Simultaneous Coordinated Design of TCSC-Based Damping Controller and AVR Based on PSO Technique

Abstract. Power system is a nonlinear system that requires accurate and robust control to improve power system stability following the occurrence of disturbance. In order to damp out oscillations, coordinated design problem of TCSC-based damping controller and AVR is formulated as an optimization problem. PSO technique has been employed to solve the optimization problem. Dynamic performance of these controllers has been appraised over a wide range of loading conditions under sever disturbance in SMIB power system. The non-linear time-domain simulation results suggest that the robustness of simultaneous coordinated design of these devices to enhance power system stability.

Streszczenie. Opisano metodę sterowania stabilnością systemu zasilania przy obecności zakłóceń. Dla tłumienia oscylacji wykorzystano kontroler TCSC a AVR (automatic voltage regulator) jest traktowany jako problem optymalizacyjny. Do sterowania wykorzystano algorytm pojedyncze PSO. (Jednoczesne skoordynowane wykorzystanie tłumienia TCSC i kontrolera napięcia sieci AVB bazujące na technice PSO)

Keywords: TCSC-Based Damping Controller, AVR, PSO Technique, Coordinated Design, Power System Dynamic Stability.

1. Introduction

Damping of power system electromechanical oscillations is an important issue and challenging problem in the power industry [1]. Low frequency oscillations are observed when a disturbance such as sudden change in loads, change in transmission line parameters, fluctuation in the output of the turbine and faults etc occurs in power system. The magnitude of these oscillations may keep growing until loss of synchronism result [2]. The lack of sufficient system damping is the major reason of the continuity and growth of oscillation in power system [3, 4].

Flexible AC Transmission Systems (FACTS) devices are one of the main purposes for enhancement of power system dynamic stability. In recent years, the fast progress in the field of power electronics has provided an appropriate bed in the power industry to utilize the FACTS controllers for damping of power system oscillations [5, 6]. Series FACTS devices are the key devices of the FACTS family, which are identified as effective and economical means to diminish the power system oscillation [7]. Thyristor Controlled Series Compensator (TCSC) is one of the most impressive series compensation devices that can play important role in the control and operation of power systems, such as: diminishing power system oscillation, improving transient stability, scheduling power flow; reducing asymmetrical components, providing voltage support; mitigating sub-synchronous resonance (SSR) phenomenon, and limiting short circuit currents [8-10]. A typical TCSC model comprises of a fixed series capacitor shunted by a Thyristor Controlled Reactor (TCR). The TCR is made by a reactor in series with a bidirectional thyristor valve which is triggered by a phase angle a ranging between 90° and 180° with respect to the capacitor voltage. The firing angle of the thyristor has been controlled to regulate the reactance of TCSC and its degree of compensation [11, 12]. From the viewpoint of power system dynamic stability, it is essential for TCSC to equip with a supplementary damping controller. For this study, lead-lag structure has been selected as supplementary control device to provide extra damping and mitigate the power system oscillations.

The experimental results have confirmed that the power system transient stability can be significantly improved through appropriate control of generator excitation [13]. The generator excitation system using an Automatic Voltage Regulator (AVR) maintains the terminal voltage magnitude of a synchronous generator on the defined level [14]. It can also improve the transient and the steady-state stability of power systems via controlling the reactive power [15].

A number of conventional methods have been employed for tuning parameters of power system stabilizers. The most common methods are based on the pole placement technique, eigenvalues sensitivities, residue compensation, and also the current control theory. Unfortunately, these conventional methods are time consuming as they are repetitive and need heavy computation burden and slow convergence. In addition, process is sensitive to be trapped in local minima and the obtained response may not be optimal [16]. The progressive methods develop a technique to search for the optimum solutions via some sort of directed random search processes [17]. A suitable trait of the evolutionary methods is that they search for solutions without prior problem perception. In recent years, a number of various ingenious computation techniques namely: Simulated Annealing (SA) algorithm, Evolutionary Programming (EP), Genetic Algorithm (GA), Differential Evolution (DE) and Particle Swarm Optimization (PSO) have been employed by scholars to solve the different optimization problems of electrical engineering. But, the PSO technique can produce an excellent solution within shorter calculation time and stable convergence characteristic than other stochastic techniques [18]. In fact, PSO is a stochastic global optimization approach based on swarm behavior such as fish and bird schooling in nature [19]. Generally, PSO is known as a simple concept, easy to perform, and computationally effective. PSO has a flexible and well-balanced mechanism to enhance the global and local exploration abilities [20].

The high performance of PSO technique to solve the non-linear, non-differentiable, and high-dimensional objectives has been confirmed in many literatures. In this paper, PSO technique is chosen to solve the coordination problem among TCSC-based damping controller and AVR. To verify the robustness of this simultaneous coordination, dynamic performance of these devices has been analyzed and appraised over a wide range of loading conditions under sever disturbance in SMIB power system.

2. Description of the Implemented PSO Technique

PSO is a stochastic global optimization method, which has been motivated by the behavior of organisms, such as fish schooling and bird flocking [21]. PSO has the flexibility than other heuristic algorithms to control the balance between the global and local configuration of the search space. This unique feature of PSO vanquishes the
premature convergence problem and enhances the search capability. Also unlike the traditional methods, the solution quality of this technique does not depend on the initial population. Starting anywhere in the search space, PSO algorithm ensures the convergence of the optimal solution. In the current research, the process of PSO technique can be summarized as follows [22-24]:

1) Initial positions of pbest and gbest are varied. However, using the different direction of pbest and gbest, all agents piecemeal receive near-by the global optimum.

2) Adjustment of the agent position is perceived by the position and velocity information. However, the method can be used to the separate problem applying grids for XY position and its velocity.

3) Didn’t have any incompatibilities in searching procedures even if continuous and discrete state variables are utilized with continuous axes and grids for XY positions and velocities. Namely, the method can be applied to mixed integer non-linear optimization problems with continuous and discrete state variables easily and naturally.

4) The above statement is based on using only XY axis (two dimensional spaces). Thus, this method can be easily employed for n-dimensional problem.

The Modified velocity and position of each particle can be calculated using the current velocity and the distances from pbest and gbest as presented in the following equations [25]:

\[
\begin{align*}
\mathbf{v}_{j+1}^{(i)} &= \mathbf{v}_{j}^{(i)} + c_1 \times (\text{pbest}_{j,g} - \mathbf{x}_{j}^{(i)}) + c_2 \times (\text{gbest}_{g,j} - \mathbf{x}_{j}^{(i)}) \\
\mathbf{x}_{j}^{(i+1)} &= \mathbf{x}_{j}^{(i)} + \mathbf{v}_{j}^{(i)}
\end{align*}
\]

Here, \( \mathbf{v}_{j}^{(i)} \) and \( \mathbf{x}_{j}^{(i)} \) are the d-axis reactance and the d-axis transient reactance of the generator, respectively. \( K_A \) and \( T_d \) are the gain and time constant of the excitation system furnished with AVR. In the figure \( V_f \) and \( V_T \) represent the generator terminal and infinite bus voltage, respectively, and also \( X_T \) and \( X_r \) are the reactance of the transformer and the transmission line, respectively. The generator is represented by the third-order model including the electromechanical swing equation and the generator internal voltage equation. The swing equation is given as follows:

\[
\dot{\delta} = \omega_b (\omega - 1)
\]

\[
\dot{\omega} = \frac{1}{M} [P_m - P_e + D (\omega - 1)]
\]

Fig. 1. Single line diagram of SMIB power system

Where \( \delta \) and \( \omega \) the rotor angle and speed, respectively; \( \omega_b \) the synchronous speed; \( P_m \) and \( P_e \) are the output and input powers of the generator, respectively; \( M \) and \( D \) the inertia constant and damping coefficient, respectively.

The power \( P_r \), the internal voltage \( E_f^i \) and the terminal voltage \( v_T \) can be represented as:

\[
\begin{align*}
P_r &= v_d i_d + v_q i_q \\
E_f^i &= \int_{T_d} E_{f_d} - (x_d - x_d') i_d - E_f^i \\
v_T &= \sqrt{v_d^2 + v_q^2}
\end{align*}
\]

Here, \( E_{f_d} \) 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.

The d-axis and q-axis components of armature current and terminal voltage can be calculated as:

\[
\begin{align*}
i_d &= \frac{E_f^i - v_b \cos \delta}{x_d + x_{eff}} \\
i_q &= x_q + x_{eff} \\
v_d &= \frac{x_q v_b}{x_q + x_{eff}} \sin \delta \\
v_q &= \frac{1}{x_d + x_{eff}} [x_{eff} E_f^i + v_b x_d' \cos \delta]
\end{align*}
\]

The following equation presents the effective reactance:

\[ x_{eff} = x_T + x_L + x_{TCSC}(\alpha) \]

where \( x_{TCSC}(\alpha) \) is the TCSC reactance at firing angle \( \alpha \)

3.2. Exciter

The IEEE Type ST1A excitation system shown in Fig. 2 is considered in this study. It can be represented as follows:

Fig. 3. IEEE type ST1A excitation system

\[ V_{ref} \]

\[ V_T \]

\[ E_{f_{d_{max}}} \]

\[ E_{f_{d_{min}}} \]

\[ V_{ref} \]

\[ K_A \]

\[ T_d \]

\[ E_{f_d} \]

where \( x_{TCSC}(\alpha) \) is the TCSC reactance at firing angle \( \alpha \)

3.3. TCSC-based damping controller

The block diagram of a TCSC-based lead-lag controller is presented in Fig. 3.
Fig. 3. Structure of the TCSC-based damping controller

The effective conduction angle \( \phi \) during dynamic conditions can be expressed by:

\[
\phi = \phi_0 + \Delta \phi, \quad \phi = 2(\pi - \alpha)
\]

where

\[
\phi = 2(\pi - \alpha)
\]

The value of firing angle \( \alpha \) is modulated according to the variation in output of TCSC controller \( \Delta \phi \). \( \phi_0 \) is the initial value of conduction angle.

3.4. The Linearized Model

In the design of electromechanical mode damping controllers, the linearized incremental model around a nominal operating point is usually employed. The Phillips-Heffron model of the power system with TCSC is derived by linearizing the set of Eq.s (5)–(15) around an operating condition of the power system:

\[
\begin{bmatrix}
\Delta \dot{\delta} \\
\Delta \dot{\omega} \\
\Delta E_p' \\
\Delta E_q'
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 & 0 \\
\frac{-K_2}{K_4} & \frac{D}{M} & \frac{K_2}{K_4} & 0 \\
\frac{-T_{do}}{T_A} & \frac{1}{T_A} & \frac{0}{T_A} & \frac{0}{T_A} \\
\frac{-K_q}{K_4} & \frac{T_{do}}{T_A} & \frac{0}{T_A} & \frac{-K_q}{K_4}
\end{bmatrix}
\times
\begin{bmatrix}
\Delta \phi \\
\Delta \phi
\end{bmatrix}
\]

(18)

where \( K_1, K_6, K_p, K_q \) and \( K_4 \) are linearization constants.

Fig. 4 shows the block diagram of the SMIB power system with TCSC which is obtained using the set of linearized Eq. (18).

4. The Proposed Approach

4.1. Problem Formulation

From the viewpoint of the washout function the value of \( T_1 \) is not critical and may be in the range of 1-20 s. The main consideration is that it be long enough to pass stabilizing signals at the frequencies of interest unchanged [3]. The time constant of \( T_2 \) and \( T_4 \) are respecified [1, 25]. In this study, \( T_{pS}=10s \) and \( T_{dS}=0.1s \) are chosen. The other parameters which should be optimized are as follows:

- TCSC-based damping controller: gain \( (K_a) \) and time constants \( (T_{1S} \text{ and } T_{3S}) \).
- AVR: gain \( (K_i) \) and time constant \( (T_{iS}) \).

During the steady-state conditions \( \Delta \phi \) and \( \phi_0 \) are constant. During dynamic conditions, conduction angle \( \phi \) and subsequently \( \Delta \phi \) is modulated to damp power system oscillations. The desired value of the compensation is acquired via change in conduction angle \( \Delta \phi \) according to the variation in \( \Delta \omega \).

4.2. Objective function

There are many different methods to appraise the response performance of a control system, namely: Integral of Time weighted Absolute value of Error (ITAE), Integrated Absolute Error (IAE), Integral of Squared Error (ISE), and Integral of Time weighted Squared Error (ITSE). To evaluate the robustness of simultaneous coordination of TCSC-based damping controller and AVR, \( F \) has been selected as the total fitness function [2, 26]:

\[
J = \sum_{i=0}^{t_{Sim}} |\Delta \omega| \tau \cdot dt
\]

(20)

\[
F = \sum_{i=1}^{N_p} J_i
\]

(21)

Where, \( t_{Sim} \) is the time range of the simulation and \( N_p \) is the total number of loading conditions. In this study, the PSO technique is applied to solve the optimization problem. The flowchart of the optimization based on simultaneous coordination of TCSC-based damping controller and AVR is presented in Fig. 5 [26]
The time-domain simulation of the non-linear system model is performed for the simulation period. It is aimed to minimize this fitness function in order to improve the system response in terms of the settling time, overshoots and undershoot. The problem constraints are the optimized parameter bounds. Therefore, the design problem is formulated as the following optimization problem:

\[(22) \quad \text{Minimize } F \]

Subject to:

\[K_S^{\text{min}} \leq K_S \leq K_S^{\text{max}} \quad \text{For TCSC-based damping controller} \]

\[T_{S,1}^{\text{min}} \leq T_{S,1} \leq T_{S,1}^{\text{max}} \]

\[T_{S,3}^{\text{min}} \leq T_{S,3} \leq T_{S,3}^{\text{max}} \]

\[K_A^{\text{min}} \leq K_A \leq K_A^{\text{max}} \quad \text{For AVR} \]

\[T_A^{\text{min}} \leq T_A \leq T_A^{\text{max}} \]

5. Simulation Results and Discussions

To evaluate the robustness of simultaneous coordination of TCSC-based damping controller and AVR in order to improve power system dynamic stability, three different loading conditions: light loading, nominal loading and heavy loading are considered. In all cases, the power system is affected by 3-phase fault in power system. AVR and TCSC controller parameters in [3] and [27] are considered as non-coordinating states, respectively. The coordinated design of TCSC-based damping controller and AVR is performed by evaluating the fitness function presented in Eq. (21) with considering the three different loading conditions. Optimal parameters of these controllers are given in Table 1.

Table 1. Optimal parameter settings of the AVR and PSS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AVR</th>
<th>TCSC-based damping controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K_A)</td>
<td>0.4582</td>
<td>0.1042</td>
</tr>
<tr>
<td>(T_A)</td>
<td>0.1042</td>
<td>0.5009</td>
</tr>
<tr>
<td>(K_S)</td>
<td>0.5009</td>
<td>0.1555</td>
</tr>
<tr>
<td>(T_S)</td>
<td>0.1555</td>
<td>0.1944</td>
</tr>
</tbody>
</table>

The following section results show the effectiveness and robustness of simultaneous coordination of TCSC-based damping controller and AVR to enhance the dynamic stability of power system.

5.1. Nominal Loading

The scheme of proposed coordinated design is apprised for \(P_e=1\text{pu}\) under 3-phase fault at the infinite bus. Fault is occurred at \(t=1\text{ s}\) that is cleared after 9 cycles. The original system is restored after the clearance of the fault. As described above, PSO-technique is applied to coordinate TCSC-based damping controller and AVR simultaneously in order to damp power system oscillations. Figs. 6 and 7 display the system response under severe disturbance. These figures approve the robustness of simultaneous coordination among TCSC-based damping controller and AVR to diminish the power system oscillations.

5.2. Light Loading

In this state, the coordination scheme is assessed for \(P_e=0.6\text{pu}\) under 3-phase fault at the infinite bus at \(t=1\text{ s}\) that fault is cleared 0.2s (12 cycles) later. The original system is restored after the clearance of the fault. The system response with and without coordination scheme is exhibited in Figs. 8 and 9. These figures portray the effectiveness of robust coordinated TCSC-based damping controller and AVR to enhance the dynamic stability of power system.

The following section results show the effectiveness and robustness of simultaneous coordination of TCSC-based damping controller and AVR to enhance the dynamic stability of power system.
reveal that the power system stability is significantly enhanced by the AVR to improve power system dynamic stability. The coordinated design of TCSC-based damping controller and AVR is presented to improve the robustness of power system stability. The high performance of PSO technique in order to acquire the optimal solution of the problem has been successfully proved. To confirm the effectiveness of the coordinated control scheme, dynamic performance of these controllers has been evaluated over a wide range of loading conditions under severe disturbance in single-machine infinite-bus power system. The non-linear time-domain simulation results suggest that the robustness of simultaneous coordinated design of TCSC-based damping controller and AVR to enhance power system dynamic stability has been evaluated.

5.3. Heavy Loading
To test the effectiveness of coordinated control scheme, a 3-phase fault is considered at the infinite bus while system is under heavy loading ($P_e=1.2\text{pu}$). Fault is occurred at $t=1\text{~s}$ and is cleared after 6 cycles. The original system is restored after the clearance of the fault. The system response with and without coordination scheme is shown in Figs. 10 and 11. As it has been expected, these figures reveal that the power system stability is significantly improved with coordinated control among TCSC-based damping controller and AVR.

6. Conclusion
In this paper, a robust control scheme based on simultaneous coordination between of TCSC-based damping controller and AVR is presented to improve dynamic stability of power system. The problem of selecting the controller’s parameters is converted to an optimization problem to damp the power system oscillations and enhance dynamic performance of power system. The high performance of PSO technique in order to acquire the optimal solution of the problem has been successfully proved. To confirm the effectiveness of the coordinated control scheme, dynamic performance of these controllers has been evaluated over a wide range of loading conditions under severe disturbance in single-machine infinite-bus power system. The non-linear time-domain simulation results suggest that the robustness of simultaneous coordinated design of TCSC-based damping controller and AVR to enhance power system dynamic stability has been evaluated.

REFERENCES

Author: Ali Darvish Falehi, Department of Electrical Engineering, Isfah Branch, Islamic Azad University, Isfah, IRAN, E-mail: falehi87@gmail.com.