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Robust Coordinated Design of PSS and TCSC using PSO Technique for Power System Stability Enhancement

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Power system stability improvement by coordinated design of a Power System Stabilizer (PSS) and a Thyristor Controlled Series Compensator (TCSC) controller is addressed in this paper. Particle Swarm Optimization (PSO) technique is employed for optimization of the parameter-constrained nonlinear optimization problem implemented in a simulation environment. The proposed controllers are tested on a weakly connected power system. The non-linear simulation results are presented for wide range of loading conditions with various fault disturbances and fault clearing sequences as well as for various small disturbances. The eigenvalue analysis and simulation results show the effectiveness and robustness of proposed controllers to improve the stability performance of power system by efficient damping of low frequency oscillations under various disturbances.

Keywords: Power system stability, PSS, TCSC, coordinated design, particle swarm optimization.

1. INTRODUCTION

Low frequency oscillations are observed when large power systems are interconnected by relatively weak tie lines. These oscillations may sustain and grow to cause system separation if no adequate damping is available [1-3]. Power system stabilizers (PSS) are now routinely used in the industry to damp out power system oscillations. However, during some operating conditions, this device may not produce adequate damping, and other effective alternatives are needed in addition to PSS. Recent development of power electronics introduces the use of Flexible AC Transmission System (FACTS) controllers in power systems. FACTS controllers are capable of controlling the network condition in a very fast manner and this unique feature of FACTS can be exploited to improve the stability of a power system [4]. Thyristor Controlled Series Compensator (TCSC) is one of the important members of FACTS family that is increasingly applied by the utilities in modern power systems with long transmission lines. It can have various roles in the operation and control of power systems, such as scheduling power flow; decreasing unsymmetrical components; reducing net loss; providing voltage support; limiting short-circuit currents; mitigating sub-synchronous resonance (SSR); damping the power oscillation; and enhancing transient stability. The applications of TCSC for power oscillation damping and stability enhancement can be found in several references [5-9]. Most of these proposals are based on small disturbance analysis that required linearization of the system involved. However, linear methods cannot properly capture complex dynamics of the system, especially during major disturbances. This presents difficulties for tuning the FACTS controllers in that the controllers tuned to provide desired performance at small signal condition do not guarantee acceptable performance in the event of major disturbances.

The problem of PSS parameter tuning in the presence of FACTS controllers is a complex exercise as uncoordinated local control of FACTS controllers and PSS may cause

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destabilizing interactions. A number of conventional techniques have been reported in the literature pertaining to design problems of conventional power system stabilizers namely: the eigenvalues assignment, mathematical programming, gradient procedure for optimization and also the modern control theory. Unfortunately, the conventional techniques are time consuming as they are iterative and require heavy computation burden and slow convergence. In addition, the search process is susceptible to be trapped in local minima and the solution obtained may not be optimal. Further, the controllers should provide some degree of robustness to the variations in system parameters, loading conditions, and configurations as the machine parameters change with operating conditions. A set of controller parameters which stabilize the system under a certain operating condition may no longer yield satisfactory results when there is a drastic change in power system operating conditions and configurations [10]. To improve overall system performance, many researches proposed the coordination between PSS and FACTS Power Oscillation Damping (POD) controllers [11-13]. Some of these methods are based on the linearized power system models and others on complex nonlinear simulations, based on the small signals.

Recently, Particle Swarm Optimization (PSO) technique appeared as a promising algorithm for handling the optimization problems. PSO is a population based stochastic optimization technique, inspired by social behavior of bird flocking or fish schooling [14]. PSO shares many similarities with Genetic Algorithm (GA); like initialization of population of random solutions and search for the optimal by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation. One of the most promising advantages of PSO over GA is its algorithmic simplicity as it uses a few parameters and easy to implement. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles [15]. In view of the above, PSO is employed in the present work to simultaneously tune the parameters of the PSS and TCSC controllers.

In this paper, PSO based optimal tuning algorithm is used to coordinate the PSS and TCSC controller simultaneously. By minimizing the objective function in which the influences of both PSS and TCSC controllers are considered, interactions among these controllers are improved. The proposed controllers have been applied and tested on a weakly connected power system under wide range of loading conditions and severe disturbances. In addition, the proposed controllers are also tested under different small disturbances. The eigenvalue analysis and non-linear simulation results are presented to demonstrate the effectiveness and robustness of the proposed controllers to enhance power system stability.

2. MODELLING THE TCSC DYNAMICS

Basically, the TCSC consists of three components: capacitor banks, bypass inductor and bidirectional thyristors. The control of the TCSC is achieved by the firing angle signal α, which changes the fundamental frequency reactance of the compensator. There exists a steady-state relationship between the firing angle α and the reactance $X_{TCSC}(\alpha)$. This relationship can be described in the following equation [16]:

$$\begin{aligned} \mathrm{X}_{\mathrm{TCSC}}(\alpha) = {} & X_C - \frac{X_C^2}{(X_C - X_P)} \frac{\sigma + \sin\sigma}{\pi} \\ & + \frac{4X_C^2}{(X_C - X_P)} \frac{\cos^2(\sigma/2)}{(k^2 - 1)} \frac{(k\tan(k\sigma/2) - \tan(\sigma/2))}{\pi} \end{aligned} \tag{1}$$

Where,

$X_C =$ Nominal reactance of the fixed capacitor C

$X_P =$ Inductive reactance of inductor L connected in parallel with C

$\sigma = 2(\pi - \alpha) =$ Conduction angle of TCSC Controller

$k = \sqrt{\dfrac{X_C}{X_P}}$ = Compensation ratio

Since the relationship between α and the equivalent fundamental frequency reactance offered by TCSC, $X_{TCSC}(\alpha)$, is a unique-valued function, the TCSC is modeled here as a variable capacitive reactance within the operating region defined by the limits imposed by α. Thus $X_{TCSC\min} \le X_{TCSC} \le X_{TCSC\max}$, with $X_{TCSC\max} = X_{TCSC}(\alpha_{\min})$ and $X_{TCSC\min} = X_{TCSC}(180°) = X_C$. In this paper, the TCSC controller is assumed to operate only in the capacitive region, i.e., $\alpha_{\min} > \alpha_r$ where α_r corresponds to the resonant point, as the inductive region associated with $90° < \alpha < \alpha_r$ induces high harmonics that cannot be properly modeled in stability studies.

3. POWER SYSTEM UNDER STUDY

The SMIB power system with TCSC (shown in Figure 1), is considered in this study. The generator has a local load of admittance $Y = G + jB$ and a double circuit transmission line of total impedance $Z = R + jX$. In the figure V_T and V_B are the generator terminal and infinite bus voltage respectively and X_T is the reactance of the transformer.

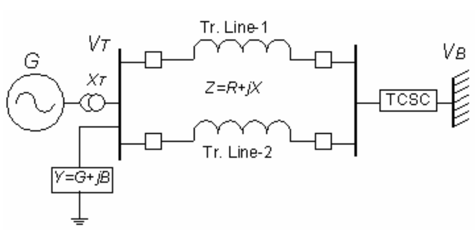


Figure 1. Single-line diagram of the study system.

The generator is represented by the third-order model comprising of the electromechanical swing equation and the generator internal voltage equation. The state equations may be written as [17]:

$$\dot{\omega} = \frac{1}{M}[P_M - P_e - D(\omega - 1)] \tag{2}$$

$$\dot{\delta} = \omega_b(\omega - 1) \tag{3}$$

where, P_M and P_e are the input and output powers of the generator respectively; M and D are the inertia constant and damping coefficient respectively; ω_b is the synchronous speed, δ and ω are the rotor angle and speed respectively.

The generator power P_e, the internal voltage E'_q and the terminal voltage V_T can be expressed as:

$$P_e = E'_q i_q + (X_q - X'_d) i_d i_q \tag{4}$$

$$\dot{E}'_q = \frac{1}{T'_{do}} [E_{fd} - E'_q - (X_d - X'_d) i_d] \tag{5}$$

$$V_T = \sqrt{[(X_q i_q)^2 + (E'_q - X'_d i_d)^2]} \tag{6}$$

In the above equation, E_{fd} is the field voltage; T'_{do} is the open circuit field time constant; X_d and X'_d are the *d*-axis reactance and the *d*-axis transient reactance of the generator respectively.

A simplified IEEE Type-ST1 excitation system is considered in this work. It can be described as:

$$\dot{E}_{fd} = \frac{K_A (V_{ref} - V_T + V_S) - E_{fd}}{T_A} \tag{7}$$

where, K_A and T_A are the gain and time constant of the excitation system; V_{ref} is the reference voltage and V_S is the output stabilizing signal of PSS.

4. OVERVIEW OF PARTICLE SWARM OPTIMIZATION TECHNIQUE

The PSO method is a member of wide category of swarm intelligence methods for solving the optimization problems. It is a population based search algorithm where each individual is referred to as particle and represents a candidate solution. Each particle in PSO flies through the search space with an adaptable velocity that is dynamically modified according to its own flying experience and also the flying experience of the other particles. In PSO each particles strive to improve themselves by imitating traits from their successful peers. Further, each particle has a memory and hence it is capable of remembering the best position in the search space ever visited by it. The position corresponding to the best fitness is known as *pbest* and the overall best out of all the particles in the population is called *gbest* [14-18].

The modified velocity and position of each particle can be calculated using the current velocity and the distance from the $pbest_{j,g}$ to $gbest_g$ as shown in the following formulas [19]:

$$v_{j,g}^{(t+1)} = w.v_{j,g}^{(t)} + c_1.r_1(.).(pbest_{j,g} - x_{j,g}^{(t)}) + c_2.r_2().(gbest_g - x_{j,g}^{(t)}) \tag{8}$$

$$x_{j,g}^{(t+1)} = x_{j,g}^{(t)} + v_{j,g}^{(t+1)} \tag{9}$$

With $j = 1,2,....,n$ and $g = 1,2,....,m$

Where,

n = number of particles in a group;

m = number of members in a particle;

t = number of iterations (generations);

$v_{j,g}^{(t)}$ = velocity of particle j at iteration *t*, $\boldsymbol{V}_g^{\min} \le v_{j,g}^{(t)} \le \boldsymbol{V}_g^{\max}$;

w = inertia weight factor;

c_1, c_2 = cognitive and social acceleration factors respectively;

r_1, r_2 = random numbers uniformly distributed in the range (0, 1);

$x_{j,g}^{(t)}$ = current position of particle j at iteration *t*;

$pbest_j$ = pbest of particle *j*;

$gbest$ = gbest of the group.

The *j*-th particle in the swarm is represented by a *g*-dimensional vector $x_j = (x_{j,1},\ x_{j,2}, ..., x_{j,g})$ and its rate of position change (velocity) is denoted by another g-dimensional vector $v_j = (v_{j,1}, v_{j,2}, ..., v_{j,g})$. The best previous position of the *j*-th particle is represented as $pbest_j = (pbest_{j,1}, pbest_{j,2}, ..., pbest_{j,g})$. The index of best particle among all of the particles in the group is represented by the $gbest_g$. In PSO, each particle moves in the search space with a velocity according to its own previous best solution and its group's previous best solution. The velocity update in a PSO consists of three parts; namely momentum, cognitive and social parts. The balance among these parts determines the performance of a PSO algorithm. The parameters c_1 & c_2 determine the relative pull of $pbest$, $gbest$ and the parameters r_1 & r_2 help in stochastically varying these pulls. In the above equations, superscripts denote the iteration number. Figure 2 shows the position update of a particle for a two-dimensional parameter space.

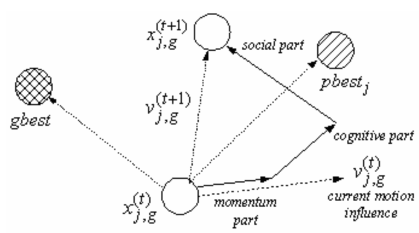


Figure 2. Position update of particles in particle swarm optimization technique.

5. PROBLEM FORMULATION

5.1 PSS and TCSC controller structure

The commonly used lead–lag structure is chosen in this study as PSS and TCSC controller. The structures of the PSS and TCSC controller are shown in Figures 3 & 4 respectively. Each structure consists of: a gain block (with gains K_P and K_T for PSS and TCSC respectively); a signal washout block and two-stage phase compensation block. The phase compensation block provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. The signal washout block serves as a high-pass filter which allows signals associated with oscillations in input signal to pass unchanged. Without it steady changes in input would modify the output. From the viewpoint of the washout function the value of washout time constant is not critical and may be in the range 1 to 20 seconds [1].

In these structures, T_W is the washout time constant of PSS and TCSC controller. A wash time constant of 10 sec. is used in the present study. Also two similar phase compensator blocks are considered so that $T_{1P} = T_{3S}, T_{2P} = T_{4P}, T_{1T} = T_{3T}$ and $T_{2T} = T_{4T}$. The gains K_p, K_T and the time constants T_{1P}, T_{2P}, T_{1T} and T_{2T} are remained to be determined.

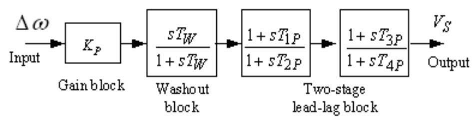


Figure 3. Block diagram of power system stabilizer.

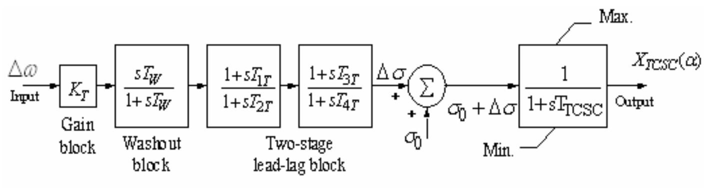


Figure 4. Block diagram of TCSC controller

In case of PSS, the input signal is the speed deviation ($\Delta\omega$), and the output signal is the stabilizing signal V_S, which is added to the excitation system reference voltage V_{ref}. The input signal of the proposed TCSC controller is the speed deviation $\Delta\omega$, and the output is TCSC reactance, $X_{TCSC}(\alpha)$. The desired value of line reactance is obtained according to the change in the conduction angle $\Delta\sigma$. In the Figure 4, σ_0 indicates the initial conduction angle as desired by the power flow control loop. The power low control loop acts quit slowly in practice and hence σ_0 is assumed to remain constant during large-disturbance transient period. The value of α is changed according to the change in conduction angle $\Delta\sigma$, as $\alpha = \pi - \sigma/2$ and $\sigma = \sigma_0 + \Delta\sigma$. This signal is put through a first order lag representing the natural response of the controller and the delay introduced by the internal control, which yields the reactance offered by the TCSC, $X_{TCSC}(\alpha)$. The effective transfer reactance (X_{Eff}) between the generator and the infinite bus is the difference between the total reactance ($X + X_T$), and the capacitive reactance $X_{TCSC}(\alpha)$. So X_{Eff} is given by:

$$X_{Eff} = X + X_T - X_{TCSC}(\alpha) \tag{10}$$

As the network parameters change due to the fault and its subsequent clearing, the updated values of X_{Eff} is used in the simulation.

5.2 Optimization problem

It is worth mentioning that the PSS and TCSC controller are designed to minimize the power angle deviation after a large disturbance so as to improve the power system stability.

Therefore the objective can be formulated as the minimization of a non-linear programming problem expressed as follows:

$$J = \sum \int_0^{t_1} t[|\,\Delta\omega(t,x)\,|]dt \tag{11}$$

Where, $\Delta\omega(t,x)$ denotes the speed deviation for a set of controller parameters *x* (note that here *x* represents K_T, T_{1T}, T_{2T}, K_P, T_{1P}, T_{2P}: the parameters of both PSS and TCSC controller), and t_1 is the time range of the simulation. With the variation of the parameters *x*, the $\Delta\omega(t,x)$ will also be changed. In case of multi-machine power system, sum of the speed deviations of local and inter-area modes of oscillations can be used as the input variable to the objective function in place of $\Delta\omega(t,x)$. For objective function calculation, the time-domain simulation of the nonlinear 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.

In this study, it is aimed to minimize the proposed objective function *J*. The problem constraints are the PSS and TCSC controller parameter bounds. Therefore, the design problem can be formulated as the following optimization problem:

Minimize J (12)

Subject to

$$K_T^{\min} \le K_T \le K_T^{\max}$$

$$T_{1T}^{\min} \le T_{1T} \le T_{1T}^{\max}$$

$$T_{2T}^{\min} \le T_{2T} \le T_{2T}^{\max}$$

$$K_P^{\min} \le K_P \le K_P^{\max}$$

$$T_{1P}^{\min} \le T_{1P} \le T_{1P}^{\max}$$

$$T_{2P}^{\min} \le T_{2P} \le T_{2P}^{\max} \quad (13)$$

The proposed approach employs particle swarm optimization technique to solve this optimization problem and search for the optimal set of PSS and TCSC controller parameters.

6. RESULTS AND DISCUSSION

6.1 Application of particle swarm optimization technique

Tuning a controller parameter can be viewed as an optimization problem in multi-modal space as many settings of the controller could be yielding good performance. Traditional method of tuning doesn't guarantee optimal parameters and in most cases the tuned parameters needs improvement through trial and error. In PSO based method, the tuning process is associated with an optimality concept through the defined objective function and the time domain simulation. Hence the PSO methods yield optimal parameters and the method is free from the curse of local optimality. The designer has the freedom to explicitly specify the required performance objectives in terms of time domain bounds on the closed loop responses. In view of the above, the proposed approach employs PSO to solve this optimization problem and search for optimal set of the PSS and TCSC Controller parameters.

In order to tune the parameters of the PSS and TCSC controller, the non-linear model of the example power system shown in Figure 1, is developed. The relevant parameters of the power system are given in appendix.

For the purpose of optimization of equation (12), routines from PSO toolbox [20] are used. The objective function is evaluated for each individual by simulating the example power system under a severe disturbance. The most severe situation where a three phase short-circuit fault occurs at the generator busbar terminal is considered in the present study for objective function calculation. The computational flow chart of PSO algorithm is shown in Figure 5. While applying PSO, a number of parameters are required to be specified. An appropriate choice of the parameters affects the speed of convergence of the algorithm. Table I shows the specified parameters for the PSO algorithm. One more important point that affects the optimal solution more or less is the range for unknowns. For the very first execution of the program, wider solution space can be given and after getting the solution one can shorten the solution space nearer to the values obtained in the previous iterations. Optimization is terminated by the prespecified number of generations. The convergence rate of objective function *J* for *gbest* with the number of generations is shown in Figure 6. Table II shows the bounds for unknown parameters of gain and time constants used in the present study and the optimal values of PSS and TCSC controller parameters obtained by the PSO algorithm. The PSO optimization is performed on a Pentium 4, 3 GHz, 504 MB RAM computer, in the MATLAB 7.0.1 environment with the time range of simulation set to 30 s. Realization of PSO optimization process consumed 3207.906 sec. of CPU time.

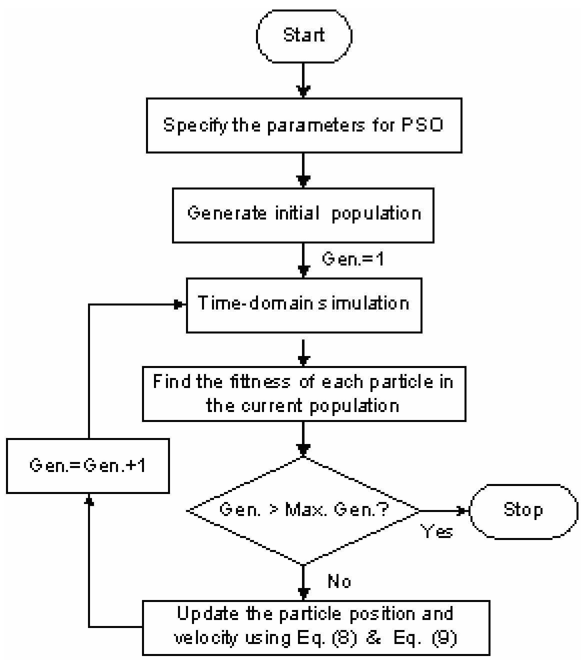


Figure 5. Flowchart of the particle swarm optimization algorithm.

Table I: Parameters used for PSO algorithm

Parameters	Value
Swarm size	20
Max. Generations	100
c1, c2	2.0, 2.0
w_{start}, w_{end}	0.9, 0.4

Table II: Bounds of unknown variables and optimized parameters obtained by PSO

Parameters	K_T	T_{1T}=T_{3T}	T_{2T}=T_{4T}	K_P	T_{1P}=T_{3P}	T_{2P}=T_{4P}
Minimum range	5	0.1	0.1	5	0.1	0.1
Maximum range	70	1	1	70	1	1
Optimized parameters obtained by PSO	35.2107	0.80904	0.75106	39.263	0.59997	0.65135

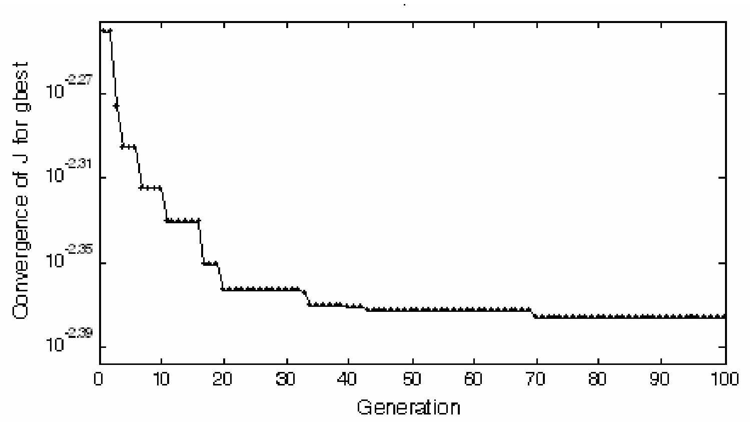


Figure 6. Convergence of objective function for *gbest*.

6.2 Simulation results

To assess the effectiveness and robustness of the proposed stabilizers, three different loading conditions given in Table III are considered. The system electromechanical mode eigenvalues without and with the proposed controllers is shown in Table IV.

Table III: Loading conditions considered

Loading Conditions	*P* (pu)	*Q* (pu)	δ_0 (deg.)
Nominal Loading	0.9	0.1513	51.7963
Light Loading	0.5	0.0457	31.5689
Heavy Loading	1.1	0.2294	60.1850

Table IV: The system electromechanical eigenvalues without and with control.

Type of control/ loading conditions	No Control	With PSO Optimized PSS & TCSC Controller
Nominal loading	-0.0795 ± 7.6831i	-1.3858± 0.0883i
Light loading	-0.2618± 6.8644i	-1.3913± 0.0330i
Heavy loading	0.0963 ± 8.0749i	-1.3909 ± 0.1199i

It is clear from the table that, the open loop system is unstable at heavy loading because of negative damping of electromechanical mode (s = 0.0963). It is also clear that, at nominal and light loading conditions, although the system is stable it is highly oscillatory. The proposed controllers shift substantially the electromechanical mode eigenvalue to the left of the line (s = -1.3858, -1.3913, -1.3909 for nominal, light and heavy loading condition respectively) in the *s*-plane. This enhances greatly the system stability and improves the damping characteristics of electromechanical mode.

6.2.1 Nominal loading

For the case of nominal loading, the behavior of the proposed controllers under transient conditions is verified by applying a 10-cycle three-phase fault at the generator terminal busbar at $t = 1$ sec. The fault is cleared by tripping of one of the parallel transmission lines. The system response under this severe disturbance is shown in Figure 7. In the Figure 7 and in the subsequent Figures, the response without control (no control), response with PSS only and response with coordinated application of both PSS & TCSC controller are shown with dotted line, dashed line and thick solid line respectively. It is clear from the Figure 7 (a) that, the system is unstable without control under this severe disturbance. It should be noted here that, the proposed controllers are designed to improve the stability during disturbance period. The reactance of the transmission line (x) increases in the post fault steady state period because the fault is cleared by permanent tripping of one parallel transmission line. With mechanical input power remaining constant, the power angle (δ) increases from 51.79^0 to 87.25^0 in the post fault period to transmit the same power P (where, $P \propto \sin\delta / x$). Further it can also be noticed from Figure 7 (a) that, the first swing in the rotor angle is significantly suppressed by coordinated application of PSS & TCSC controller. So, the coordinated application of proposed controllers will also help in increasing the critical fault clearing time. It can be concluded that coordination enhances greatly the system transient stability by increases the critical clearing time. From the system responses given in Figure 7 (b)- (e), it can be seen that the response with coordinated application of PSS & TCSC controller provides good damping characteristics to low frequency oscillations and stabilizes the system much faster compared to the case where only PSS is acting. Hence, coordinated design of PSS & TCSC controller extends the power system stability limit and the power transfer capability.

Another severe disturbance is considered at this loading condition; that is, a 10-cycle fault is applied as above. However, the faulty line is restored after 50 ms. The system response to this disturbance is shown in Figure 8. It can be seen that coordinated application of PSS & TCSC controller suppress substantially the first swing in rotor angle, provides good damping characteristics to electromechanical modes of oscillations and improves greatly the system voltage profile.

6.2.2 Light loading

A 10-cycle three-phase fault is applied at the generator terminal busbar at $t = 1$ s. The fault is cleared by tripping one of the parallel lines and the faulty line is restored after 4 s. The system response under this disturbance is shown in Figure 9. It can be seen that coordinated application of PSS & TCSC controller suppress substantially the first swing in rotor angle, provides good damping characteristics to electromechanical modes of oscillations.

6.2.3 Heavy loading

A 5-cycle three-phase fault is applied at the generator terminal busbar at $t = 1$ s. The fault is cleared by tripping one of the parallel lines and the faulty line is restored after 50 ms. Figure 10 shows the system response to this disturbance. The Figures shows the effectiveness and robustness of proposed controllers to loading conditions. It is clear from the figure that, for the above contingency the system is unstable without controllers at heavy loading conditions. Stability of the system is maintained and power system oscillations are effectively damped out with the proposed controllers.

6.2.4 Small disturbances

For completeness and verification, the proposed controllers are also tested under different small disturbances. Nominal loading condition is used to study the performance of proposed controllers under small disturbances. Figure 11 shows the system response for a 10 % step increase in mechanical power input at t =1 sec. It is clear from the Figure 11, that simultaneous coordinated tuning of PSS and TCSC controller is also effective in damping low frequency oscillations resulting from small disturbances.

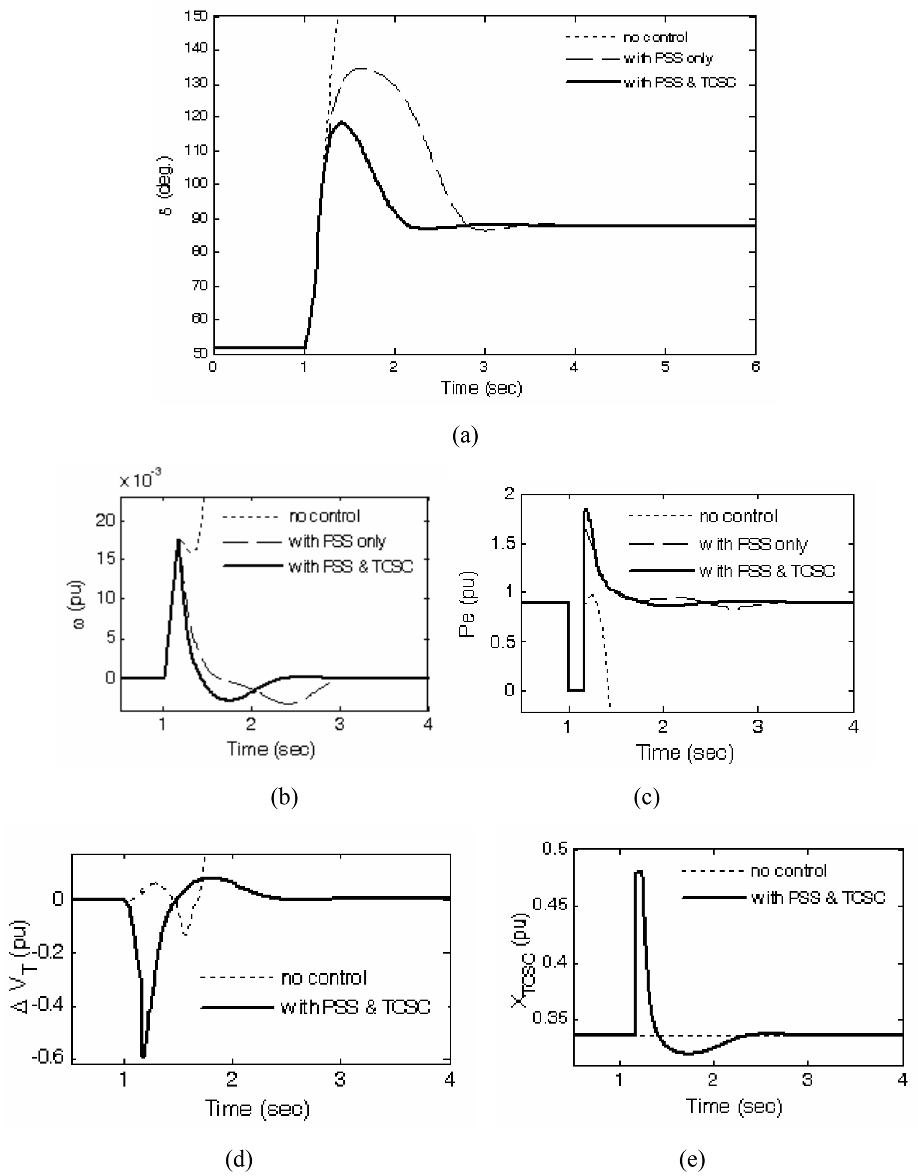


Figure 7. System response for a three-phase fault and subsequent line tripping disturbance at nominal loading condition. (a) power angle δ (b) relative speed ω (c) electrical power Pe (d) terminal voltage deviation ΔV_T (e) reactance offered by TCSC X_{TCSC}

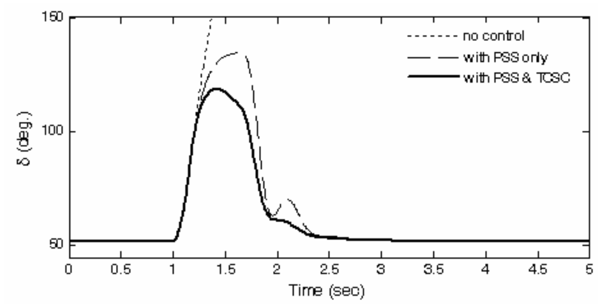


Figure 8. System power angle response for a 10-cycle fault and 50 ms line tripping disturbance at nominal loading condition.

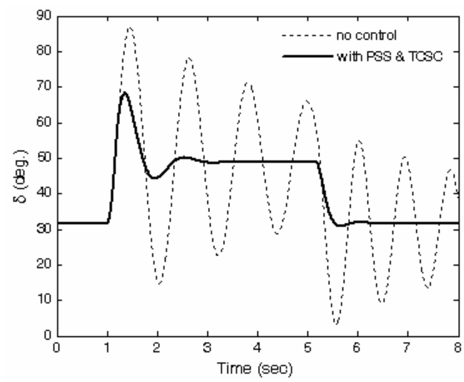
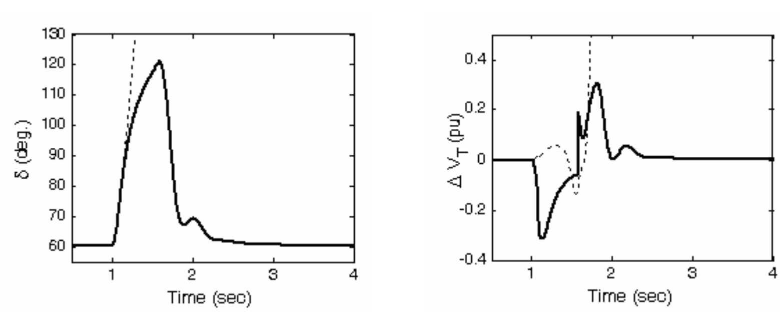


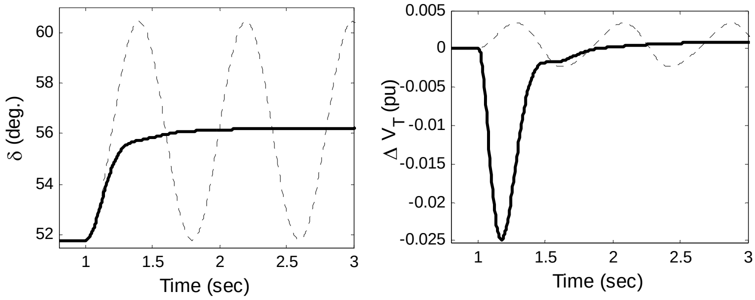
Figure 9. System power angle response for a 10-cycle fault and 4 s line tripping disturbance at light loading condition.



(a) (b)

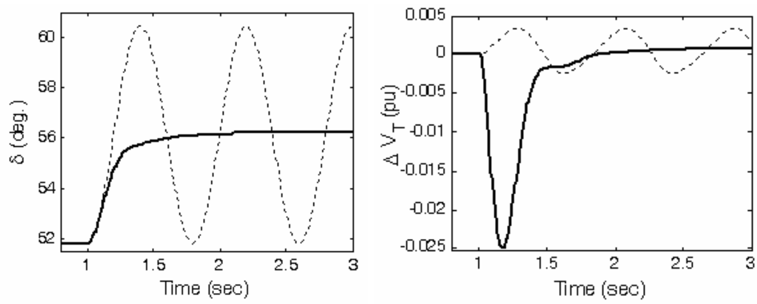
Figure 10. System response for a 5 cycle fault and 50 ms line tripping disturbance at heavy loading condition. (a) power angle δ (b) terminal voltage deviation ΔV_T

The performance of the proposed controller is also tested under a disturbance in reference voltage setting. The reference voltage is increased by a step of 5 % at t =1 s and the system response is shown in Figure 12. The Figs shows the effectiveness of coordinated design of PSS & TCSC controller in damping low frequency oscillations. It is clear from the Figures that the PSO optimized coordinated PSS & TCSC controller is robust and ensures stability for wide variations in loading conditions and disturbances.



(a) (b)

Figure 11. System response for a 10 % step increase in mechanical power input at $t = 1$ s at nominal loading condition. (a) power angle δ (b) terminal voltage deviation ΔV_T



(a) (b)

Figure 12. System response for a 5 % step increase in reference voltage setting $t = 1$ s at nominal loading condition. (a) power angle δ (b) terminal voltage deviation ΔV_T

7. CONCLUSIONS

In this paper, power system stability enhancement by coordinated design of PSS & TCSC controller is presented. The minimization of the rotor speed deviation following a severe disturbance is formulated as an optimization problem and particle swarm optimization technique is employed to optimally tune the parameters of the proposed controllers. The proposed controllers are applied and tested on a weakly connected power system under different loading conditions, and fault clearing sequences. The performance of the proposed controllers is also tested under different small disturbances. The eigenvalue analysis and non-linear simulation results show the effectiveness and robustness of the proposed controllers to enhance the power system stability.

The proposed coordinated design approach is simple, robust and takes little computational time. Validation of the present approach to multi machine power system is currently being carried out by the authors and further investigations are required before reporting the same.

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APPENDIX

System data: All data are in pu unless specified otherwise.

Generator: V_T=1.0; H = 4.0 s.; T'_{do} = 5.044; D = 4.4; X_d =1.0; X_q=0.8; X'_d = 0.3; $R_a = 0$;

Exciter :(Simplified IEEE Type ST1): $K_A = 200$; $T_A = 0.01$ s.

Transmission line, Transformer and Load:
$R + jX = 0 + j0.6$; $X_T = 0.1$; $G + jB = 0 + j0$.

Power System Stabilizer (PSS): $T_{1P} = T_{3P}$; $T_{2P} = T_{4P}$; $T_W = 10\text{s}$.

TCSC Controller: $\alpha_0 = 158^0$; $X_{TCSC0} = 0.\ 3367$; $k = 2$; $K_C = 0.5X$; $T_{1T} = T_{3T}$;
$T_{2T} = T_{4T}$.; $K_P = 0.25X_C$; T_{TCSC} =15 ms; $X_{TCSCMax.} = 0.8X$; $X_{TCSCMin.} = 0$;