Optimal Tuning of TCSC Controller Using Particle Swarm Optimization

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Abstract – This paper presents parameters setting by optimization algorithm of Particle Swarm Optimization (PSO) for modeling Thyristor Controlled Series Capacitor (TCSC) in power system. This is done by minimizing a time-domain based objective function of PSO. The results obtained from simulations in MATLAB/Simulink verified the effectiveness of proposed modeling and improving power system stability.

Keywords – Thyristor Controlled Series Compensator (TCSC); optimal tuning; particle swarm optimization; power system stability.

1. Introduction

One important member of FACTS family, TCSC (Thyristor Controlled Series Capacitor) is an impedance compensation which is applied in series reactance on an AC transmission system to provide smooth control of series reactance [1]. The use of these controllers had given grid planners and operators a greater flexibility regarding the type of control actions that could be taken at any given time. The detailed explanations about the FACTS controllers are well documented in the literature and be founded in [2, 3], developed a continuous-time, large-signal dynamic model for a TCSC. The model is based on the representation of voltages and currents as time-varying Fourier series, and focused on the dynamics of the short-term Fourier coefficients [4]. The detailed analysis of the TCSC with the analysis of the periodic state equations, using the state variable approach. Transient characteristics as well as steady state characteristics of the TCSC were also presented using the analytical equations for three operating modes of the TCSC. A fundamental frequency model for TCSC for analyzing the factors that influence the transient stability of TCSC with the changing in operating conditions was developed in 1998 [5]. A new TCSC model for angle stability studies was used to design a simple controller based primarily on the dynamic response of the system. An analysis of different locally measurable controller input signals was also presented a small signal, Phillips-Heffron [6] model of single-machine infinite bus power system installed with a TCSC where the parameters of the TCSC damping controller are optimized by a multi-objective Particle Swarm Optimization. This presents difficulties for tuning the FACTS controllers in that, the controllers tuned to provide desired performance at small signal condition never guarantee acceptable performance in the event of major disturbances. A conventional lead-lag controller structure is preferred by the power system utilities because of the ease of on-line tuning and also lack of assurance of the stability by some adaptive or variable structure techniques. The problem of FACTS controller parameter tuning is a complex exercise. A number of conventional techniques have been done.

In the literature belonging to design problems of conventional power system stabilizers namely: the eigenvalue assignment, mathematical programming, gradient procedure for optimization and also the modern control theory. The conventional techniques were took more time as they are iterative and require heavy computation burden and slow convergence. In addition, the search process was faced to be trapped in local minima and the solution obtained may not be optimal [7]. Recently, PSO is becoming more famous to solve the optimization problems in different fields of applications. Particle swarm optimization is a kind of population-based evolutionary algorithm . It is as similar as other population based evolutionary algorithms that the algorithm is initialized with a population of random solutions. In PSO has motivated by the simulation of social behavior instead of survival of the fittest, and each candidate solution is associated with producer. The candidate solutions, called particles, then “fly” through the search space. The velocity is constantly adjusted according to the corresponding particle’s experience and the particle’s companions’ experience. It is seem that the particles will towards better solution area. Simulation results show the advantages of using the modeling and tuning method when performing control and stability analysis in a power system including a TCSC controller. The remainder of this paper is organized in five major sections. A brief explain of TCSC is presented in Section 2. Power system modeling with the presented TCSC controller structure is presented in Section 3. In Section 4, application of PSO is presented. The results are presented and discussed in Section 5. Finally, in last Section have compared between PSO and GA and conclusions are given. Effective design and accurate evaluation of the TCSC control strategy is depend on the simulation accuracy of this process. This paper is presenting a function model of the TCSC in the MATLAB/SIMULINK environment. The PSO based optimal tuning algorithm is used to optimize the parameters of the TCSC controller. Simulation results
show the advantages of using the modeling and tuning method when performing control and stability analysis in a power system with a TCSC controller.

2. Thyristor Controlled Series Capacitor (TCSC)

Adjusting TCSC reactance is in accordance with a system control algorithm, normally in response to some system parameter chance variations [3]. Assuming that current passing through the TCSC was sinusoidal, the equivalent reactance at the fundamental frequency will be represented as a variable reactance $X_{TCSC}$. There exists a steady-state relationship between $\alpha$ and the reactance $X_{TCSC}$. This relationship can be described by the following equation [8]:

$$X_{TCSC}(\alpha) = X_C - \frac{X_C^2}{X_C - X_P} \times \frac{(\sigma + \sin \sigma)}{\pi} + \frac{4X_C^2}{X_C - X_P} \times \frac{\cos^2(\sigma/2)}{(k^2 - 1)} \times k \tan(k\sigma/2) - \tan(\sigma/2)$$

where:
- $X_C$: Nominal reactance of the fixed capacitor C.
- $X_P$: Inductive reactance of inductor L connected in parallel with C.
- $\Sigma$: $2(\pi - \alpha)$, the conduction angle of TCSC controller.
- $k$: $X_C/X_P$, the compensation ratio.

Since the relationship between $\alpha$ and the equivalent fundamental frequency reactance offered by TCSC, $X_{TCSC}(\alpha)$ was a unique-valued function, the TCSC is modeled here as a variable capacitive reactance within the operating region defined by the limits imposed inductor L and bidirectional thyristors. The firing angles of the thyristors were controlled by $\alpha$. As $X_{TCSC-min} \leq X_{TCSC} \leq X_{TCSC-max}$, with $X_{TCSC-max} = X_{TCSC}(\alpha_{min})$ and $X_{TCSC-min} = X_{TCSC}(180^\circ) = X_C$. In this paper, the controller was assumed to operate only in the capacitive region, i.e., $\alpha_{min} > \alpha_r$, where $\alpha_r$ corresponds to the resonant point, as the inductive region associated with $90^\circ < \alpha < \alpha_r$ induces high harmonics that could not be properly modeled in stability studies [9]. The structure of TCSC-based damping controller, to modulate the reactance offered by the TCSC, $X_{TCSC}(\alpha)$, is shown in Fig. 1. The input signal of the proposed controllers is the speed deviation ($\Delta \omega$), and the output signal is the reactance $X_{TCSC}(\alpha)$. The structure consists of a gain block with gain $K_T$, a signal washout block and two-stage phase compensation blocks. The signal washout block serves worked as a high-pass filter, the time constant $T_{wT}$, high enough to allow signals associated with oscillations in input signal to pass unchanged.

3. Power System Modelling

The SMIB power system with TCSC (shown in Fig. 2), is considered in this study. The synchronous generator is delivering power to the infinite-bus through a double circuit transmission line and a TCSC. In Fig. 2, $V_t$ and $E_b$ are the generator terminal and infinite bus voltage respectively, $X_T$, $X_L$ and $X_{TH}$ represent the reactance of the transformer, transmission line per circuit and the Thevenin’s impedance of the receiving end system respectively. The state equations may be written as [10]

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

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

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 [10]:

$$i_d = \frac{E_b \cos \sigma - E'_d}{(x_e + x'_d)}$$

$$i_q = \frac{E_b \sin \sigma + E'_q}{(x_e + x'_q)}$$

$$\frac{dE'_d}{dt} = \frac{1}{T_{do}} \left[ -E'_d + (x_d - x'_d)i_d + E_{fd} \right]$$

$$\frac{dE'_q}{dt} = \frac{1}{T_{qo}} \left[ -E'_q + (x_q - x'_q)i_q \right]$$

$$v_q = -x_e i_d + E_b \cos \sigma$$

$$v_d = x_e i_q - E_b \sin \sigma$$
4. Application of Particle Swarm Optimization

Particle Swarm Optimization (PSO) technique is a optimization method developed by Eberhart, et al. [11], [12]. It is a multi-agent search technique that traces its evolution to the emergent motion of the convergence of PSO, so indicated that use of a constriction function may be necessary [12]. PSO starts with a population of random solutions 'particles' in a D-dimension space. The $i^{th}$ particle is represented by $X_i = (x_{i1}, x_{i2}, ..., x_{iD})$. Each particle keeps track of its coordinates in hyperspace, which are associated with the fittest solution it has achieved so far. The value of the fitness for particle $i$ (pbest) is also stored as $P_i = (p_{i1}, p_{i2}, ..., p_{iD})$. The global version of the PSO keeps track of the overall best value (g best), and its location, obtained thus far by any particle in the population. PSO is consists of at each step, changing the velocity of each particle toward its pbest and gbest according to Eq. (10). The velocity of particle $i$ is represented as $V_{id} = (v_{i1}, v_{i2}, ..., v_{iD})$. Acceleration is weighted by a random term, with separate random numbers on the interval $[0,1]$ applied to ith Particle being generated for acceleration toward Pbest and Gbest. The position of the $i_{th}$ particle is then updated according to Eq. (10), (11) [13].

$$V_{id} = w \times v_{id} + c_1 \times r_1 \times (P_{id} - X_{id}) + c_2 \times r_2 \times (P_{gd} - X_{id}) \quad (10)$$

$$X_{id} = x_{id} + cv_{id} \quad (11)$$

where $P_{id}$ and $P_{gd}$ are p best and g best. $c_1$ and $c_2$ are two positive constants, called cognitive and social parameters respectively. $r_1$ and $r_2$, are random numbers, uniformly distributed in $[0,1]$. Several modifications have been proposed in the literature to improve the PSO algorithm speed and convergence toward the global minimum. One modification is to median number of iterations to converge. However, p best version with neighborhoods of two is most resistant to local minima.

PSO algorithm is further improved via using a time introduce a local-oriented paradigm ($l_{best}$) with different neighborhoods. It is concluded that $g_{best}$ version performs best in terms of decreasing inertia weight, which leads to a reduction in the number of iterations [14].

4.1. Optimization problem

Tuning a controller parameter could be viewed as an optimization problem in multi-modal space as many settings of the controller could be yielding suitable 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 method, the tuning process is associated with an optimality concept through the defined objective function $n_d$ the time domain simulation. Hence this method yields optimal parameters and the method is free from the curse of local optimality. In PSO optimization technique, the designer has the freedom to explicitly specify the required performance objectives in terms of time domain bounds on the closed loop responses. So, the proposed approach employs PSO to solve this optimization problem and search for optimal TCSC controller parameters. In this study, it is aimed to minimize the proposed objective functions $J$. The problem constraints are the TCSC controller parameter bounds. Therefore, the design problem can be formulated as the following optimization problem according above named Minimize $J$ by:

$$K_T \min < K_T < K_T \max$$
$$T_1 \min < T_1 < T_1 \max$$
$$T_3 \min < T_3 < T_3 \max$$

4.2. Objective function

It is worth mentioning that the TCSC controller was designed to minimize the power the power angle deviation after a large disturbance and to quickly damp the power system oscillations. These oscillations were reflected in the deviations in the generator rotor angle ($\Delta \omega$), speed ($\Delta \omega$) and accelerating power ($\Delta P_a$). Therefore the objective can be formulated as the minimization of $J$:

$$J = \int_0^{T_{sim}} t \times |\Delta \omega(t)| \, dt \quad (13)$$

where, $\Delta \omega(t)$ is the rotor speed deviation and $T_{sim}$ is the time range of the simulation. For objective function calculation, the time-domain simulation of the non-linear 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. Conclusions For show the advantages of modeling the TCSC controller dynamics and tuning its parameters this paper, simulation studies of a SMIB power system with TCSC are carried out. The MATLAB/SIMULINK model of the example power system is developed [15] using equations (1-9).

The SIMULINK model for calculation of $Id$ and $Iq$ is shown in Fig.3.

The parameters could be seen in Appendix. The operating point considered is:

PM = 0.95 pu, VB = 1.0 pu, $\alpha = 158^0$, $\delta = 56.4^0$

For more damping could connect in parallel PSS system with TCSC Typical ranges of the optimized parameters are $[0.01–150]$ for $K_{TCSC}$ and $[0.01–10]$ for $K_{PSS}$. The proposed approach employs PSO algorithm to solve this optimization problem and search for an optimal set of output feedback controller parameters.
The optimization of TCSC controller parameters is carried out by evaluating the objective cost function in Eq. (13). For PSO technique, the parameters utilized in this simulation are shown in Table 1.

Table 1. Typical Parameter Value for PSO

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value / Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of flights</td>
<td>100</td>
</tr>
<tr>
<td>number of swarm beings</td>
<td>50</td>
</tr>
<tr>
<td>$w_{max}$</td>
<td>0.9</td>
</tr>
<tr>
<td>$w_{min}$</td>
<td>0.4</td>
</tr>
<tr>
<td>deviation of initial velocity</td>
<td>10</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>1.5</td>
</tr>
</tbody>
</table>

5. Simulation Results and Discussions and comparison PSO responding with GA

For PSO technique, the parameters used in this simulation are shown in Table 1. The performance of the optimized controller was tested by nonlinear simulations of the power system subjected to a severe disturbance. A three phase fault is applied at the generator terminals at $t = 1$ sec and cleared after 100 ms. The original system is restored upon the fault clearance. To study the Performance of controller, two cases are considered; with PSOTCSC and with GATCSC genetically tuned TCSC controller. Figs. 4 (a)-(c) show the system response with respect to time for the two cases. Here though the TCSC is in the system and the legend PSO TCSC indicates the response with genetically tuned TCSC controller. It is clear from the Figs.4 (a)-(c) that, the genetically tuned TCSC controller with PSO algorithm improves the stability performance of the example power system and power system oscillations are well damped out. To assess the damping characteristics of genetically tuned TCSC controller, a small disturbance in mechanical power input is considered. Figure 4: System response for a 100ms three-phase fault. Then in this paper deals with the application of Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) to find out the optimal number, the optimal locations, and the optimal parameter settings of multiple TCSCs devices to minimum cost of installation of these devices. For comparison the parameters utilized in this simulation are shown in Table 2.

Particle Swarm Optimization (PSO) is a kind of stochastic global optimization. Unlike Genetic Algorithm (GA) and other heuristic Algorithms, PSO has more the flexibility than other to control the balance between the global and local exploration of the search space. This unique feature of PSO overcomes the premature convergence problem and enhances the search capability. Also it is unlike the other methods, the solution quality doesn’t need to the initial Starting anywhere in the search space the PSO algorithm ensures the convergence to the optimal solution.
Figure 4. (a) Accelerating power \( (P_a) \), (b) Power angle \( (\delta) \), and (c) Deviation in \( w \) GA-TCSC and PSO-TCSC response.

Table 2. Values of \( K_p \), \( T_1 \), \( T_3 \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( K_p )</th>
<th>Time Constants ( T_1 )</th>
<th>Time Constants ( T_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum range</td>
<td>40</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Maximum range</td>
<td>120</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Optimised parameters obtained by PSO</td>
<td>68.069</td>
<td>0.6851</td>
<td>0.3853</td>
</tr>
<tr>
<td>Optimised parameters obtained by GA</td>
<td>55.660</td>
<td>0.1692</td>
<td>0.0447</td>
</tr>
</tbody>
</table>

6. Conclusion

This paper presents a systematic procedure for modeling, simulation and optimal tuning of TCSC controller for enhancing power system stability. A MATLAB/SIMULINK model is developed for a single-machine infinite bus power system with TCSC. For the TCSC controller design problem, a parameter-constrained, time-domain based, objective function is developed to improve the performance of power system subjected to a disturbance. Then, PSO and GA are employed to searching for the optimal TCSC controller parameters. The controller is tested on example power system
subjected to large and small disturbances. The simulation results show that, the genetically tuned TCSC controller improves the stability performance of the power system and power system oscillations are effectively damped out. Further it is observed that the proposed PSO-TCSC controller is effective in damping low frequency oscillations resulting from small disturbances conditions like increase in mechanical power input and reference voltage settings is better than GA-TCSC controller. In this paper, two of the most powerful evolutionary optimization techniques, namely, Genetic Algorithm and Particle Swarm Optimization were proposed and implemented to solve the optimization problem under consideration. Three variables were considered to be optimized, $K_P$ gain of TCSC, Time constants $T_1$ and Time constants $T_3$ with compare between System response of PSO-TCSC and GA-TCSC we can see that the disturbance is damping by PSO Optimizer sooner than GA Optimizer. Generally PSOTCSC has time responding faster than GA-TCSC.

7. Appendix

All system data are in P.U. unless specified items.

<table>
<thead>
<tr>
<th>Generator</th>
<th>$H = 3.0 \text{ s}$</th>
<th>$D = 4$</th>
<th>$X_d = 1.0$</th>
<th>$X_q = 0.6$</th>
<th>$T_{do} = 0.3$</th>
<th>$T_{do}^* = 5.044$</th>
<th>$R_a = 0$</th>
<th>$P_e = 0.95$</th>
<th>$Q_e = 0.2084$</th>
<th>$\delta_0 = 56.4^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exciter</td>
<td>$K_A = 10$</td>
<td>$T_A = 0.01 \text{ s}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Transmission Line</td>
<td>$R = 0$</td>
<td>$X = 0.7$</td>
<td>$G = 0$</td>
<td>$B = 0$</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>TCSC Controller</td>
<td>$T_{TCSC} = 15 \text{ ms}$</td>
<td>$\alpha_0 = 158^\circ$</td>
<td>$X_{TCSC} = 0.3591$</td>
<td>$k=2$</td>
<td>$T_F = T_L = 0.1 \text{ s}$</td>
<td>$T_W = 10 \text{ s}$</td>
<td>$X_{MAX} = 0.7 \times$</td>
<td>$X_{MIN} = 0$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8. References

