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

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
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 vector of the best fitness. This particle has achieved so far. The fitness value \( p = (p_1, p_2, ..., p_m) \) is also stored. This position is called \( p_{best} \). 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 \( g = (g_1, g_2, ..., g_m) \) 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.

\[
v_{i}(k+1) = wv_{i}(k) + r_1c_1\left[ p_1 - x_i(k) \right] + r_2c_2\left[ p_{g} - x_i(k) \right]
\]

(1)

\[
x_{i}(k+1) = x_i(k) + v_{i}(k + 1)
\]

(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; \( \omega \) 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.

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. $\omega_b$ is the synchronous speed. $\delta$ and $\omega$ are the rotor angle and speed, respectively.

\[
\dot{E}_q' = \frac{E_{fd} - (X_d' - X_d^*)i_d' - E_q'}{T_{do}}
\]  

(5)

\[
\dot{E}_{fd} = \frac{K_A (V_{ref} - V_t) - E_{fd}}{T_A}
\]  

(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:

\[
V_t = V_{id} + jV_{iq}
\]  

(7)

\[
V_{id} = X_q' I_q
\]  

(8)

\[
V_{iq} = E_q' - X_d' I_d
\]  

(9)

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

\[
C_1 I_d + C_2 I_q = V_b \sin(\delta) + C_3 E_q'
\]  

(10)

\[
C_4 I_d + C_5 I_q = V_b \cos(\delta) - C_6 E_q'
\]  

(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)

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td></td>
</tr>
<tr>
<td>$M$</td>
<td>4.74 MJ/MVA</td>
</tr>
<tr>
<td>$T_{do}$</td>
<td>5.9s</td>
</tr>
<tr>
<td>$D$</td>
<td>0</td>
</tr>
<tr>
<td>$\omega_b$</td>
<td>120π rad/s</td>
</tr>
<tr>
<td>$X_d$</td>
<td>1.7</td>
</tr>
<tr>
<td>$X_q$</td>
<td>1.64</td>
</tr>
<tr>
<td>$X_a$</td>
<td>0.245</td>
</tr>
<tr>
<td>Excitation System</td>
<td></td>
</tr>
<tr>
<td>$K_A$</td>
<td>400</td>
</tr>
<tr>
<td>$T_A$</td>
<td>0.05</td>
</tr>
<tr>
<td>Transmission Line</td>
<td></td>
</tr>
<tr>
<td>$R_e$  ; $X_e$</td>
<td>0.6</td>
</tr>
</tbody>
</table>

### 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:

\[
\Delta \delta = \omega \Delta \omega
\]  

(12)

\[
\Delta \omega = \frac{\Delta P_m - \Delta P_e - \Delta D \omega}{M}
\]  

(13)

\[
\Delta E'_q = \frac{\Delta E_{fd} - (X_d - X_d') \Delta i_d - \Delta E'_q}{T_{do}}
\]  

(14)

\[
\Delta E_{fd} = \frac{(K_A (\Delta V_{ref} - \Delta V_t) + U_{pss}) - \Delta E_{fd}}{T_A}
\]  

(15)

\[
\Delta I_q = c_7 \Delta \delta + c_8 \Delta X_{TCSC}
\]  

(16)

\[
\Delta I_d = c_9 \Delta \delta + c_{10} \Delta E'_q + c_{11} \Delta X_{TCSC}
\]  

(17)

\[
\Delta P_e = K_1 \Delta \delta + K_2 \Delta E'_q + K_3 \Delta X_{TCSC}
\]  

(18)

\[
\Delta V_t = K_4 \Delta \delta + K_4 \Delta E'_q + K_6 \Delta X_{TCSC}
\]  

(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]:

\[
\begin{bmatrix}
\Delta \delta \\
\Delta \omega \\
\Delta E'_q \\
\Delta E_{fd}
\end{bmatrix}
= \begin{bmatrix}
0 & \frac{K_1}{T_A} & -D & \frac{K_2}{T_A} & 0 \\
\frac{1}{T} & 0 & -\frac{1}{T} & 0 & -\frac{1}{T} \\
\frac{1}{T} & 0 & -\frac{1}{T} & 0 & -\frac{1}{T} \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta \delta \\
\Delta \omega \\
\Delta E'_q \\
\Delta E_{fd}
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
\Delta \delta \\
\Delta \omega \\
\Delta E'_q \\
\Delta E_{fd}
\end{bmatrix}
\]

(20)

In short,

\[
\dot{X} = AX + BU
\]  

(21)

\[
Y = CX
\]  

(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:

\[
U = -HX
\]  

(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:

\[
(X_d - X'_d)c_q = K_7
\]  

(24)

\[
(X_d - X'_d)c_{10} + 1 = K_8
\]  

(25)

\[
(X_d - X'_d)c_{11} = K_9
\]  

(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, \(\alpha\) and \(\beta\) are the weight factors.

\[
\text{fitness} = \int_{0}^{t_{sim}} t \times [\alpha \times |dw| + \beta \times |dv_t|] dt
\]  

(27)
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 \( P_e=0.8 \) and \( Q_e=0.16 \). 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

<table>
<thead>
<tr>
<th>controller</th>
<th>( h_1 )</th>
<th>( h_2 )</th>
<th>( h_3 )</th>
<th>( h_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCSC</td>
<td>-6.1</td>
<td>1328.9</td>
<td>63.9</td>
<td>0.4</td>
</tr>
<tr>
<td>PSS</td>
<td>45</td>
<td>-1297.4</td>
<td>127.6</td>
<td>1.9</td>
</tr>
</tbody>
</table>

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).

Scenario 2:
In this scenario, moreover applying the previous disturbance, one of the transmission lines between TCSC and infinite bus is tripped at $t=1$s 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]:

\[
\text{ITAE} = 100 \int_0^5 t \left[ |dw| + |dv| + |d\delta| \right] dt \\
\text{ITSE} = 1000 \int_0^5 t \left[ (dw)^2 + (dv)^2 + (d\delta)^2 \right] dt \\
\text{FD} = (1000 \times \text{OS})^2 + (4000 \times \text{US})^2 + (T_S)^2
\]

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 (TS) 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)
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.

Table 3. Performance Indices

<table>
<thead>
<tr>
<th>Controller</th>
<th>Without tripping line</th>
<th>With tripping line</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base Case (Normal)</td>
<td>Case 1 (Heavy)</td>
</tr>
<tr>
<td></td>
<td>ITAE</td>
<td>ITSE</td>
</tr>
<tr>
<td>PSS</td>
<td>5.77</td>
<td>1.98</td>
</tr>
<tr>
<td>TCSC</td>
<td>1.48</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Case 3 (Normal)</td>
<td>Case 4 (Heavy)</td>
</tr>
<tr>
<td></td>
<td>ITAE</td>
<td>ITSE</td>
</tr>
<tr>
<td>PSS</td>
<td>10.33</td>
<td>5.01</td>
</tr>
<tr>
<td>TCSC</td>
<td>1.00</td>
<td>0.12</td>
</tr>
</tbody>
</table>

References


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