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# Robust Coordinated Designing of PSS and UPFC Damping Controller

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***Abstract***

*This paper presents the simultaneous coordinated designing of the UPFC robust power oscillation damping controller and the conventional power system stabilizer. On the basis of the linearized Phillips-Herffron model, the coordinated design problem of PSS and UPFC damping controllers over a wide range of loading conditions and system configurations is formulated as an optimization problem with the eigenvalue-based multiobjective function which is solved by a particle swarm optimization algorithm (PSO) that has a strong ability to find the most optimistic results. The stabilizers are tuned to simultaneously shift the undamped electromechanical modes to a prescribed zone in the s-plane. To ensure the robustness of the proposed simultaneous coordinated controllers 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 eigenvalue analysis, 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 simultaneous coordinated controller has an excellent capability in damping power system oscillations and enhance greatly the dynamic stability of the power system.*

***Keyword:*** *coordinated designing, UPFC, dynamic stability, multiobjective optimization, PSO*

## 1. Introduction

Electromechanical oscillations in power systems are a problem that has been challenging engineers for decades. These oscillations may be very poorly damped in some cases, resulting in mechanical fatigue at the machines and unacceptable power variations across important transmission lines. For this reason, the use of controllers to provide better damping for these oscillations is of utmost importance [1]. With increasing transmission line loading over long distances, the use of conventional power system stabilizers might in some cases, not provide sufficient damping for inter-area power swings. In these cases, other effective solutions are needed to be studied [2]. In recent years, advances in the high power solid-state switches. e.g. Gate Turn Off (GTO) Thyristors, have led to the development of transmission controllers that provide controllability and flexibility for power transmission [3]. Flexible ac transmission system (FACTS) is the technology that provides the needed corrections of the transmission functionality in order to fully utilize the existing transmission facilities and hence, minimizing the gap between the stability limit and thermal limit [4]. The Unified Power Flow Controller (UPFC) is regarded as one of the most versatile devices in the FACTS device family 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 [5-8]. A traditional lead-lag damping controller structure is preferred by the power system utilities because of the ease of on-line tuning and also lack of assurance of the stability by some adaptive or variable structure methods [9]. In addition, Reference [10] has demonstrated that the CPSS provide satisfactory damping performance over a wide range of system loading conditions. The robustness nature of the CPSS is due to the fact that the torque-reference voltage transfer function remains approximately invariant over a wide range of operating conditions.

The interaction among stabilizers may enhance or degrade the damping of certain modes of rotor's oscillating modes. The improvement hinges on an adequate coordination of

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controllers in order to solve marginal operating problems, ensuring robustness for several operating conditions. To improve overall system performance, many researches were made on the coordination between PSSs and FACTS damping controllers [11-14]. Some of these methods are based on the complex nonlinear simulation, while the others are based on the linearized power system model. In this paper, an optimization-based tuning algorithm is proposed to coordinate among PSS and UPFC power oscillation damping controllers simultaneously. This algorithm optimizes the total system performance by means of PSO method. This method is proposed to improve optimization synthesis such that the global optima are guaranteed and the speed of algorithms convergence is extremely improved, too. PSO algorithm can be used to solve many of the same kinds of problems as GA and does not suffer from of GA's difficulties. 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. 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-linearing, non-differentiability and high-dimensionality [15-18].

In this study, the problem of simultaneous coordinated designing of the UPFC POD controller and the conventional power system stabilizer is formulated as a multiobjective optimization problem. The multiobjective problem is concocted to optimize a composite set of two eigenvalue-based objective functions comprising the desired damping factor, and the desired damping ratio of the lightly damped and undamped electromechanical modes. By minimizing the objective function in which the influences of both PSSs and FACTS POD controllers are considered, interactions among these controllers are improved. The effectiveness of the proposed controller is demonstrated through eigenvalue analysis, nonlinear time simulation studies and some performance indices to damp low frequency oscillations under different operating conditions.

## 2. PSO Technique

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 [15]. The PSO has also been found to be robust in solving problem featuring non-linearing, non-differentiability and high-dimensionality [16]. In PSO a number of simple entities, the particles, are placed in the search space of some problem or function, and each evaluates the objective function at its current location. Each particle then determines its movement through the search space by combining some aspect of the history of its own current and best locations with those of one or more members of the swarm, with some random perturbations. The next iteration takes place after all particles have been moved. Eventually the swarm as a whole, like a flock of birds collectively foraging for food, is likely to move close to an optimum of the fitness function [19].

In the PSO technique, the trajectory of each individual in the search space is adjusted by dynamically altering the velocity of each particle, according to its own flying experience and the flying experience of the other particles in the search space. The position vector and the velocity vector of the ith particle in the D-dimensional search space can be represented as $X_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$ and $V_i = (v_{i1}, v_{i2} \ldots v_{iD})$ respectively. According to a user defined fitness function, let us say the best position of each particle, which corresponds to the best fitness value (*pbest*) obtained by that particle at time, is $P_i = (p_{i1}, p_{i2}, \ldots, p_{iD})$ , and 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. Then, the new velocities and the positions of the particles for the next fitness evaluation are calculated using the following two equations [15].

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

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

Where, $P_{id}$ and $P_{gd}$ are *pbest* and *gbest*. Here *w* is the inertia weight parameter which controls the global and local exploration capabilities of the particle. Constants $c_1$, $c_2$ are cognitive and social co- efficients, respectively, and $r_1$, $r_2$are random numbers between 0 and 1. A larger inertia weight factor is used during initial exploration its value is gradually reduced as the search proceeds. The following weighting function w is used in (1):

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter\_\max} iteration \quad (3)$$

Equation (3) shows how the inertia weight is updated, considering $w_{max}$ and $w_{min}$ are the initial and final weights, respectively. Figure 1 shows the flowchart of the proposed PSO algorithm.

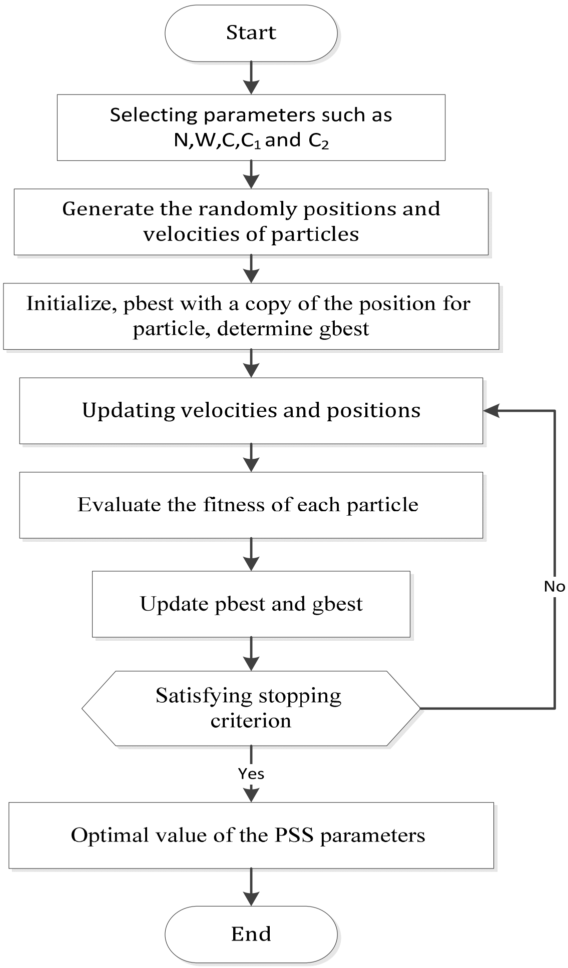



Figure 1. Flowchart of the Proposed PSO Technique

## 3. Description of Case Study

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, a boosting transformer, two three-phase GTO based VSC and a DC link capacitors [5, 8, 15]. 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 given in Appendix. By employing Park's transformation and neglecting transients of the ET and BT transformers, the UPFC can be modeled as [5, 8, 15]:

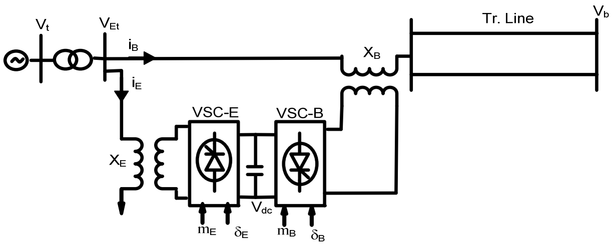



Figure 2. SMIB Power System Equipped with UPFC

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

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

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

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 as shown in Figure 2 is described by [15, 21]:

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

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

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

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

A linear dynamic model is obtained by linearizing the nonlinear model round an operating condition. The linearized model of power system as shown in Figure 2 is given in [15].

## 4. PSS and UPFC Damping Controller

The operating function of a PSS is to produce a proper torque on the rotor of the machine involved in such a way that the phase lag between the exciter input and the machine electrical torque is compensated. The supplementary stabilizing signal considered is one proportional to speed. A widely speed based used conventional PSS is considered throughout the study. The transfer function of the PSS is [9, 15]:

$$U_{pss} = K\frac{sT_W}{1+sT_W}\left[\frac{(1+sT_1)}{(1+sT_2)}\right]\Delta\omega(s) \quad (11)$$

Where, Δω is the deviation in speed from the synchronous speed. This type of stabilizer consists of a washout filter, a dynamic compensator. The output signal is fed as a supplementary input signal, $U_{pss}$, to the regulator of the excitation system. The washout filter, which essentially is a high pass filter, is used to reset the steady-state offset in the output of the

PSS. The value of the time constant $T_w$ is usually not critical and it can range from 0.5 to 20 s [20]. In this study, it is fixed to 10 s. The dynamic compensator is made up to a lead-lag stage and an additional gain. The adjustable PSS parameters are the gain of the PSS, *K*, and the time constants, $T_1$, $T_2$. The four control parameters of the UPFC ($m_B$, $m_E$, $\delta_B$ and $\delta_E$) can be modulated in order to produce the damping torque [4]. In this paper $\delta_E$ is modulated in order to coordinated design. The speed deviation $\Delta\omega$ is considered as the input to the damping controllers. The structure of UPFC based damping controller, as shown in Figure 3, is similar to the PSS controllers. The parameters of the damping controllers for the purpose of simultaneous coordinated design are obtained using PSO algorithm. In the proposed method, we must tune the PSS and UPFC POD controller parameters optimally to improve overall system dynamic stability in a robust way under different operating conditions and disturbances. To acquire an optimal combination, this paper employs PSO [16] to improve optimization synthesis and find the global optimum value of fitness function. For our optimization problem, an eigenvalue based multiobjective function reflecting the combination of damping factor and damping ratio is considered as follows [15, 20]:

$$J = J_1 + aJ_2 \tag{12}$$

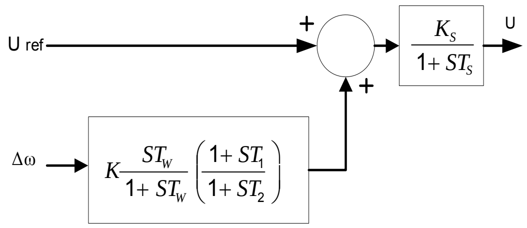



Figure 3. UPFC with Lead-lag Controller

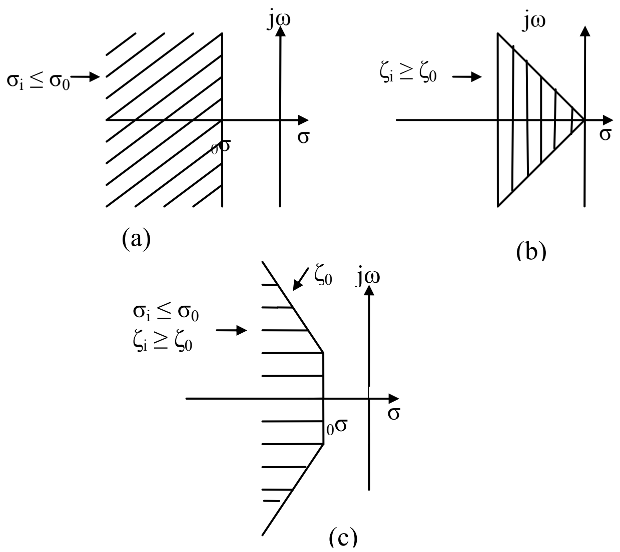



Figure 4. Region of Eigenvalues Location for Objective Function

Where, $J_1 = \sum_{j=1}^{NP} \sum_{\sigma_i \geq \sigma_0} (\sigma_0 - \sigma_i)^2$, $J_2 = \sum_{j=1}^{NP} \sum_{\zeta_i \leq \zeta_0} (\zeta_0 - \zeta_i)^2$, $\sigma_{i,j}$ and $\zeta_{i,j}$ are the real part and the damping ratio of the *i*th eigenvalue of the *j*th operating point. The value of *α* is chosen at 10. *NP* is the total number of operating points for which the optimization is carried out. The value of $\sigma_0$ determines the relative stability in terms of damping factor margin provided for constraining the placement of eigenvalues during the process of optimization. The closed loop eigenvalues are placed in the region to the left of dashed line as shown in Figure 4(a), if only $J_1$ were to be taken as the objective function. Similarly, if only $J_2$ is considered, then it limits the maximum overshoot of the eigenvalues as shown in Figure 4(b). In the case of $J_2$, $\xi_0$ is the desired minimum damping ratio which is to be achieved. When optimized with $J_3$ , the eigenvalues are restricted within a D-shaped area as shown shaded in Figure 4(c). It is necessary to mention here that only the unstable or lightly damped electromechanical modes of oscillations are relocated [15, 20].

It is necessary to mention here that only the unstable or lightly damped electromechanical modes of oscillations are relocated. The design problem can be formulated as the following constrained optimization problem, where the constraints are the controller parameters bounds:
*Minimize J Subject to:*

$$\begin{aligned} & K^{\min} \le K \le K^{\max} \\ & T_1^{\min} \le T_1 \le T_1^{\max} \\ & T_2^{\min} \le T_2 \le T_2^{\max} \end{aligned} \tag{13}$$

The proposed approach employs PSO algorithm to solve this optimization problem and search for an optimal set of coordinated controller parameters. Linearzing the system model at each loading condition of the specified range, the electromechanical mode is identified and its damping ratio and damping factor are calculated. Then, the multiobjective function is evaluated and PSO is applied to search for optimal settings of the optimized parameters of the proposed control schemes. The optimization of UPFC controller parameters is carried out by evaluating the multiobjective cost function as given in Equation (12), which considers a multiple of operating conditions. The operating conditions considered are:

a) Base case: P = 0.80pu, Q = 0.114 pu and $X_L$=0.3 pu. (Nominal loading)
b) Case 1: P = 0.2 pu, Q = 0.01 and $X_L$=0.3 pu. (Light loading)
c) Case 2: P = 1.20 pu, Q = 0.4 and $X_L$=0.3 pu. (Heavy loading)
d) Case 3: The 30% increase of line reactance $X_L$ at nominal loading condition.
e) Case 4: The 30% increase of line reactance $X_L$ at heavy loading condition.

In our implementation, the values of $\sigma_0$ and $\zeta_0$ are taken as −2 and 0.4, respectively. In order to acquire better performance, number of particle, particle size, number of iteration, $c_1$, $c_2$ , and $c$ is chosen as 30, 3, 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 multiobjective function, $J$, are given in Table 1.

Table 1. The Optimal Parameter Setting of the Proposed Method

| Controller parameters | Uncoordinated design | | Coordinated design | |
|---|---|---|---|---|
| | PSS | $\delta_E$ | PSS | $\delta_E$ |
| K | 82.51 | 71.65 | 17.62 | 54.43 |
| $T_1$ | 0.3135 | 0.021 | 0.2540 | 0.3166 |
| $T_2$ | 0.011 | 0.0824 | 0.0788 | 0.3319 |

The electromechanical modes and the damping ratios obtained for all operating conditions both with and without proposed controllers in the system are given in Table 2. When stabilizer is not installed, it can be seen that some of the modes are poorly damped and in some cases, are unstable (highlighted in Table 2). Moreover, it is also clear that the system damping with the proposed PSO based coordinated design of PSS and UPFC damping controllers are significantly improved.

Table 2. Eigenvalues and Damping Ratios of Electromechanical Modes with and without Proposed Controllers

| Controller | Base case | Case1 | Case2 | Case3 | Case4 |
|---|---|---|---|---|---|
| Without controller | **0.166 ± j4.503, -0.04**<br>-3.253, -96.582 | **0.01 ± j5.317, -0.006**<br>-3.256, -96.268 | **0.256 ± j4.49, -0.06**<br>-3.3718, -96.643 | **0.127 ± j4.01, -0.036**<br>-3.357, -96.407 | **0.213 ± j3.87, -0.059**<br>-3.455, -96.48 |
| PSS | -3.687 ± j4.786, 0.609<br>-3.095, -1.404<br>-131.62, -0.1086 | -3.242 ± j4.537, 0.58<br>-3.338, -69.932<br>-119.75, -0.1020 | -30.91 ± j14.14, 0.90<br>-2.966, -1.316<br>-133.37, -0.1094 | -2.932 ± j2.553, 0.754<br>-69.625, -3.992<br>-120.02, -0.1037 | -2.694 ± j1.821, 0.828<br>-5.556, -67.125<br>-121.43, -0.1045 |
| $\delta_E$ | -5.712± j2.983, 0.886<br>-2.106 ± j3.964, 0.469<br>-2.62, -0.1013<br>-96.582 | 3.163 ± j6.429, 0.44<br>-6.064, -3.714<br>-2.586, -0.1019<br>-96.268 | -5.908 ± j3.784, 0.84<br>-2.089 ± j3.73, 0.49<br>-2.623, -0.1012<br>-96.644 | -5.557 ± j5.591, 0.705<br>-2.456 ± j2.218, 0.741<br>-2.883, -0.1029<br>-96.409 | -5.955 ± j5.904, 0.71<br>-2.029 ± j2.225, 0.674<br>-2.898, -0.1029<br>-96.48 |
| PSS and $\delta_E$ | -3.189 ± j3.97, 0.626<br>-3.495 ± j0.272, 0.99<br>-2.6635, -8.10<br>-0.1, -0.1026, -96.948 | -2.58 ± j5.083, 0.452<br>-3.124 ± j0.119, 0.99<br>-11.342, -2.7154<br>-0.1, -0.1019, -96.418 | 3.366 ± j3.436, 0.696<br>-5.782 ± j1.330, 0.974<br>-2.643, -3.265<br>-0.1, -0.1027, -97.051 | -3.217 ± j2.339, 0.808<br>-5.086, -2.831<br>-3.254, -8.179<br>-0.1, -0.1038, -96.688 | -7.302 ± j2.478, 0.946<br>-2.595 ± j1.968, 0.792<br>-3.195, -2.8801<br>-0.1, -0.1041, -6.798 |

## 5. Nonlinear Time Domain Simulation

In order to show the effectiveness of the proposed model of power system with PSS and UPFC damping 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.

### 5.1. 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 damping 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 Figure 5. It is clear from this figure that, the simultaneous design of PSS and UPFC damping controller by the proposed approach significantly improves the stability performance of the example power system and low frequency oscillations are well damped out.

### 5.2. Scenario 2

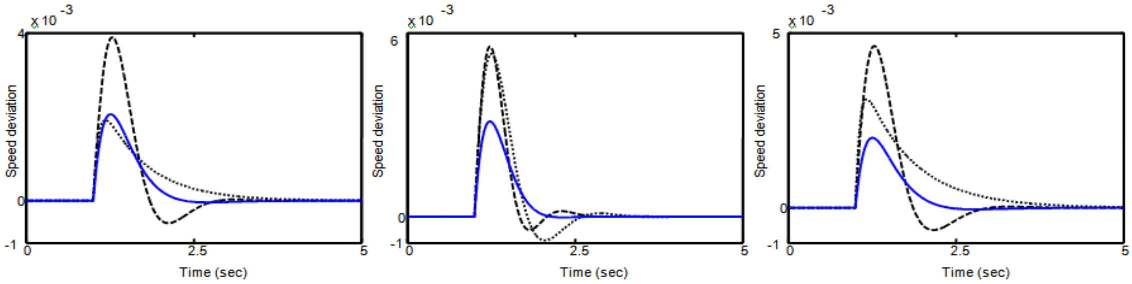
In this scenario, another severe disturbance is considered for different loading conditions; that is, a 6-cycle, three-phase fault is applied at the same above mentioned location in scenario 1. The fault is cleared without line tripping and the original system is restored upon the clearance of the fault.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

### 5.3. Performance Index

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 and Figure of Demerit based on the system performance characteristics are defined as [15]:

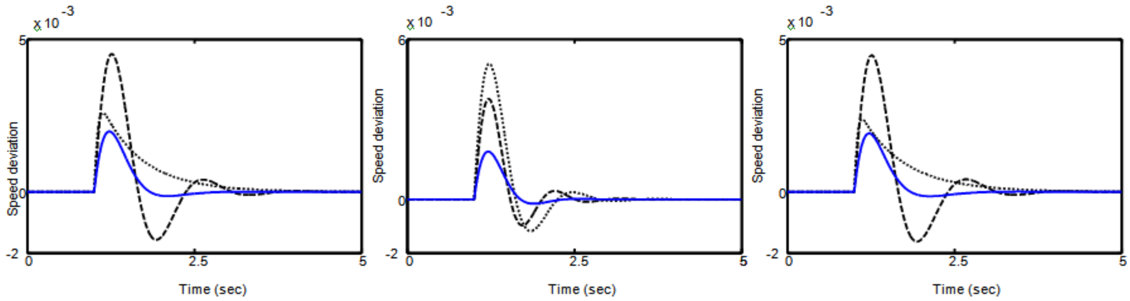
$$ITAE = 10000\int_0^5 t\,|\Delta\omega|\,dt$$
$$FD = (500 \times OS)^2 + (2000 \times US)^2 + TS^2 \qquad (14)$$

Where, speed deviation (Δω), 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 nominal, light and heavy loading conditions are shown in Figure 7 and 8. It is also clear from the Figures that, application both PSS and UPFC damping controller where the controllers are tuned by the proposed simultaneous design approach gives the best response in terms of overshoot, undershoot and settling time.



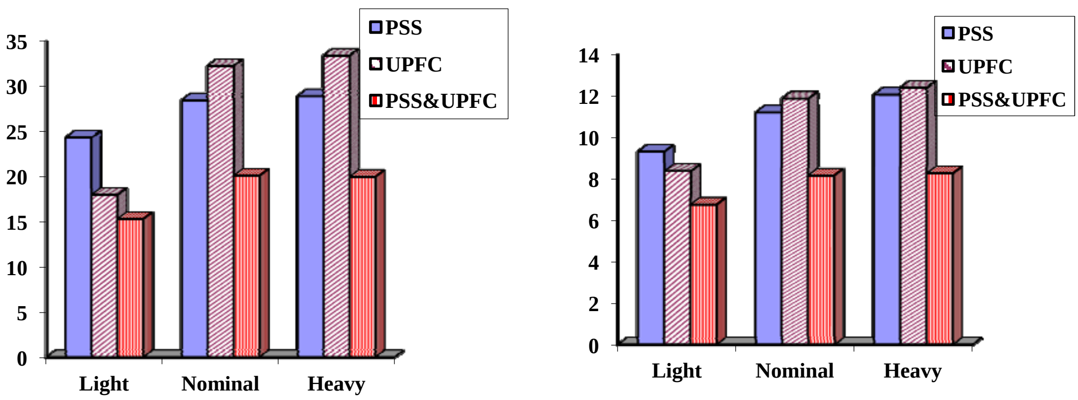

(a) (b) (c)

Figure 5. Dynamic Responses for Δω at (a) nominal (b) light (c) heavy loading conditions; Solid (UPFC & PSS), Dashed (UPFC) and Dotted (PSS)



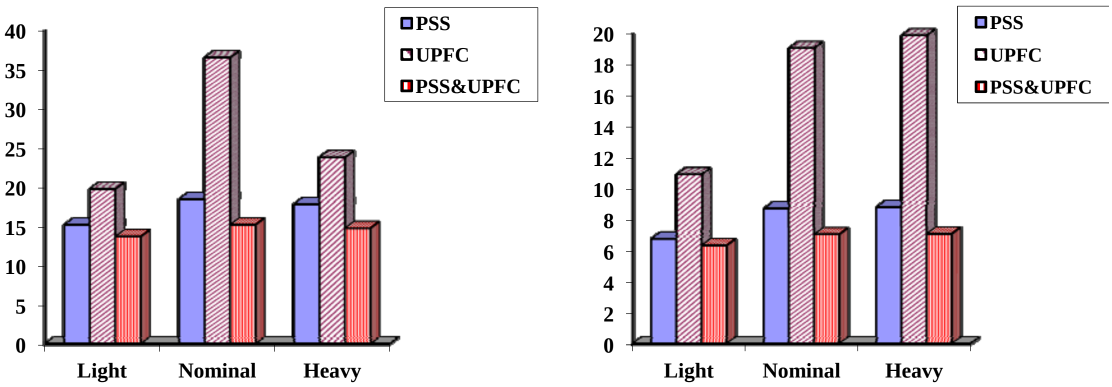

(a) (b) (c)

Figure 6. Dynamic Responses for Δω at (a) nominal (b) light (c) heavy loading conditions; Solid (UPFC & PSS), Dashed (UPFC) and Dotted (PSS)




(a) (b)

Figure 7. Values of Performance Index in Scenario 1 a) ITAE and b) FD




(a) (b)

Figure 8. Values of Performance Index in Scenario 2 a) ITAE and b) FD

## 6. Conclusion

In this paper, the simultaneous coordinated designing of the UPFC power oscillation damping controller and the conventional power system stabilizer in single-machine infinite-bus power system is investigated. For the design problem, a parameter-constrained, eigenvalues-based, multi-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 damping controller. 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 eigenvalues analysis and 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 the simultaneous coordinated designing of the UPFC power oscillation damping controller and the PSS demonstrates its superiority than both the uncoordinated designed stabilizers of the PSS and UPFC damping controller at various fault disturbances and fault clearing sequences.

## APPENDIX:

The nominal parameters of the system are listed in Table 3.

Table 3. 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 | | $X_T = 0.1 pu$ | $X_E = 0.1 pu$ |
| | | $X_B = 0.1 pu$ | |
| OPERATING CONDITION | | $P = 0.8 pu$ | $V_b = 1.0 pu$ |
| DC LINK PARAMETER | | $V_{DC} = 2 pu$ | $C_{DC} = 1 pu$ |
| 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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