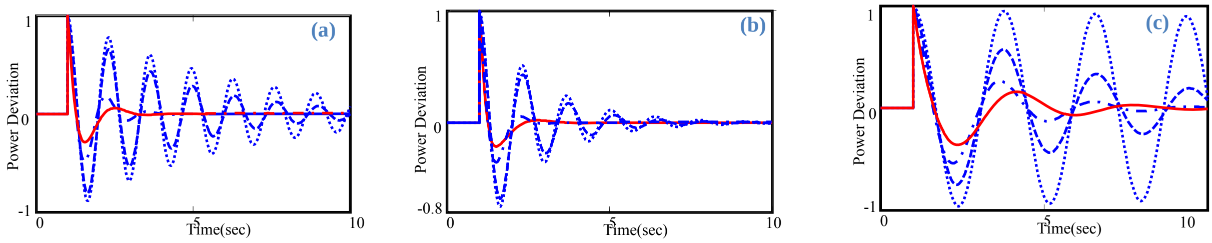

Figure 7. Dynamic responses for ΔP_e with controller at (a) Base case (b) Case 1 and (c) Case 2 loading: Solid (m_1), Dot-Dashed (m_2), Dashed (δ_1) and Dotted (δ_2)

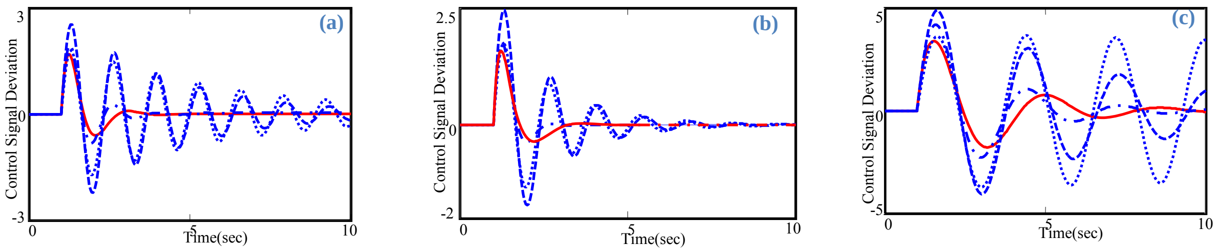

Figure 8. Dynamic responses for Δu with controller at (a) Base case (b) Case 1 and (c) Case 2 loading: Solid (m_1), Dot-Dashed (m_2), Dashed (δ_1) and Dotted (δ_2)

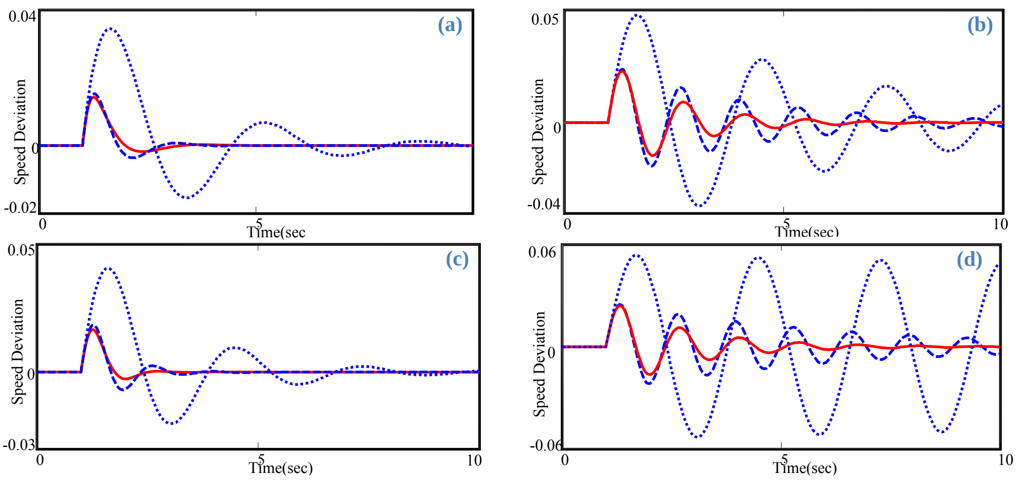

Figure 9. Dynamic response for $\Delta\omega$ of VSC1: (a) m_1 (b) δ_1 and VSC2: (c) m_2 (d) δ_2 in various load conditions: Solid (heavy), Dashed (nominal) and Dotted (light)

IV. SIMULATION RESULTS

A. Description the Considered Scenario

Simulation studies are carried out for a fault disturbance occurred in an occasional scenario. As such, we can assess the robustness of the designed damping controller by PSO algorithm. A 6-cycle three-phase fault occurred at $t = 1$ sec at the middle of the one transmission line is considered. The fault is cleared without the line tripping and the original system is restored upon the clearance of the fault. This severe disturbance is considered for different loading conditions and the performance of the proposed controller under these conditions is verified. The system response to this disturbance is shown in Figures 5, 6, 7, 8 and 9. From the above conducted tests, it can be concluded that the m_1 controller is superior to compare to the other three controllers.

B. Performance Index

We use the Integral of the Time multiplied Absolute value of the Error (ITAE) as a performance index to demonstrate the effectiveness of the proposed approach. Due to the system performance, this index is defined as:

$$ITAE = 10\left(\int_0^{10} t.\left(|\Delta\omega| + |\Delta\delta| + |\Delta P_e| + |\Delta U|\right)dt\right) \qquad (12)$$

where, speed deviation ($\Delta\omega$), angle deviation ($\Delta\delta$), power deviation (ΔP_e) and the output control signal of the controller (ΔU) is considered for evaluation the ITAE performance index. It is worth mentioning that the lower the value of this index is the better the system response in terms of time-domain characteristics. Numerical results of performance robustness for all system loading cases are listed in Table 2.

Table 2. Values of Performance Index ITAE

Control signal	Base Case	Case 1	Case 2	Case 3
	δ=37.3°	δ=51.8°	δ=14.2°	δ=39.1°
m_1	106.5829	102.2326	467.0539	110.2705
δ_1	131.7472	128.9435	517.0491	136.0401
m_2	107.0740	102.7176	468.1011	110.7705
δ_2	139.7908	129.1732	548.5413	145.6714

It can be seen that the values of these system performance characteristics in all operational cases with the m_1 based tuned controller are smaller compared to m_2, δ_1 and δ_2 based tuned damping controllers. As such, it can be concluded that the m_1 controller is the most robust controller. Also, by increasing the reactance of the compensating lines for a constant load, the ITAE index is increased. In other words, the controller performance is declined in lines with high reactance. Moreover, in a constant line reactance, with decreasing in load, therewith, decreasing in the transmission angle (δ), the line current is dropping. As a result, the active power which the series VSCs interchange with the uncompensated lines will be decreased. As such, the active power injection decreases with decreasing the transmission angle [2]. Therefore, LFOs which occurred in light loading are damped posterior due to nominal or heavy loading conditions. The ITAE index upper values in light loading are verifying the above discussion. In other words, decreasing in load may have a castrating effect in weakening these four controller performances.

V. CONCLUSIONS

In this paper, IPFC's effect on the dynamic stability of power system has been investigated. The design problem of the IPFC's supplementary lead-lag controller is converted into an optimization problem which is solved by a PSO technique with an ITAE performance index applied as an objective function. The effectiveness of the proposed IPFC signal controllers for improving dynamic stability performance of a power system are demonstrated by a weakly connected example power system subjected to different severe disturbances. Then, we compare the IPFC's different control signals in order to demonstrate the most effective control signal in order to provide good damping low frequency oscillations in single-machine power system. The system performance characteristics in terms of the ITAE index and non-linear time domain analysis reveal that the proposed controller based on m_1 control signal has superiority than other three signal based controllers due to the different operating conditions.

NOMENCLATURES

ACO: Ant Colony Optimization
AVR: Automatic Voltage Regulator
FACTS: Flexible AC Transmission System
GA: Genetic Algorithm
GTO: Gate Turn-Off thyristor
m_1: Amplitude modulation ratio of VSC1
m_2: Amplitude modulation ratio of VSC2
δ: Rotor angle
δ_1: Phase angle of control signal of VSC1
δ_2: Phase angle of control signal of VSC2
ω: Rotor speed
P_e: Active power
VSC: Voltage Source Converter

REFERENCES

[1] A.J. Keri, X. Lombard and A.A. Edris, "Unified Power Flow Controller: Modeling and Analysis", IEEE Transactions on Power Delivery, Vol. 14, Issue 2, pp. 648-654, 1999.
[2] L. Gyugyi, K.K. Sen and C.D. Schauder, "The Interline Power Flow Controller Concept: A New Approach to Power Flow Management in Transmission Systems", IEEE Transactions on Power Delivery, Vol. 14, Issue 3, pp. 1115-1123, July 1999.
[3] R. Vasquez-Arnez and L. Cero Zanetta, "A Novel Approach for Modeling the Steady-State VSC-Based Multiline FACTS Controllers and Their Operational Constraints", IEEE Transactions on Power Delivery, Vol. 23, Issue 1, pp. 457-464, Jan. 2008.
[4] Z. Yankui, Z. Yan and C. Chen, "A Novel Power Injection Model of IPFC for Power Flow Analysis

Inclusive of Practical Constraints", IEEE Transactions on Power Systems, Vol. 4, Issue 21, pp. 1550-1556, Nov. 2006.
[5] A.M. Parimi, I. Elamvazuthi and N. Saad, "Damping of Inter Area Oscillations Using Interline Power Flow Controller (IPFC) Based Damping Controllers", International Conference of Power and Energy, pp. 67-72, 1-3 Dec. 2008.
[6] A. Kazemi, E. Karimi, "The Effect of Interline Power Flow Controller (IPFC) On Damping Inter-area Oscillation in the Interconnected Power Systems", IEEE ISIE Quebec, Canada, pp. 1911-1915, July 2006.
[7] Y. Del Valle, G.K. Venayagamoorthy, S. Mohagheghi, J. Carlos and R.G. Harlry, "Particle Swarm Optimization: Basic Concepts, Variants and Application in Power Systems", IEEE Transactions on Evolutionary Computation, Vol. 12, Issue 2, pp. 171-195, Apr. 2008.
[8] H. Shayeghi, H.A. Shayanfar, S. Jalilzadeh and A. Safari, "A PSO Based Unified Power Flow Controller For Damping of Power System Oscillation", Energy Conversion and management, Vol. 50, pp. 2583-2592, June 2009.

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