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SIMULTANEOUS COORDINATED DESIGNING OF UPFC AND PSS OUTPUT FEEDBACK CONTROLLERS USING PSO

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In this paper, a novel method presents the simultaneous coordinated designing of the UPFC and the power system stabilizer with output feedback controllers in single-machine infinite-bus power system. On the basis of the linearized Phillips-Herffron model, the coordinated design problem of PSS and UPFC with output feedback controllers over a wide range of loading conditions and system configurations is formulated as an optimization problem based on the time domain-based objective function which is solved by a particle swarm optimization algorithm (PSO) which has a strong ability to find the most optimistic results. Only local and available state variables are adopted as the input signals of each output feedback controller for the coordinated design. To ensure the robustness of the proposed simultaneous coordinated tuning, the design process takes into account a wide range of operating conditions and system configurations. The effectiveness of the proposed method is demonstrated through nonlinear time-domain simulation and some performance indices studies under various disturbance conditions of over a wide range of loading conditions. The results of these studies show that the PSO based output feedback controllers for coordinated designing has an excellent capability in damping power system oscillations and enhance greatly the dynamic stability of the power system.

K e y w o r d s: simultaneous coordinated designing, UPFC, output feedback, power oscillation damping, PSO

1 INTRODUCTION

As power demand grows rapidly and expansion in transmission and generation is restricted with the limited availability of resources and the strict environmental constraints, power systems are today much more loaded than before. This causes the power systems to be operated near their stability limits. In addition, interconnection between remotely located power systems gives rise to low frequency oscillations in the range of 0.2-3.0 Hz. If not well damped, these oscillations may keep growing in magnitude until loss of synchronism results [1-2]. In order to damp these power system oscillations and increase system oscillations stability, the installation of Power System Stabilizer (PSS) is both economical and effective. PSSs have been used for many years to add damping to electromechanical oscillations. 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 [3].

In recent years, the fast progress in the field of power electronics had opened new opportunities for the application of the FACTS devices as one of the most effective ways to improve power system operation controllability and power transfer limits [1-4]. 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. Because of the extremely fast control action associated with FACTS-device operations, they have been very promising candidates for utilization in power system damping enhancement. It has been observed that utilizing a feedback supplementary control, in addition to the FACTS-device primary control, can considerably improve system damping and can also improve system voltage profile, which is advantageous over PSSs.

The Unified Power Flow Controller (UPFC) is regarded as one of the most versatile devices in the FACTS device family [5-6] which 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 [1,4]. The application of the UPFC to the modern power system can therefore lead to the more flexible, secure and economic operation [7]. When the UPFC is applied to the interconnected power systems, it can also provide significant damping effect on tie line power oscillation through its supplementary control.

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 neu-

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ral networks method [8] and robust control methodologies [7, 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. Also, some authors used fuzzy logic based damping control strategy for TCSC, UPFC and SVC in a multi-machine power system [10-12]. The damping control strategy employs non-optimal fuzzy logic controllers that is why the system's response settling time is unbearable. Moreover, the initial parameters adjustment of this type of controller needs some trial and error. Chen et al. [13] used a output feedback controller designed by simulated annealing (SA) for TCSC to improve power system low frequency oscillations. The proposed method has without to have in view PSS much settling time. Mok et al. [14] applied a GA-based Proportional-Integral (PI) type fuzzy controller for UPFC to enhance power system damping. Although, the fuzzy PI controller is simpler and more applicable to remove the steady state error, it is known to give poor performance in the system transient response.

However, uncoordinated control of FACTS devices and PSS may cause destabilizing interactions. To improve overall system performance, many researches were made on the coordination between PSSs and FACTS damping controllers [15-18]. Some of these methods are based on the complex nonlinear simulation, while the others are based on the linearized power system model. 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 favourable. In this paper, study is concentrated on the selection of the output feedback gains of the controllers for coordinated designing of UPFC and PSS.

PSO technique is used for tuning of PSS and UPFC output feedback controller parameters in order to enhance the damping of power systems low frequency oscillations and achieves the desired level of robust performance under different operating conditions and disturbances. 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. Also, it suffices to specify the objective function and to place finite bounds on the optimized parameters. This algorithm has also been found to be robust in solving problems featuring non-linearity, non-differentiability and high-dimensionality [20,21].

A new approach for the simultaneous coordinated designing of the UPFC and the power system stabilizer with output feedback controllers is investigated in this paper. 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 problem of robust output feedback controller coordinated design is formulated as an optimization problem and PSO is used to solve this problem. Since only local and available states ($\Delta\omega$ and ΔV_t) are used as the inputs of each controller, the optimal decentralized design of controllers can be accomplished. The effectiveness of the proposed method is demonstrated through nonlinear time simulation studies and some performance indices to damp low frequency oscillations under different operating conditions. Results evaluation show that the proposed coordinated design achieves good robust performance for a wide range of operating conditions and is superior to uncoordinated design.

2 PSO TECHNIQUE

Particle swarm optimization algorithm, which is tailored for optimizing difficult numerical functions and based on metaphor of human social interaction, is capable of mimicking the ability of human societies to process knowledge [20]. It has roots in two main component methodologies: artificial life (such as bird flocking, fish schooling and swarming); and, evolutionary computation. 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. It lies somewhere in between evolutionary programming and the genetic algorithms. 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. It keeps track of its coordinates in hyperspace which are associated with its previous best fitness solution, and also of its counterpart corresponding to the overall best value acquired thus far by any other particle in the population. Vectors are taken as presentation of particles since most optimization problems are convenient for such variable presentations. In fact, the fundamental principles of swarm intelligence are adaptability, diverse response, proximity, quality, and stability. It is adaptive corresponding to the change of the best group value. The allocation of responses between the individual and group values ensures a diversity of response. 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. The principle of stability is adhered to since the population changes its state if and only if the best group value changes. As it is reported in [21], this optimization technique can be used to solve many of the same kinds of

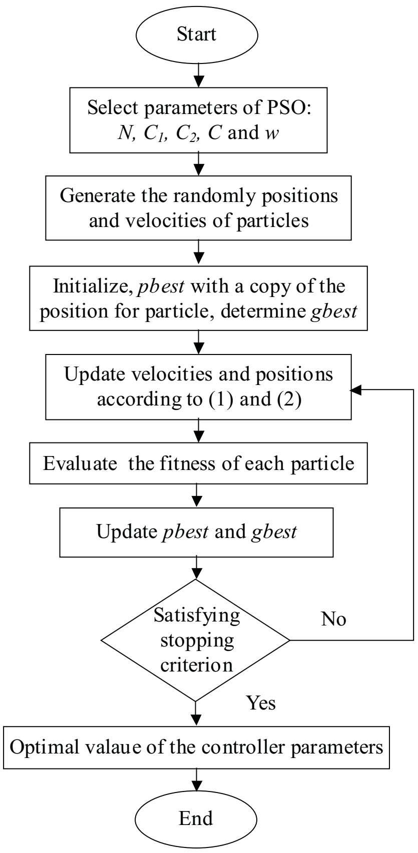

Fig. 1. Flowchart of the proposed PSO technique

problems as GA, and does not suffer from some of GAs difficulties. It has also been found to be robust in solving problem featuring non-linearity, non-differentiability and high-dimensionality. PSO is the search method to improve the speed of convergence and find the global optimum value of fitness function.

PSO starts with a population of random solutions "particles" in a D-dimension space. The ith particle is represented by $X_i = (x_{i1}, x_{i2}, \dots, x_{iD})$. 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 $P_i = (p_{i1}, p_{i2}, \dots, p_{iD})$. 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. 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 $V_i = (v_{i1}, v_{i2}, \dots, v_{iD})$. 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), [20].

$$v_i^{k+1} = \omega\, v_i^k + c_1\, r_1 (P_{id}^k - x_{id}^k), + \\ + c_2\, r_2 (P_{gd}^k - x_{gd}^k) \tag{1}$$

$$x_{id}^{k+1} = x_{id}^k + c\, v_{id}^{k+1} \tag{2}$$

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 inertia weight w is responsible for dynamically adjusting the velocity of the particles, so it is responsible for balancing between local and global searches and hence requiring less iteration for the algorithm to converge.

Several modifications have been proposed in the literature to improve the PSO algorithm speed and convergence toward the global minimum. One modification is to introduce a local-oriented paradigm (lbest) with different neighborhoods. It is concluded that *gbest* version performs best in terms of median number of iterations to converge. However, *pbest* version with neighborhoods of two is most resistant to local minima. PSO algorithm is further improved via using a time decreasing inertia weight, which leads to a reduction in the number of iterations [19]. Figure 1 shows the flowchart of the proposed PSO algorithm.

This new approach features many advantages; it is simple, fast and easy to be coded. Also, its memory storage requirement is minimal. Moreover, this approach is advantageous over evolutionary and genetic algorithms in many ways. First, PSO has memory. That is, every particle remembers its best solution (local best) as well as the group best solution (global best). Another advantage of PSO is that the initial population of the PSO is maintained, and so there is no need for applying operators to the population, a process that is time and memory-storage-consuming. In addition, PSO is based on "constructive cooperation" between particles, in contrast with the genetic algorithms, which are based on "the survival of the fittest".

3 DESCRIPTION OF CASE STUDY SYSTEM

Figure 2 shows a SMIB power system equipped with a UPFC. The synchronous generator is equipped with a PSS and it is delivering power to the infinite-bus through a double circuit transmission line and a UPFC. The UPFC consists of an excitation transformer (ET), a boosting transformer (BT), two three-phase GTO based voltage source converters (VSCs), and a DC link capacitors. 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.

3.1 Power system nonlinear model with UPFC

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. The system data is

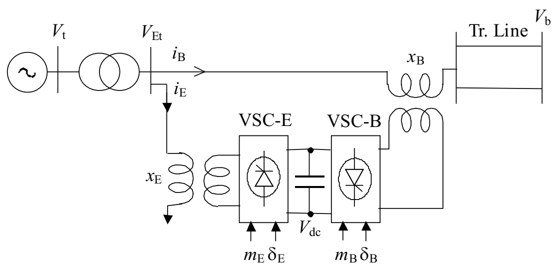

Fig. 2. SMIB power system equipped with UPFC

given in the Appendix. 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]

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

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

$$\begin{aligned} \dot{v}_{dc} = \frac{3m_E}{4C_{dc}} [\cos\delta_E \;\; \sin\delta_E] \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \\ + \frac{3m_B}{4C_{dc}} [\cos\delta_B \;\; \sin\delta_B] \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} \end{aligned} \tag{5}$$

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 as shown in Fig. 2 is described by [1]

$$\dot{\delta} = \omega_0(\omega - 1) \tag{6}$$

$$\dot{\omega} = (P_m - P_e - D\Delta\omega)/M \tag{7}$$

$$\dot{E}'_q = (-E_q + E_{fd})/T'_{do} \tag{8}$$

$$\dot{E}_{fd} = (-E_{fd} + K_a(V_{ref} - V_t))/T_a \tag{9}$$

where

$$\begin{aligned} &P_e = V_{td}I_{td} + V_{tq}I_{tq}; E_q = E'_{qe} + (X_d - X'_d)\, I_{td} \\ &V_t = V_{td} + jV_{tq}; V_{td} = X_q I_{tq}; V_{tq} = E'_q - X'_d I_{td} \\ &I_{td} = I_{tld} + I_{Ed} + I_{Bd}; I_{tq} = I_{tlq} + I_{Eq} + I_{Bq} \end{aligned} \tag{10}$$

3.2 Power system linearized model

A linear dynamic model is obtained by linearizing the nonlinear model round an operating condition. The linearized model of power system as shown in Fig. 2. is given as follows

$$\Delta\dot{\delta} = \omega_0 \Delta\omega \tag{11}$$

$$\Delta\dot{\omega} = (-\Delta P_e - D\Delta\omega)/M \tag{12}$$

$$\Delta\, \dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \tag{13}$$

$$\Delta\dot{E}_{fd} = (K_A(\Delta v_{ref} - \Delta v) - \Delta E_{fd})/T_A \tag{14}$$

$$\begin{aligned} \Delta\dot{v}_{dc} = K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta v_{dc} + K_{ce}\Delta m_E \\ + K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B \end{aligned} \tag{15}$$

$$\begin{aligned} \Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{pd}\Delta v_{dc} + K_{pe}\Delta m_E \\ + K_{p\delta e}\Delta\delta_E + K_{pb}\Delta m_B + K_{p\delta b}\Delta\delta_B \end{aligned} \tag{16}$$

$$\begin{aligned} \Delta E'_q = K_4\Delta\delta + K_3\Delta E'_q + K_{qd}\Delta v_{dc} + K_{qe}\Delta m_E \\ + K_{q\delta e}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta b}\Delta\delta_B \end{aligned} \tag{17}$$

$$\begin{aligned} \Delta V_t = K_5\Delta\delta + K_6\Delta E'_q + K_{vd}\Delta v_{dc} + K_{ve}\Delta m_E \\ + K_{v\delta e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B \end{aligned} \tag{18}$$

where K_1, $K_2 \dots K_9$, 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.

3.3. Output feedback controller for PSS and UPFC

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

$$\dot{X} = AX + BU \tag{19}$$

$$Y = CX \tag{20}$$

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 structures

$$U = GX \tag{21}$$

Substituting (20) into (21) the resulting state equation is

$$\dot{X} = A_c X \tag{22}$$

where, A_c is the closed-loop state matrix. For output feedback

$$A_c = A + BGC \tag{23}$$

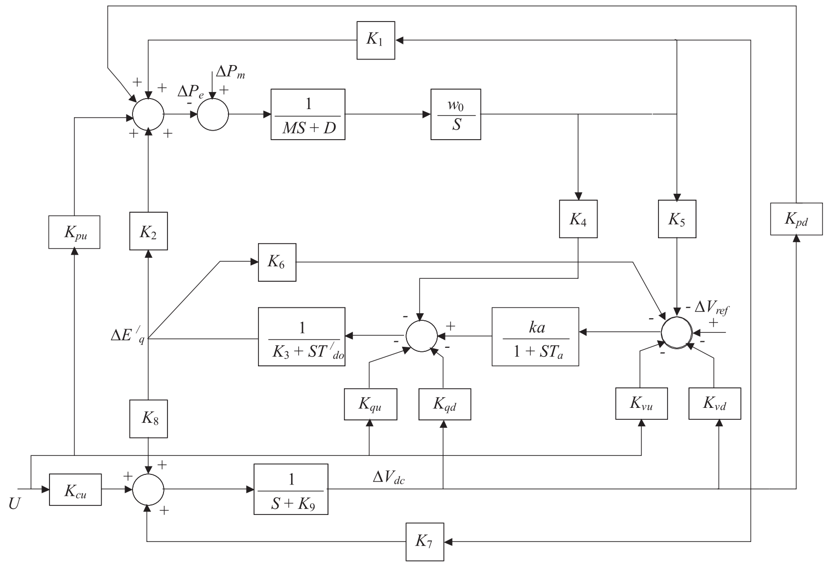

Fig. 3. Modified Heffron-Phillips transfer function model

By properly choosing the feedback gain G, 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. The output feedback signals can be selected by using mode observability analysis [13]. Once the output feedback signals are selected, only the selected signals are used in forming (23). Therefore, the remaining problem in the design of output feedback controllers 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. At the same time, the magnitude of controller gains must be kept within pre-specified limits.

In this study an optimal design for the PSS with output feedback schemes is presented. The following output feedback gain matrix is taken to form the optimal design for the PSS.

$$U_{PSS} = [G_1 \quad G_2]\,Y \tag{24}$$

Since only local and available states ($\Delta\omega$ and ΔV_t) are used as the inputs of each controller, the optimal decentralized design of controllers can be accomplished. The four control parameters of the UPFC (m_B, m_E, δ_B and δ_E) can be modulated in order to produce the damping torque. In this paper δ_E is modulated in order to coordinated design. The proposed controllers must be able to work well under all the operating conditions where the improvement in damping of the critical modes is necessary. The selection of the output feedback gains for simultaneous coordinated designing of the UPFC and the PSS described above is an optimization problem, which can be solved by using the PSO algorithm.

To acquire an optimal combination, this paper employs PSO [20] to improve optimization synthesis and find the global optimum value of fitness function. A performance index based on the system dynamics after an impulse disturbance alternately occurs in the system is organized and used to form the objective function of the design problem. For our optimization problem, an Integral of Time multiplied Absolute value of the Error (ITAE) is taken as the objective function. The objective function is defined as follows [23]

$$J = \sum_{i=1}^{Np} \int_0^{t_{sim}} t\,|\Delta\omega_i|dt \tag{25}$$

In the above equations, 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. For objective function calculation, the time-domain simulation of the power system model is carried out for the simulation period. It is aimed to minimize this objective function in order to improve the system response in terms of the settling time and overshoots. The coordinated design problem can be formulated as the following constrained optimization problem, where the constraints are the controller parameters bounds [17]

$$\begin{aligned} &\text{Minimize } J \text{ Subject to:}\\ &G_1^{\min} \leqslant G_1 \leqslant G_1^{\max}\\ &G_2^{\min} \leqslant G_2 \leqslant G_2^{\max} \end{aligned} \tag{26}$$

Typical ranges of the optimized parameters are [0.01-150] for G_1 and [0.01-10] for G_2. The proposed approach employs PSO algorithm to solve this optimization problem and search for an optimal set of coordinated controller parameters. The optimization of PSS and UPFC output feedback controller parameters is carried out by evaluating the multiobjective cost function as given in (25), which considers a multiple of operating conditions. The operating conditions considered are

- Base case: $P = 0.80$ pu, $Q = 0.114$ 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: The 30% increase of line reactance X_L at nominal loading condition.
- Case 4: The 30% increase of line reactance X_L at heavy loading condition.

In our implementation, in order to acquire better performance, number of particle, particle size, number of iteration, c_1, c_2 , and c is chosen as 30, 4, 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 PSO algorithm is run several times and then optimal set of coordinated controller parameters is selected. The final values of the optimized parameters with objective function, J, are given in Table 1.

Table 1. The optimal parameter settings of the proposed controllers

Controller parameters	Uncoordinated design		Coordinated design	
	PSS	δ_E	PSS	δ_E
G_1	118.5	60.18	16.65	78.32
G_2	0.5112	0.31	0.3140	1.8012

4 NONLINEAR TIME–DOMAIN SIMULATION

In order to show the effectiveness of the proposed model of power system with PSS and UPFC output feedback controller and simultaneous tuning the controller parameters in the way presented in this paper, simulation studies are carried out for various fault disturbances and fault clearing sequences for two scenarios.

4.1 Scenario 1

In this scenario, 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. To evaluate the performance of the proposed simultaneous design approach the response with the proposed controllers are compared with the response of the PSS and UPFC output feedback controller individual design. The speed deviation of generator at nominal, light and heavy loading conditions with coordinated and uncoordinated design of the controllers is shown in Fig. 4. Also, Fig. 5 shows the internal excitation voltage variations, terminal voltage deviation and output electrical power deviation with the proposed controllers, respectively. It is clear from these Figures that, the simultaneous design of PSS and UPFC output feedback controller by the proposed approach significantly improves the stability performance of the example power system and low frequency oscillations are well damped out.

4.2 Scenario 2

In this scenario, another severe disturbance is considered for different loading conditions; that is, a 6-cycle, three-phase fault is applied at the same above mentioned location in scenario 1. The fault is cleared without line tripping and the original system is restored upon the clearance of the fault. The system response to this disturbance is shown in Fig. 6. It is also clear form the Fig. that the first swing stability is greatly improved with the coordinated design approach.

From the above conducted tests, it can be concluded that the coordinated controllers are superior to the uncoordinated controllers. To demonstrate performance robustness of the proposed method, two performance indices: the Integral of the Time multiplied Absolute value of the Error (ITAE) and Figure of Demerit (FD) based on the system performance characteristics are defined as [23]

$$ITAE = 10000 \int_0^5 t\,|\Delta\omega|\,dt$$
$$FD = (1000 \times OS)^2 + (3000 \times US)^2 + TS^2 \qquad (27)$$

where, speed deviation $(\Delta\omega)$, Overshoot (OS), Undershoot (US) and settling time of speed deviation of the machine is considered for evaluation of the ITAE and FD indices. It is worth mentioning that the lower the value of these indices 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. It is also clear from the Table 2 that, application both PSS and UPFC output feedback controller where the controllers are tuned by the proposed simultaneous design approach gives the best response in terms of overshoot, undershoot and settling time.

5 CONCLUSIONS

In this paper, the simultaneous coordinated designing of the UPFC and the conventional power system stabilizer with output feedback controllers is investigated. For the design problem, a parameter-constrained, time domain objective function is developed to improve the performance of power system subjected to a disturbance. Then, PSO is employed to coordinately tune the parameters of the PSS and UPFC output feedback controllers. The effectiveness of the proposed control approach for improving transient stability performance of a power system are demonstrated by a weakly connected example power system subjected to different severe disturbances. The non-linear time domain simulation results show the effectiveness of the proposed method using multiobjective function and their ability to provide good damping of low frequency oscillations. The system performance characteristics in terms of 'ITAE' and 'FD' indices reveal that

Table 2. Values of Performance Indices ITAE and FD

Fault case	Controller	Base Case		Case 1		Case 2		Case 3		Case 4	
		ITAE	FD	ITAE	FD	ITAE	FD	ITAE	FD	ITAE	FD
With tripping line	PSS	31.25	23.48	27.49	30.88	31.8	24.97	45	30.17	50.45	34.28
	δ_E	45.87	32.72	22.41	15.32	48.01	33.78	43.87	21.55	50.08	23.18
	PSS & δ_E	24.69	12.15	19.59	8.99	24.3	12.04	41.52	17.88	46	20.6
Without tripping line	PSS	21.8	19.09	23.9	28.02	21.59	21.22	26.26	21.29	28.31	21.51
	δ_E	48.91	46.09	21.3	19.33	52.78	48.89	33.83	21.02	38.13	26.54
	PSS & δ_E	18.03	12.65	14.39	10.24	17.2	12.15	21.17	10.7	22.46	11.15

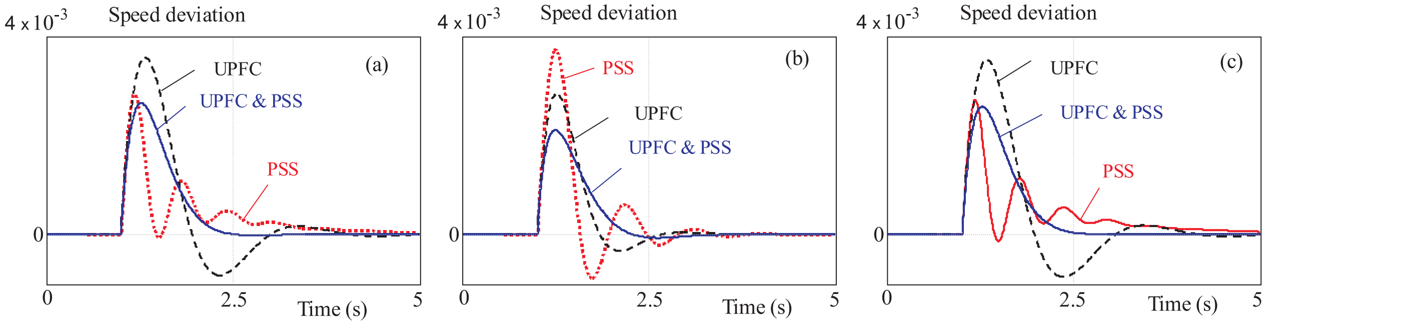

Fig. 4. Dynamic responses for $\Delta\omega$ at: (a) – nominal, (b) – light, (c) – heavy loading conditions; Solid (UPFC & PSS), Dashed (UPFC) and Dotted (PSS)

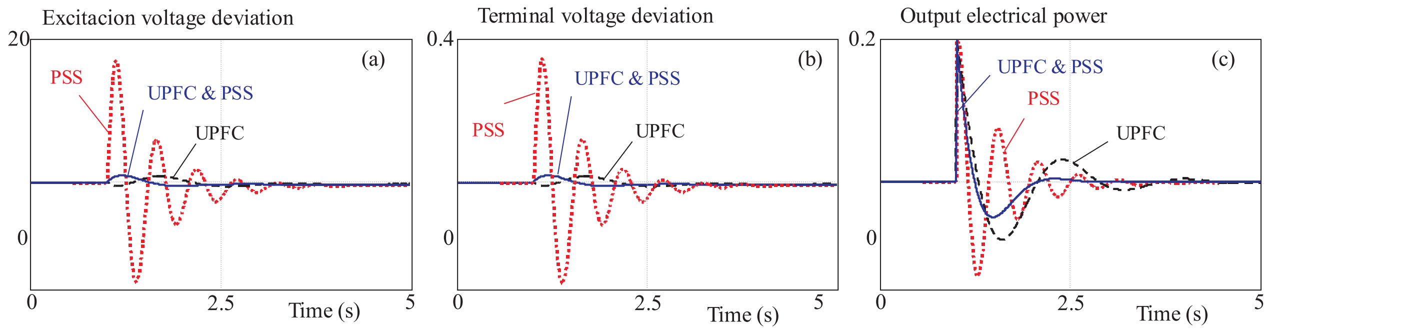

Fig. 5. Dynamic responses at nominal loading: (a) – Excitation voltage, (b) – Terminal voltage, (c) – Output electrical power; Solid (UPFC & PSS), Dashed (UPFC) and Dotted (PSS)

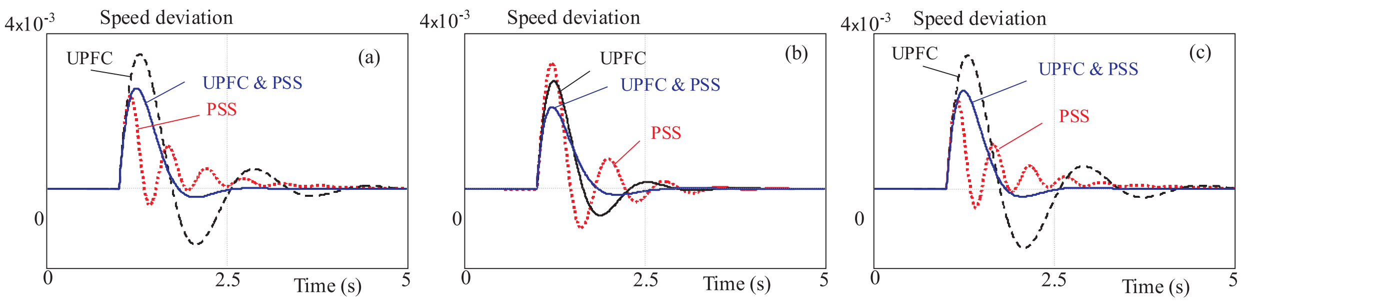

Fig. 6. . Dynamic responses for $\Delta\omega$ at: (a) – nominal, (b) – light, (c) – heavy loading conditions; Solid (UPFC & PSS), Dashed (UPFC) and Dotted (PSS)

the simultaneous coordinated designing of the UPFC and the PSS with output feedback controllers demonstrates its superiority than both the uncoordinated designed stabilizers of the PSS and UPFC output feedback controller at various fault disturbances and fault clearing sequences.

Appendix:

The nominal parameters and operating condition of the system are listed bellow.

Generator: $M = 8$ MJ/MVA, $T'_{d0} = 5.044$ s, $X_q = 0.6$ pu, $X_d = 0.6$ pu, $X'_d = 0.3$ pu, $D = 0$

Excitation system: $K_a = 10$, $T_a = 0.05$ s

Transformers: $X_T = 0.1$ pu, $X_E = 0.1$ pu, $X_B = 0.1$ pu

Transmission line: $X_L = 0.1$ pu

Operating condition: $P = 0.8$ pu, $V_b = 1$ pu, $V_t = 1$ pu

DC link parameter: $V_{DC} = 2$ pu, $C_{DC} = 1$ pu

UPFC parameter: $m_B = 0.08$, $m_E = 0.04$, $\delta_B = -78.21$ deg, $\delta_E = -83.35$ deg, $K_S = 1$, $T_S = 0.05$ s

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