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OPTIMIZATION BASED CONTROL COORDINATION OF STATCOM AND PSS OUTPUT FEEDBACK DAMPING CONTROLLER USING PSO TECHNIQUE

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Abstract- An optimal procedure for designing coordinated output feedback damping controllers of power system stabilizer (PSS) and STATCOM is developed for achieving and enhancing dynamic stability in single-machine infinite-bus power system. The coordinated design problem of STATCOM and PSS with output feedback controllers over a wide range of loading conditions is formulated as an optimization problem with the time domain-based objective function which is solved by a particle swarm optimization (PSO) algorithm that 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. The effectiveness of the proposed controllers for damping low frequency oscillations are tested and demonstrated through nonlinear time-domain simulation and some performance indices studies. The coordinated design has been demonstrated to provide extremely good damping characteristics over a range of operating conditions and disturbances.

Keywords: PSO, Output Feedback Damping Controller, Dynamic Stability, STATCOM, PSS.

I. INTRODUCTION

Damping of power system oscillations plays an important role in dynamic stability not only in increasing the transmission capability but also in stabilizing the power system, especially after critical disturbances [1]. In order to damp these power system oscillations and increase system stability, the installation of PSS is both economical and effective. The 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 [2]. Flexible alternating current transmission system (FACTS) devices are among the recent propositions to alleviate such situations by controlling the power flow along transmission lines and improving power oscillation damping. 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 [3, 4].

The STATCOM is based on the principle that a voltage-source converter (VSC) generates a controllable AC voltage source behind a transformer leakage reactance so that the voltage difference across the reactance produces active and reactive power exchange between the STATCOM and the transmission network [5]. It is reported that STATCOM can offer a number of performance advantages for reactive power control applications over the conventional approaches, such as Static VAR Compensators (SVC), because of its greater reactive current output capability at depressed voltage, faster response, better control stability, lower harmonics and smaller size, etc. [6].

Several trials have been reported in the literature to dynamic models of STATCOM in order to design suitable controllers for AC, DC voltage and damping controls. Wang [7] presents the establishment of the linearized Phillips-Heffron model of a power system installed with a STATCOM. The author has not presented a systematic approach for designing the damping controllers. Further, no effort seems to have been made to identify the most suitable STATCOM control parameter, in order to arrive at a robust damping controller.

For the simplicity of practical implementation of the controllers, output feedback damping controller with feedback signals available at the location of the each controlled device is used for control of STATCOM and PSS over a wide range of power system operating conditions [8-10]. 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 [11-13]. Some of these methods are based on the complex nonlinear simulation, while the others are based on the linearized power system model.

PSO technique is used for designing of PSS and STATCOM output feedback controller parameters in order to enhance the damping of power system low frequency oscillations and achieves the desired level of robust performance under different operating conditions and disturbances. 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 [14-18].

In this study, the problem of output feedback damping controllers coordinated design is formulated as an optimization problem and PSO algorithm is used to solve it. A performance index is defined based on the system dynamics after an impulse disturbance alternately occurs in system and used to form the objective function of the design problem. Since only local and available states ($\Delta\omega$, ΔP_e and ΔV_t) are used as the inputs of each controller, the optimal design of controller can be accomplished. The effectiveness of the proposed controller is demonstrated through nonlinear time-domain simulation studies and some performance indices. Results evaluation show that the proposed coordinated design achieves good robust performance for a wide range of operating conditions and is superior to individual uncoordinated design.

II. POWER SYSTEM MODELING

A single machine infinite bus power (SMIB) system installed with a STATCOM in Figure 1, which is widely used for studies of power system oscillations, is adopted in this paper to demonstrate the proposed method. The synchronous generator is delivering power to the infinite-bus through a double circuit transmission line and a STATCOM. The system data is listed in the Appendix.

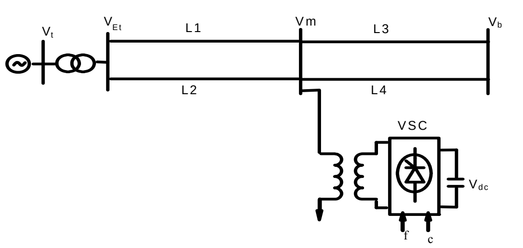


Figure 1. SMIB power system equipped with STATCOM

The dynamic model of the STATCOM is required in order to study the effect of the STATCOM for enhancing the small signal stability of the power system. The VSC of STATCOM generates a controllable AC voltage source $v_0(t) = V_0 \sin(\omega t - \phi)$ behind the leakage reactance. The voltage difference between the STATCOM bus AC voltage, $v_L(t)$ and $v_0(t)$ produces active and reactive power exchange between the STATCOM and the power system, which can be controlled by adjusting the magnitude V_0 and the phase φ. The dynamic relation between the capacitor voltage and current in the STATCOM circuit are expressed as [7]:

$$\bar{I}_{Lo} = I_{Lod} + jI_{Loq} \qquad (1)$$

$$V_0 = cV_{dc}(\cos\phi + j\sin\phi) = cV_{dc}\angle\phi \qquad (2)$$

$$\dot{V}_{dc} = \frac{I_{dc}}{C_{dc}} = \frac{c}{C_{dc}}(I_{Lod}\cos\phi + I_{Loq}\sin\phi) \qquad (3)$$

where for the PWM inverter $c = mk$ and k is the ratio between AC and DC voltage depending on the inverter structure, m and c are the modulation ratio and phase defined by the PWM. The C_{dc} is the dc capacitor value and I_{dc} is the capacitor current while i_{Lod} and i_{Loq} are the d-and q-components of the STATCOM current, respectively.

The dynamics of the generator and the excitation system are expressed through a fourth order model is given as [2, 9]:

$$\dot{\delta} = \omega_0(\omega - 1) \qquad (4)$$

$$\dot{\omega} = (P_m - P_e - D\Delta\omega)/M \qquad (5)$$

$$\dot{E}'_q = (-E_q + E_{fd})/T'_{do} \qquad (6)$$

$$\dot{E}_{fd} = (-E_{fd} + K_a(V_{ref} - V_t))/T_a \qquad (7)$$

The expressions for the d-q axes currents in the transmission line and STATCOM, respectively, are given as follows [5]:

$$I_{tld} = \frac{(1+\frac{X_{LB}}{X_{SDT}})e'_q - \frac{X_{LB}}{X_{SDT}} mV_{dc}\sin\phi - V_b\cos\phi}{X_{tL} + X_{LB} + \frac{X_{tL}}{X_{LB}} + (1+\frac{X_{LB}}{X_{SDT}})x'_d} \qquad (8)$$

$$I_{tlq} = \frac{\frac{X_{LB}}{X_{SDT}} mV_{dc}\cos\phi + V_b\sin\phi}{X_{tL} + X_{LB} + \frac{X_{tL}}{X_{LB}} + (1+\frac{X_{LB}}{X_{SDT}})x_q} \qquad (9)$$

$$I_{Lod} = \frac{e'_q - (x'_d + X_{tL})I_{tLq} - mV_{dc}\sin\phi}{X_{SDT}} \qquad (10)$$

$$I_{Loq} = \frac{mV_{dc}\cos\phi - (x'_d + X_{tL})I_{tLq}}{X_{SDT}} \qquad (11)$$

where

$$X_{tL} = X_T + \frac{X_L}{2}, \; X_{LB} = \frac{X_L}{2}$$

The X_T, x'_d and x_q are the transmission line reactance, d-axis transient reactance, and q-axis reactance, respectively. 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.1 is given as follows [5, 7]:

$$\Delta \dot{\delta} = \omega_0 \Delta\omega \quad (12)$$

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

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

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

$$\Delta \dot{v}_{dc} = K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta v_{dc} + K_{dc}\Delta c + K_{d\phi}\Delta\phi \quad (16)$$

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{pdc}\Delta v_{dc} + K_{pc}\Delta c + K_{p\phi}\Delta\phi \quad (17)$$

$$\Delta E'_q = K_4\Delta\delta + K_3\Delta E'_q + K_{qdc}\Delta v_{dc} + K_{qc}\Delta c + K_{q\phi}\Delta\phi \quad (18)$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E'_q + K_{vdc}\Delta v_{dc} + K_{vc}\Delta c + K_{v\phi}\Delta\phi \quad (19)$$

where the K_1, K_2, ... K_9, K_{pu}, K_{qu} and K_{vu} are linearization constants. The state-space model of power system is given by:

$$\dot{x} = Ax + Bu \quad (20)$$

where, the state vector x, control vector u, A and B are:

$$x = [\Delta\delta \quad \Delta\omega \quad \Delta E'_q \quad \Delta E_{fd} \quad \Delta v_{dc}]^T, \; u = [\Delta c \quad \Delta\phi]^T \quad (21)$$

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & 0 & -\frac{K_{pdc}}{M} \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & -\frac{1}{T'_{do}} & -\frac{K_{qdc}}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vdc}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ -\frac{K_{pc}}{M} & -\frac{K_{p\phi}}{M} \\ -\frac{K_{qc}}{T'_{do}} & -\frac{K_{q\phi}}{T'_{do}} \\ -\frac{K_A K_{vc}}{T_A} & -\frac{K_A K_{v\phi}}{T_A} \\ K_{dc} & K_{d\phi} \end{bmatrix}$$

III. PARTICLE SWARM OPTIMIZATION

The PSO method is a population-based one and is described by its developers as an optimization paradigm, which models the social behavior of birds flocking or fish schooling for food. Therefore, PSO works with a population of potential solutions rather than with a single individual [15]. 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. 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. This optimization technique can be used to solve many of the same kinds of 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-linearing, non-differentiability and high-dimensionality [4, 18].

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. PSO consists of, at each step, changing the velocity of each particle toward its pbest and gbest according to (22). 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 (23) [2, 9, 17-18]:

$$v_{id} = w \times v_{id} + c_1 \times \text{rand}(\,) \times (P_{id} - x_{id}) + c_2 \times \text{rand}(\,) \times (P_{gd} - x_{id}) \quad (22)$$

$$x_{id} = x_{id} + c v_{id} \quad (23)$$

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 [16]. The following weighting function w is used in (22):

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter\_\max} \times iteration \quad (24)$$

where, $iter\_\max$ is the maximum number of iterations and $iteration$ is the current number of iteration. The (24) presents how the inertia weight is updated, considering $w_{\max}$ and $w_{\min}$ are the initial and final weights, respectively. Figure 2 shows the flowchart of the proposed PSO algorithm.

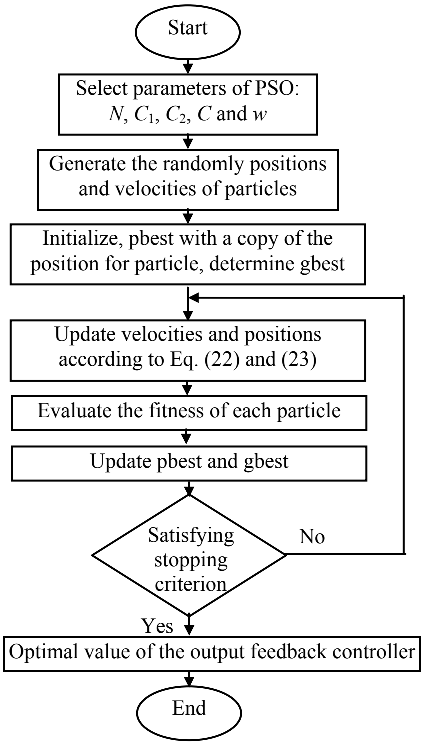


Figure 2. Flowchart of the proposed PSO technique

IV. PSO-BASED OUTPUT FEEDBACK CONTROLLER COORDINATED DESIGN

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

$$\dot{x} = Ax + Bu \tag{25}$$

$$y = Cx \tag{26}$$

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 [9]:

$$u = -Gy \tag{27}$$

Substituting (27) into (26) the resulting state equation is:

$$\dot{x} = A_C x \tag{28}$$

where, A_C is the closed-loop state matrix and is given by:

$$A_C = A - BGC \tag{29}$$

Only the local and available state variables $\Delta\omega$, ΔP_e and ΔV_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 *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 [10].

The two control parameters of the STATCOM (φ and *C*) can be modulated in order to produce the damping torque. In this paper φ is modulated in order to coordinated 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. Since the selection of the output feedback gains for mentioned STATCOM based damping controller is a complex optimization problem. Thus, to acquire an optimal combination, this paper employs PSO [9] to improve optimization synthesis and find the global optimum value of objective function. In this study, an Integral of Time multiplied Absolute value of the Error (ITAE) is taken as the objective function. For our optimization problem, objective function is time domain-based objective function [12]:

$$J = \sum_{i=1}^{Np} \int_0^{t_{sim}} |\Delta\omega_i| .\, tdt \tag{30}$$

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:

$$\begin{aligned} G_1^{\min} &\le G_1 \le G_1^{\max} \\ G_2^{\min} &\le G_2 \le G_2^{\max} \\ G_3^{\min} &\le G_3 \le G_3^{\max} \end{aligned} \tag{31}$$

The proposed approach employs PSO to solve this optimization problem and search for an optimal set of output feedback controller parameters. The optimization of controller parameters is carried out by evaluating the objective function as given in (30), which considers a multiple of operating conditions. The operating conditions are considered as:

- Nominal loading: $P = 0.80$ pu, $Q = 0.2$ pu.
- Lightly loading: $P = 0.2$ pu, $Q = 0.01$ pu.
- Heavy Loading: $P = 1.20$ pu, $Q = 0.4$ pu.

to acquire better performance, number of particle, particle size, number of iteration, C_1 ,and C_2 is chosen as 25, 6, 50, 2 and 2 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 controllers parameters are selected. The final values of the optimized parameters are given in Table 1.

Table 1. Optimal parameters of the coordinated controllers

Controller parameters	Uncoordinated design		Coordinated design	
	PSS	φ	PSS	φ
G_1	55.64	129.78	42.49	106.14
G_2	4.52	1.015	9.87	1.19
G_3	-0.117	2.681	-0.985	1.66

V. SIMULATION RESULTS

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

A. Scenario 1

To assess the performance of the proposed method, a small disturbance of 0.2 pu input torque is applied to the machine at t = 1 sec. The study is performed at three different operating conditions. The results are shown in Figure 3. It is also clear from the figure that the first swing stability is greatly improved with the coordinated design approach.

B. Scenario 2

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 L_1 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 STATCOM 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 Figure 4. It is clear from this figure that, the coordinated design of PSS and STATCOM output feedback damping controller by the proposed approach significantly improves the stability performance of the example power system and electromechanical oscillations are well damped out.

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:

$$ITAE = 1000 \int_0^{t_{sim}} |\Delta\omega| . \, tdt \qquad (32)$$

$$FD = (OS \times 500)^2 + (US \times 2000)^2 + T_s^2$$

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 the performance and robustness for all system loading cases are shown in Figures 5 and 6. It can be seen that the application of both PSS and STATCOM output feedback damping controller where the controllers are tuned by the proposed simultaneous coordinated design approach gives the best response in terms of overshoot, undershoot and settling time.

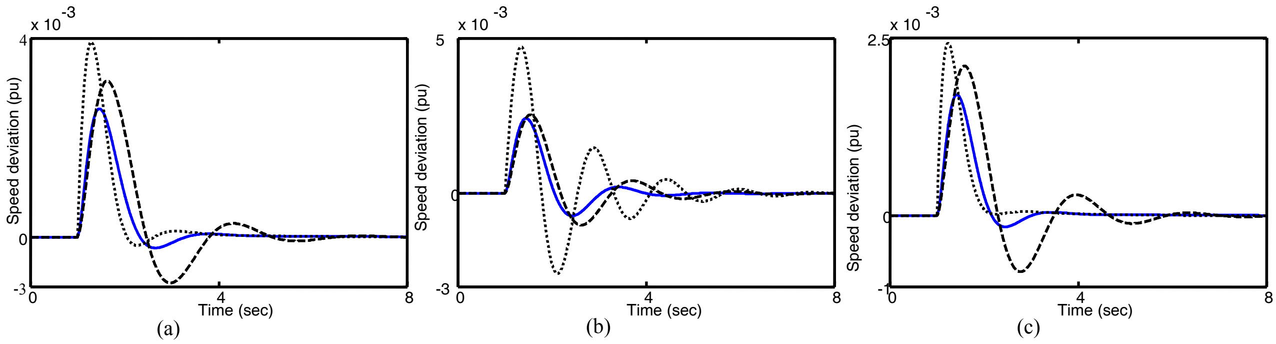


Figure 3. Dynamic responses for $\Delta\omega$ in scenario 1 at (a) nominal (b) light (c) heavy loading conditions; Solid (STATCOM & PSS), Dashed (STATCOM) and Dot (PSS)

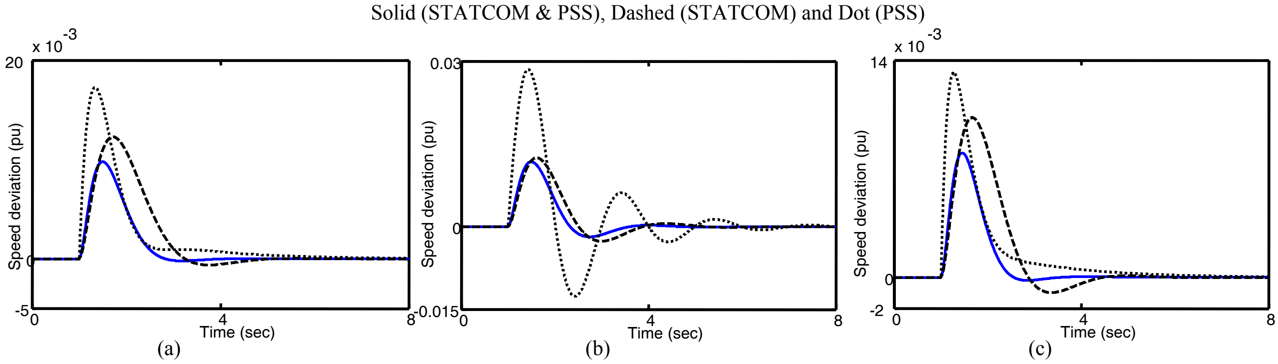
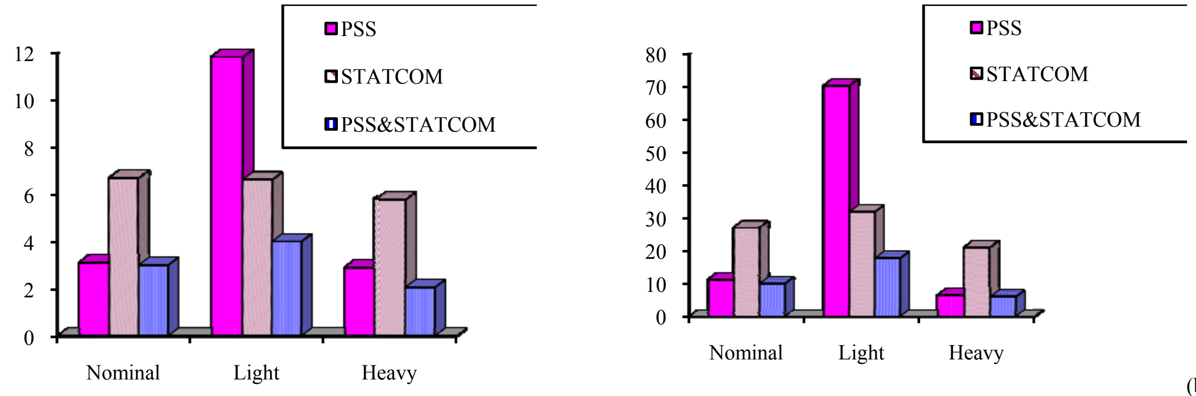
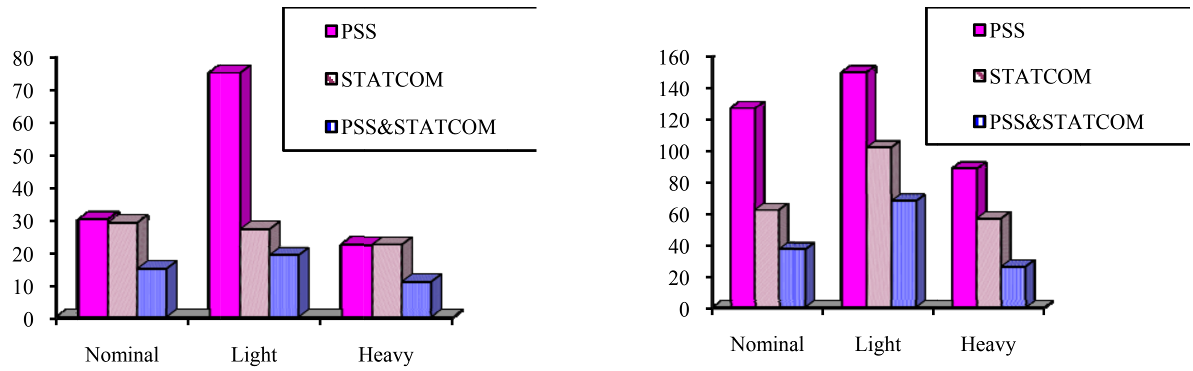


Figure 4. Dynamic responses for $\Delta\omega$ in scenario 2 at (a) nominal (b) light (c) heavy loading conditions; Solid (STATCOM & PSS), Dashed (STATCOM) and Dot (PSS)



(a) (b)

Figure 5. Values of the performance index in scenario 1: a) ITAE and b) FD



(a) (b)

Figure 6. Values of the performance index in scenario 2: a) ITAE and b) FD

VI. CONCLUSIONS

This paper presents the coordinated designing of the STATCOM and the PSS with output feedback damping controllers. The design problem of the selecting output feedback controller parameters is converted into an optimization problem which is solved by a PSO with the time domain-based objective function. Only the local and available state variables $\Delta\omega$, ΔP_e and ΔV_t are taken as the input signals of each controller, so the implementation of the designed controllers become more feasible and practical.

The effectiveness of the proposed controllers for improving dynamic stability performance are validated by an example power system considered too severe disturbance under different operating conditions. The non-linear time domain simulation results show that the oscillations of synchronous machines can be quickly and effectively damped with the proposed method. The system performance characteristics in terms of 'ITAE' and 'FD' indices reveal that the coordinated controllers the overshoot, undershoot, settling time and speed deviation of rotor are greatly reduced at various operating conditions and disturbances.

APPENDIX

System data: The nominal parameters of the system are listed in Table 2.

Table 2. System parameters

Generator	$M = 8$ MJ/MVA	$T'_{do} = 5.044$s	$X_d = 1$pu
	$X_q = 0.6$pu	$X'_d = 0.3$pu	$D = 0$
Excitation System		$K_a = 50$	$T_a = 0.05$s
Transformers		$X_T = 0.1$pu	$X_{SDT} = 0.1$pu
Transmission Line		$X_q = 0.4$pu	
DC link Parameter		$V_{DC} = 1$pu	$C_{DC} = 1$pu
STATCOM Parameter		$C = 0.25$	$\phi = 52^{\circ}$
		$K_s = 1$	$T_s = 0.05$

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