Multi Objective Fitness Function Based State Feedback Controllers for PSS and TCSC to Cope with the Low Frequency Oscillations

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Abstract: *TCSC is one of the FACTS devices which can control the line impedance, improve network stability and damp the low frequency oscillations (LFOs). Power System Stabilizer (PSS) like TCSC has an effective role to damp the low frequency oscillations. This paper focuses on the designing of state feedback controller for PSS and TCSC based on particle swarm optimization (PSO) algorithm while a multi objective fitness function is used. The controllers' performance are evaluated on a Single Machine Infinite Bus (SMIB) system. The coefficients of state feedback for TCSC and PSS are optimized by PSO algorithm in order to damp the oscillations. The system with proposed controllers is simulated for two scenarios; firstly, the input power of generator is changed abruptly, and the dynamic response of generator is shown. Next, moreover applying the previous disturbance, one of the transmission lines has been tripped, too. The effectiveness of the proposed controllers has been explained through some performance indices studies. Simulation results show that considered controllers have outstanding performances for improving the stability of power system. In addition, the operation of proposed controllers for wide ranges of operating condition investigated. Results show that TCSC based controller is superior than PSS based controller.*

Keywords: *FACTS, TCSC, PSS, State feedback Controller, PSO*

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1.Introduction

Power systems experience low frequency oscillations during and after a large or small disturbance has happened to a system, especially for middle to heavy loading conditions [1]. These oscillations may sustain and grow to cause system separation if no adequate damping is available [2]. Power System Stabilizers (PSS) have been extensively used as supplementary excitation controllers to damp out the low frequency oscillations and to enhance the overall system stability [3]. Therefore, the generators are equipped with PSS [4]. To improve the performance of conventional PSSs, numerous techniques have been proposed for their design, such as using intelligent optimization methods [5-7], Fuzzy Logic Controller [8, 9], neural networks and many other nonlinear control techniques [10]. Although PSSs provide supplementary feedback stabilizing signals, they suffer a drawback of being liable to cause great variations in the voltage profile and they may even result in leading Power Factor (PF) operation under severe disturbances [11]. The power electronics development has allowed the application of new devices to improve power system performance. The Flexible AC Transmission Systems (FACTS), for example, are examples of such devices that may be used to damp oscillations in power systems [12]. Thyristor controlled series compensator (TCSC) is one of the important members of FACTS family that is increasingly applied with long transmission lines by the utilities in modern power systems [13]. This controller consists of a series capacitor paralleled by a thyristor-controlled reactor in order to provide smooth variable series compensation [14].

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 subsynchronous resonance (SSR); damping the power oscillation; and enhancing transient stability [13]. Because of the extremely fast control action associated with FACTS-devices 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-devices primary control can considerably improve system damping and can also improve system voltage profile, which is advantageous over PSSs [15]. The effect of TCSC and PSS on power system stability with different controllers is demonstrated in several trials, for instance: in [16, 17] a comprehensive assessment of the effects of PSS-based damping controller has been carried out. In [18], a fuzzy logic controller has been designed for TCSC. The Linear Parameter Varying (LPV) controller design technique is applied in the design of a supplementary damping controller (SDC) for a TCSC in [19]. The coordination design for TCSC and PSS has been done in [20]. In this paper the designing of state feedback controller for PSS and TCSC in order to damp the Low Frequency Oscillations has been carried out. Selection of the best gains for PSS and TCSC state feedback controllers is converted to optimization problem, and then Particle Swarm Optimization (PSO) algorithm with consideration of multi objective fitness function has been used.

For evaluation the proposed controllers, various disturbances applied to the system and the dynamic response of the generator has been shown. Simulation results depict that the TCSC based controller is superior to PSS based controller. The remainder of the paper is organized as follows: The PSO algorithm has been presented in Section 2. Section 3 describes the linear and nonlinear model of the case study system. The State feedback controller and PSO based State feedback controller are described in section 4 and 5 respectively. The simulation results for system under study are presented and discussed in Section 6. The paper ended with conclusions in Section 7.

2.PSO Algorithm

PSO is a population based stochastic optimization technique developed by Kennedy and Eberhart [21]. The PSO algorithm is inspired by social behavior of bird flocking or fish schooling.

The standard PSO algorithm employs a population of particles. The particles fly through the n-dimensional domain space of the function to be optimized (in this paper, minimization is assumed). The state of each particle is represented by its position $x_i = (x_{i1}, x_{i2},..., x_{in})$ and velocity $v_i = (v_{i1}, v_{i2},..., v_{in})$, the states of the particles are updated. The flow chart of the procedure is shown in Fig. 1.

During every iteration, each particle is updated by following two "best" values. The first one is the position vector of the best fitness. This particle has achieved so far. The fitness value $p_i = (p_{i1}, p_{i2},\dots p_{in})$ is also stored. This position is called *pbest*. Another "best" position that is tracked by the particle swarm optimizer is the best position, obtained so far, by any particle in the population. This best position is the current global best $p_g = (p_{g1}, p_{g2}, ..., p_{gn})$ and is called g_{best}. At each time step, after finding the two best values, the particle updates its velocity and position according to (1) and (2), respectively.

$$\begin{aligned} v_i(k+1) = wv_i(k) + r_1 c_1\left[p_i - x_i(k)\right] \\ + r_2 c_2\left[p_{gi} - x_i(k)\right] \end{aligned} \quad (1)$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (2)$$

where, $v_i(k+1)$ is the velocity of particle number (i) at the ($k+1$)th iteration, x_{ik} is the current particle (solution or position). r_1 and r_2 are random numbers between *0* and *1*. c_1 is the self confidence (cognitive) factor; c_2 is the swarm confidence (social) factor. Usually c_1 and c_2 are in the range from *1.5* to *2.5*; ω is the inertia factor that takes values downward from *1* to *0* according to the iteration number. When a predetermined termination condition is reached, p_g is returned as the optimal value found [21].

3.Description of Case Study

A synchronous machine with an IEEE type-ST1 excitation System connected to an infinite bus through a double circuit transmission Line has been selected to demonstrate the derivation of simplified linear models of power system for dynamic stability analysis. The single-machine infinite-bus power system is shown in Fig. 2, while The TCSC is installed in transmission line [22]. Corresponding to Fig. 2, PSO based state feedback controller is explained in section 4, 5.

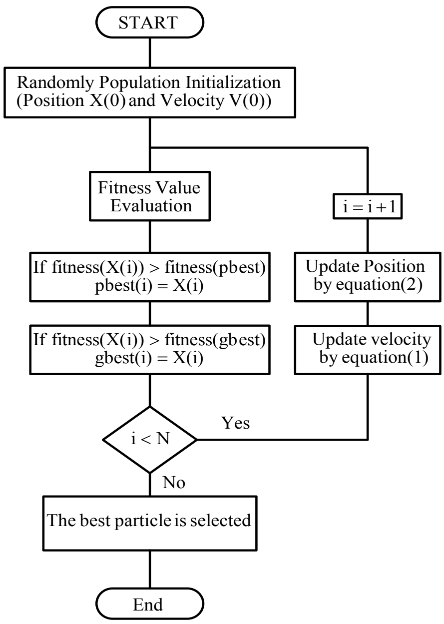

Fig. 1. Flowchart of the PSO algorithm

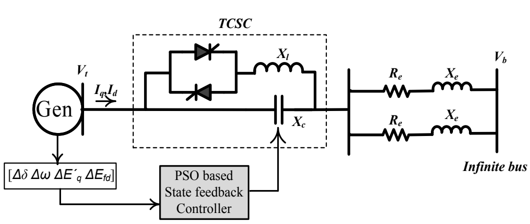

Fig. 2. SMIB system model with a TCSC

3.1 Power System nonlinear model:

The equations that describe the generator and excitation system have been represented in following equations:

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

$$\dot{\omega} = \frac{P_m - P_e - D(\omega - 1)}{M} \tag{4}$$

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.

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

$$\dot{E}_{fd} = \frac{K_A(V_{ref} - V_t) - E_{fd}}{T_A} \tag{6}$$

where, E'_q is the internal voltage. 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. K_A and T_A are the gain and time constant of the excitation system, respectively. V_{ref} is the reference voltage. V_t is the terminal voltage. Also V_t can be expressed as:

$$V_t = V_{td} + jV_{tq} \tag{7}$$

$$V_{td} = X_q I_q \tag{8}$$

$$V_{tq} = E'_q - X'_d I_d \tag{9}$$

where, X_q is the q-axis reactance of the generator.

$$C_1 I_d + C_2 I_q = V_b \sin(\delta) + C_3 E'_q \tag{10}$$

$$C_4 I_d + C_5 I_q = V_b \cos(\delta) - C_6 E'_q \tag{11}$$

Solving (10) and (11) simultaneously, I_d and I_q expressions can be obtained. C_1 to C_6 are constant and V_b is the infinite bus voltage. The various parameters of the system and controllers are listed in Table 1.

Table. 1. Parameters of the studied system (PU)

Generator	$M = 4.74$ MJ/MVA; $T'_{do} = 5.9$s $D = 0$; $w_b = 120\pi$ rad/s $X_d = 1.7$; $X_q = 1.64$; $X'_d = 0.245$
Excitation System	$K_A = 400$; $T_A = 0.05$
Transmission Line	$R_e = 0$; $X_e = 0.6$

3.2 Power System Linearized model:

A linear dynamic model has been obtained by linearizing the nonlinear model round an operating condition (P_e = 0.8, Q_e = 0.16). The linearized model of power system as shown in Fig. 2 is given as follows:

$$\Delta\dot{\delta} = \omega_b \Delta\omega \tag{12}$$

$$\Delta\dot{\omega} = \frac{\Delta P_m - \Delta P_e - D\Delta\omega}{M} \tag{13}$$

$$\Delta\dot{E}'_q = \frac{\Delta E_{fd} - (X_d - X'_d)\Delta i_d - \Delta E'_q}{T'_{do}} \tag{14}$$

$$\Delta\dot{E}_{fd} = \frac{(K_A(\Delta V_{ref} - \Delta V_t + U_{pss}) - \Delta E_{fd})}{T_A} \tag{15}$$

$$\Delta I_q = c_7\Delta\delta + c_8\Delta X_{TCSC} \tag{16}$$

$$\Delta I_d = c_9\Delta\delta + c_{10}\Delta E'_q + c_{11}\Delta X_{TCSC} \tag{17}$$

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_3\Delta X_{TCSC} \tag{18}$$

$$\Delta V_t = K_4\Delta\delta + K_5\Delta E'_q + K_6\Delta X_{TCSC} \tag{19}$$

where K_1 to K_6 and c_7 to c_{11} are linearization constants. The above linearizing procedure yields the following linearized power system model [23]:

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}'_q \\ \Delta\dot{E}_{fd} \end{bmatrix} = \begin{bmatrix} 0 & \omega_b & 0 & 0 \\ -\frac{k_1}{M} & \frac{-D}{M} & -\frac{k_2}{M} & 0 \\ -\frac{(X_d - X'_d)c_9}{\tau'_{do}} & 0 & -\frac{(X_d - X'_d)c_{10} + 1}{\tau'_{do}} & \frac{1}{\tau'_{do}} \\ -\frac{k_A k_4}{T_A} & 0 & -\frac{k_A k_5}{T_A} & -\frac{1}{T_A} \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & -\frac{k_3}{M} \\ 0 & -\frac{(X_d - X'_d)c_{11}}{\tau'_{do}} \\ \frac{K_A}{T_A} & \frac{-K_6 K_A}{T_A} \end{bmatrix} \times \begin{bmatrix} U_{PSS} \\ \Delta X_{TCSC} \end{bmatrix}$$

In short,

$$\dot{X} = AX + BU \tag{20}$$

where the state vector X is $[\Delta\delta \quad \Delta\omega \quad \Delta E'_q \quad \Delta E_{fd}]^T$ and the control vector U is $[U_{pss} \; \Delta X_{TCSC}]^T$ [11].

4.State Feedback Controller Design

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

$$\dot{X} = AX + BU \tag{21}$$

$$Y = CX \tag{22}$$

where, X, U and Y are state, input and output vectors, respectively. A, B and C are constant matrixes. The aim of designing of State feedback controller is to move the eigenvalues of power system to the left hand side of the complex plane.

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 [15].

The structure of State feedback controller is as follow:

$$U = -HX \tag{23}$$

where, the gain vector H is $[h_1 \; h_2 \; h_3 \; h_4]$ and the state vector X is $[\Delta\delta \; \Delta\omega \; \Delta E'q \; \Delta E_{fd}]^T$. the power system linearized model with integration of PSO based state feedback controller for TCSC and PSS is depicted in Fig. 3, while K_7, K_8, and K_9 are constants defined as:

$$(X_d - X'_d)c_9 = K_7 \tag{24}$$

$$(X_d - X'_d)c_{10} + 1 = K_8 \tag{25}$$

$$(X_d - X'_d)c_{11} = K_9 \tag{26}$$

5.PSO Based State Feedback Controller Design

In this paper, the multi objective fitness function which is represented in (27), has been applied for PSO algorithm. In this equation t_{sim} is the simulation time, dw is the deviation of speed, dv_t is the deviation of terminal voltage of generator, α and β are the weight factors.

$$\text{fitness} = \int_0^{t_{sim}} t \times [\alpha \times |dw| + \beta \times |dv_t|]dt \tag{27}$$

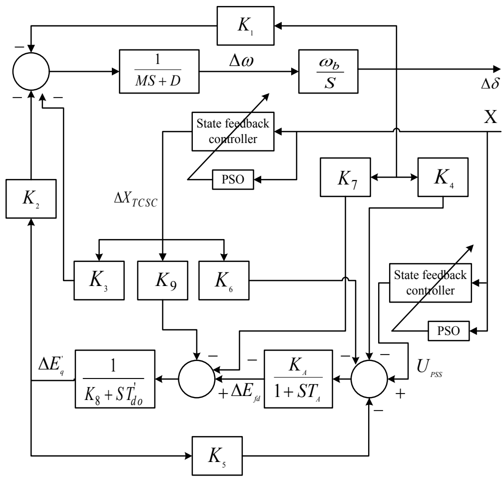

Fig. 3. Power system linearized model with state feedback controllers

Optimized parameters have been earned when the input power of generator has been changed 10% at t=1 (s) for six cycle, and the operating condition is Pe=0.8 and Qe=0.16. Table 2 shows the optimized parameters found by PSO algorithm. Fig. 4 shows the overall PSO method and how it interplays with the simulation model during optimization.

Table 2. Optimized Values

controller	h_1	h_2	h_3	h_4
TCSC	-6.1	1328.9	63.9	0.4
PSS	45	-1297.4	127.6	1.9

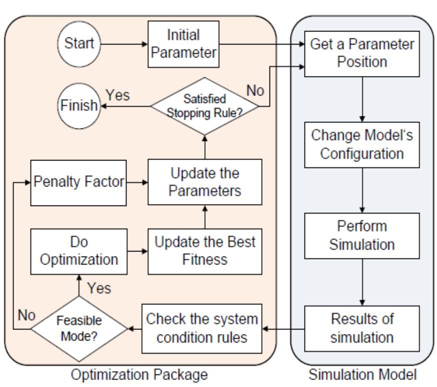

Fig. 4. Optimization method on stochastic simulation

6.Simulation Result

The simulation studies and the optimization of the state feedback controller parameters are performed in the MATLAB software. The aim of designing process of the state feedback controller for PSS and TCSC is fast damping ratio of electromechanical modes, reduces the system response's overshoots, undershoots, settling times and improves the system damping characteristics.

To achieve good performances of the system, it is necessary that the parameters of the controller be optimized well. Stability of the power system is strongly depended on the robustness of the controllers. To evaluate the effectiveness and robustness of the TCSC and PSS based state feedback controllers, simulation studies are considered for various operating conditions. In this study, the performance of the considered state feedback controller is tested and compared with various configurations. However, for simulation studies, two scenarios are presented as follows:

Scenario 1:

In this scenario, the performances of the system are assessed while the input power of generator is changed 10% for 6 cycles at t=1s suddenly. Moreover, for showing the robustness of the proposed controllers, previous disturbance is applied for various operating conditions as follows:

- Base Case: P=0.8pu , Q=0.16pu
- Case 1: P=1pu , Q=0.26pu
- Case 2: P=0.6pu , Q=0.09pu

The dynamic response of the generator for rotor speed variation and terminal voltage variation with and without proposed controllers have been shown in figures 5, 6, 7. It can be seen that the system is unstable without controllers. When the PSS was installed, the system has been stabilized, but the oscillations have been poorly damped. Next, the TCSC has been installed. Installation of the TCSC caused to achieve better dynamic response. As a result, the values of the overshoots, the undershoots and the settling times reduced. Also it is clear that the performance of TCSC based state feedback controller has good damping characteristics for low frequency oscillations and stabilizes the system quickly. However, the performance of the TCSC based state feedback controller is superior than PSS based state feedback controller.

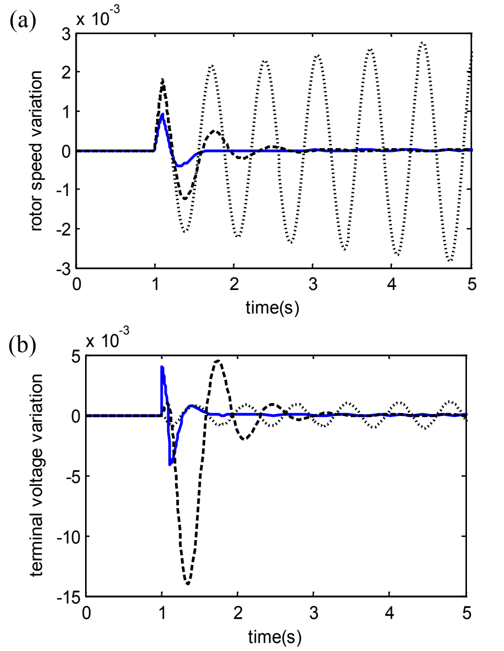

Fig. 5. Dynamic response of generator, (a) rotor speed variation and (b) terminal voltage variation, at Base Case , solid(TCSC based controller), dash(PSS based controller) , dash-dotted(without controller)

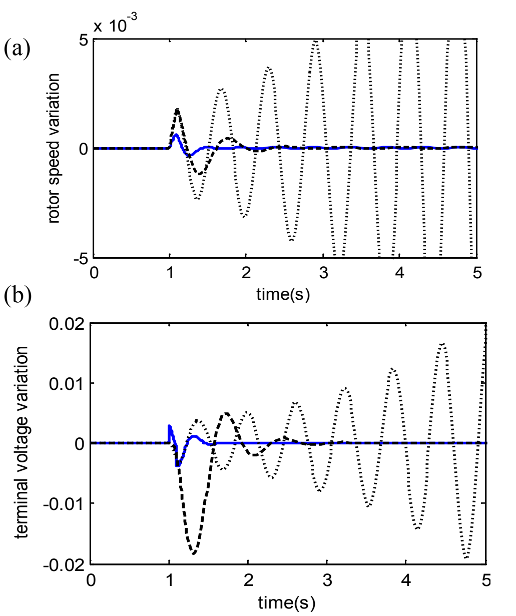

Fig. 6. Dynamic response of generator, (a) rotor speed variation and (b) terminal voltage variation, at Case 1 , solid (TCSC based controller), dash (PSS based controller) , dash-dotted (without controller)

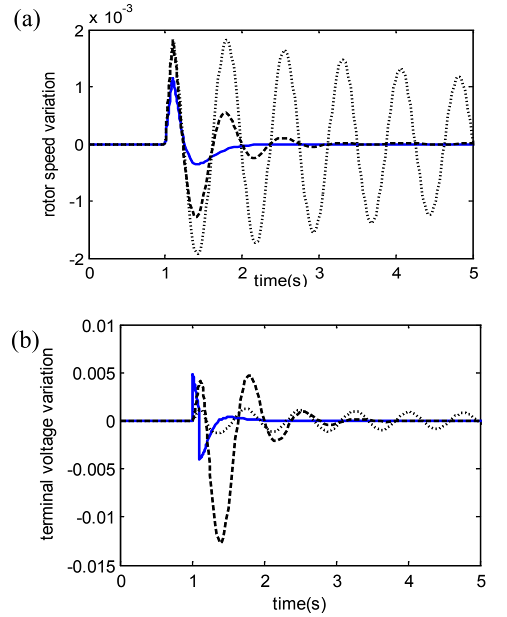

Fig. 7. Dynamic response of generator, (a) rotor speed variation, and (b) terminal voltage variation, at Case 2 , solid (TCSC based controller), dash (PSS based controller) , dash-dotted (without controller)

Scenario 2:

In this scenario, moreover applying the previous disturbance, one of the transmission lines between TCSC and infinite bus is tripped at t=1s and the simulation studies carry out for various operating conditions as follows:

- Case 3: P=0.8pu , Q=0.28pu
- Case 4: P=1pu , Q=0.5pu
- Case 5: P=0.6pu , Q=0.15pu

Figures 8, 9 and 10 show the system response for rotor speed variation and terminal voltage variation. It can be seen with inclusion of proposed controllers under these severe faults, the dynamic response of the generator is improved greatly and system have a good damping profile over a range of operating condition. Similar to scenario 1, when TCSC is installed, the values of the overshoots, the undershoots and the settling times reduced and the system is more stable. In addition, the supremacy of TCSC based controller for damping the low frequency oscillations is clear.

To demonstrate robust performances of the proposed controller, three performance indices are defined as follows [13]:

$$ITAE = 100\int_0^5 t \times [|dw| + |dv_t| + |d\delta|]dt \quad (28)$$

$$ITSE = 1000\int_0^5 t \times [(dw)^2 + (dv_t)^2 + (d\delta)^2]dt \quad (29)$$

$$FD = (1000 \times OS)^2 + (4000 \times US)^2 + (T_S)^2 \quad (30)$$

where ITAE is the integral of the time multiplied absolute value of the error, ITSE is the integral of the time multiplied square of the error and FD is the figure of demerit. Overshoot (OS), undershoot (US) and settling time of speed deviation of the machine (T_S) are considered to calculate the FD. Table 3 shows the values of performance indices for all cases. Clearly, the lower values of these indices show better performance of the system. Corresponding to Table 3, outstanding predominance of the TCSC based controller is clear.

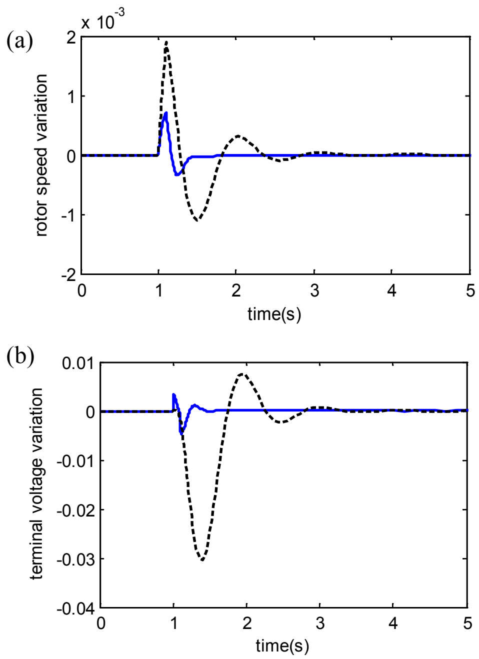

Fig. 8. Dynamic response of generator, (a) rotor speed variation and (b) terminal voltage variation, at Case 3, solid (TCSC based controller), dash (PSS based controller)

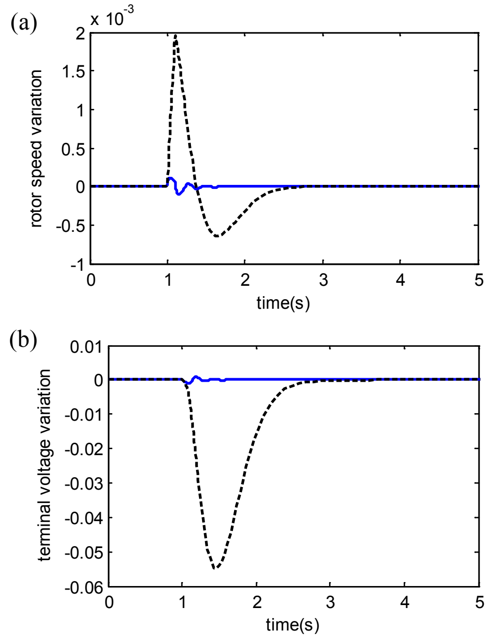

Fig. 9. Dynamic response of generator, (a) rotor speed variation and (b) terminal voltage variation, at Case 4, solid (TCSC based controller), dash (PSS based controller)

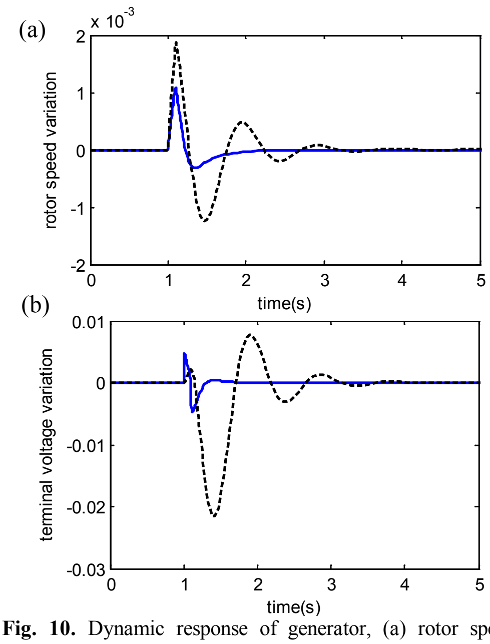

Fig. 10. Dynamic response of generator, (a) rotor speed variation and (b) terminal voltage variation, at Case 5, solid (TCSC based controller), dash (PSS based controller)

Table 3. Performance Indices

	Controller	Base Case (Normal)			Case 1 (Heavy)			Case 2 (Light)		
		ITAE	ITSE	FD	ITAE	ITSE	FD	ITAE	ITSE	FD
Without tripping line	PSS	5.77	1.98	43.25	5.68	2.54	40.5	6.55	2.26	50.18
	TCSC	1.48	0.34	7.32	0.63	0.07	8.76	3.64	1.26	9.26
	Controller	Case 3 (Normal)			Case 4 (Heavy)			Case 5 (Light)		
		ITAE	ITSE	FD	ITAE	ITSE	FD	ITAE	ITSE	FD
With tripping line	PSS	10.33	5.01	40.04	19.7	14.9	18.5	10.39	4.27	50.66
	TCSC	1.00	0.12	7.21	0.09	0.001	3.18	3.23	0.82	9.47

7.Conclusion

In this paper, the state feedback controller has been designed for PSS and TCSC by PSO algorithm to improve the power system stability. The SMIB system which TCSC is located at the terminal of generator has been considered to evaluate the proposed state feedback controllers. Selecting the optimum coefficients for TCSC and PSS based state feedback controllers is converted into an optimization problem. The PSO algorithm has been used to solve this problem. The operation of the system has been presented for wide range of operating condition and different severe disturbances, for rotor speed variation, rotor angle variation, and terminal voltage variation with and without proposed controllers. The system performance characteristics in terms of 'ITAE', 'ITSE' and 'FD' indices expose exceptional performances of the proposed controllers. Simulation results showed that the performance of state feedback based TCSC controller is better than PSS based controller.

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