Downloaded from https://iranpaper.ir

https://www.tarjomano.com/order

ترجمه تخصصی این مقاله

This article was downloaded by: [North Dakota State University]
On: 19 November 2014, At: 19:09
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK

IETE Journal of Research

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tijr20

A Novel Current Injection Model of GCSC for Control and Damping of Power System Oscillations

Amin Safari[a] & Navid Rezaei[b]

[a] Department of Electrical Engineering, Ahar Branch, Islamic Azad University, Ahar

[b] Department of Electrical Engineering, Ahar Branch, Islamic Azad University, Tehran, Iran

Published online: 01 Sep 2014.

To cite this article: Amin Safari & Navid Rezaei (2013) A Novel Current Injection Model of GCSC for Control and Damping of Power System Oscillations, IETE Journal of Research, 59:6, 768-773

To link to this article: http://dx.doi.org/10.4103/0377-2063.126962

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the “Content”) contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

A Novel Current Injection Model of GCSC for Control and Damping of Power System Oscillations

Amin Safari and Navid Rezaei[1]

Department of Electrical Engineering, Ahar Branch, Islamic Azad University, Ahar, [1]Department of Electrical Engineering, Iran University of Science and Technology, Tehran, Iran

ABSTRACT

The paper proposes the theory and the modeling technique of the new invention of the flexible AC transmission system (FACTS) device, i.e., Gate controlled series capacitor (GCSC) for power flow control of power transmission lines and damping of low-frequency oscillations. In this study, a current injection model of the GCSC is used for studying the effect of the GCSC on the low-frequency oscillations, which is incorporated in the transmission system model. To be sure of optimal adjustment of the applied damping controller, the particle swarm optimization algorithm is employed as an efficient heuristic optimizer to find out the near global optimum set of the damping controller parameters. The proposed model is applied to a damping controller design of a multi-machine power system. Detailed simulations are carried out with MATLAB/SIMULINK environment and the effect of the GCSC-based damping controller and the current injection model over the system stability is studied.

Keywords:
Enhancing dynamic stability, Gate controlled series capacitor, ITAE performance index, Particle swarm optimization algorithm.

1. INTRODUCTION

In the last decades, the capacitive-based power system series compensation is identified to the aim of increasing the available transmitted power. Recently, invention of Flexible AC Transmission System (FACTS) technology demonstrated that the variable series compensation is much more effective in either power flow control or improvement of the system stability margins. Indeed, the controlled series dynamic compensation is the basis of FACTS devices [1-4]. Primarily, series controllers inject a voltage in series with the transmission line whether it is produced by a converter or changeable impedance. It could be said that the main capability of series compensation in the light of the transmittable power flow control is enhancing the transient stability margins and power oscillation damping. Thus, with the purpose of power system damping, the series FACTS controllers are more preferable [3]. Accordingly, in the last years, more researchers have been focused on the development and application of series FACTS controllers with the scope of improving power system stability. Deployment of the TCSC and TSSC compensators are the throughput of the literature [4,5]. With the emergence of gate-commutated switches, a significant transition in FACTS structure and control strategy is engendered. It is because of the more controllability feature of gate-commutated switches in both on and off statuses. Gate Controlled Series Capacitor (GCSC) was first presented by Karady *et al*. [6]. The idea of the GCSC is derived with the aim of providing a better power control process in the TCSC scheme. Obviously, referring to the overall controllability of the gate-commutated switches, GCSC has more profitableness to its elder scheme, i.e. TCSC. In the literature [7-9], compared the GCSC and TCSC with a thorough insight, including the structural and operational aspects. Larger available series compensation area, smaller rating of inserted capacitance, lower rated current of switch valves, and continuous voltage injection in the light of continuous control angle are dominant benefits of the GCSC over the TCSC. Premier that due to the lack of reactor in the GCSC module, it is impossible for the GCSC to trap in the resonance bound as occurred in the case of the TCSC. Furthermore, in [10], it is studied that the GCSC is more economical than the SSSC. Although, SSSC is a higher and faster controllable series compensator through the VSC utilization but due to its complex and expensive structure, the GCSC with simpler scheme has superior preference to the SSSC in the techno-economical purposes. Consequently, it could be said that the GCSC may be soon replaced by the TCSC or even SSSC in most of the series compensation scopes. The main motivation of this work is to damp out the electromechanical oscillations using the GCSC as novel FACTS device in an example power system.

The effectiveness of the GCSC in enhancing the power system stability has been explored in some references [8-12]. However, a more detailed and overall investigation is considered to be applied to the GCSC dynamic performance evaluation. Usually, with the aim of overcoming to the destabilizing effects of the power system inherent uncertainties a supplementary controller is anticipated to reinforce the FACTS generated damping torque. In the literature, some methodologies such as fuzzy sets [11] and neural networks [9] are employed to investigate the GCSC series compensatory characteristic by designing a GCSC-based supplementary controller, but due to the trial and error basic procedure of these algorithms, their performance might be degraded. In this study, knowing that Particle Swarm Optimization (PSO) is great at exploring the near global optimum solutions in the high dimensional search spaces; it is employed to find out the optimistic set of the damping controller parameters. Thus, various operating conditions are taken into account to the problem of optimizing the GCSC-based damping controller parameters in an overall operation range. The PSO algorithm is regulated in a way in which the best set of damping controller parameters are effectively optimized under a wide range of different operating conditions. The simulations are performed in a two area test power system so that both inter-area and local oscillation modes are assessed. It is worth mentioning to simplify the GCSC dynamic equation, the current injection model is picked here to be used for dynamic modeling of the GCSC. This model not only preserves the power system impedance matrix and helps accelerate the computations but it also explains the dynamic behavior of the GCSC using detailed nonlinear equations and thus is appropriate for the dynamic studies.

The main contribution of this paper is to investigate the damping function of the GCSC subject to the nonlinear behavior of a practically large-scale multi machine power system. Thus, on the basis of conducting the current injection model of the GCSC, the dynamic performance of the power system is studied precisely. Analyzing the results reveals suitable damping function of the optimized controller and the proper stabilization performance of the GCSC current injection model.

2. DYNAMIC MODELING OF GCSC

The basic single module of the GCSC is constructed of a parallel connection of a capacitance and a pair of anti-parallel gate-commutated switches. As shown in Figure 1, the main target of the GCSC module is to control the transmittable power flow (P12) by continuously adjusting the blocking angle. The active duration of the series compensation corresponds to the hold-off angle in which the switches are off and the capacitance is activated. By contract, when the switches are on, the capacitance is bypassed and the series compensation is deactivated. Remarkably, the blocking angle of 90° is meant by initialization of the bypassed mode [1]. Truism, the active mode results in the range of 0 to 90° of the blocking angle operation. As a result, the GCSC can be modeled as series capacitive impedance between the buses *i* and *j* as displayed in Figure 2.

$$X_{GCSC}(\gamma)=X_C\left(1-\frac{2\gamma}{\pi}-\frac{\sin(2\gamma)}{\pi}\right) \qquad (1)$$

Where, γ is the blocking angle of the GCSC module. The current flow between the buses *i* and *j* can be written as:

$$\bar{I}_{se}=\frac{\bar{V}_i-\bar{V}_j}{r_l+j(x_l-x_c)} \qquad (2)$$

Where, $\bar{V}_i$ and $\bar{V}_j$ are the voltage phasors of the buses *i* and *j*, respectively, and r_l and x_l are the resistance and the reactance of the transmission line, and x_c is the equivalent reactance of the GCSC. To extract the GCSC current injection model, the series-generated voltage is converted to a shunt current source as in Figure 3. Then, the injected current to each of the buses i and j are calculated. The final descriptive equations corresponding to the Figure 4 are given in Equations. (5) and (6):

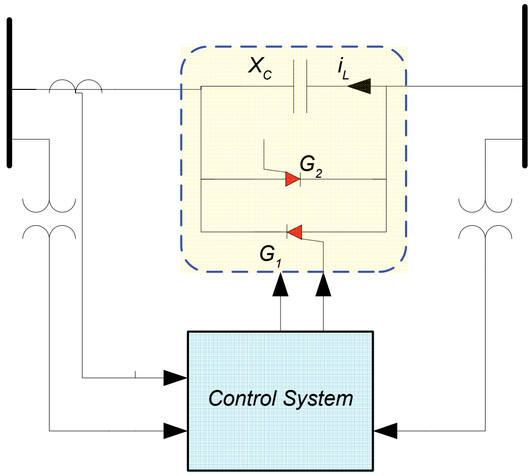

Figure 1: The GCSC installed between buses *i* and *j*.

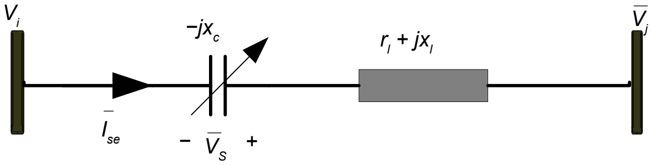

Figure 2: The equivalent circuit of the GCSC installed between buses *i* and *j*.

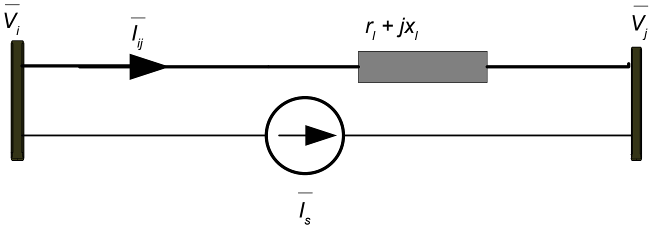

Figure 3: Substitution the voltage source with a current source.

$$\bar{V}_s = -jx_c\bar{I}_{se} \tag{3}$$

$$\bar{I}_s = \frac{\bar{V}_s}{r_l + jx_l} = \frac{-jx_c\bar{I}_{se}}{r_l + jx_l} \tag{4}$$

$$\bar{I}_{si} = \frac{-jx_c}{r_l + jx_l} \cdot \frac{\bar{V}_i - \bar{V}_j}{r_l + j(x_l - x_c)} \tag{5}$$

$$\bar{I}_{si} = -\bar{I}_{sj} \tag{6}$$

The proposed current injection model for the GCSC is applied to four machine two area test power system represented in Figure 5. The nonlinear equations of the system parameters are utilized in the simulation platform. The considered nonlinear equations of the i^{th} generator are [4,13]:

$$\dot{\delta}_i = \omega_0(\omega_i - 1) \tag{7}$$

$$\dot{\omega}_i = \frac{P_{mi} - P_{ei} - D_i(\omega_i - 1)}{M_i} \tag{8}$$

$$\dot{E}'_{qi} = \frac{E_{fdi} - (x_{di} - x'_{di})i_{di} - E'_{qi}}{T'_{doi}} \tag{9}$$

$$\dot{E}_{fdi} = \frac{K_{Ai}(V_{refi} - V_{ti}) - E_{fdi}}{T_{Ai}} \tag{10}$$

$$T_{ei} = E'_{qi}i_{qi} - (x_{di} - x'_{di})i_{di}i_{qi} \tag{11}$$

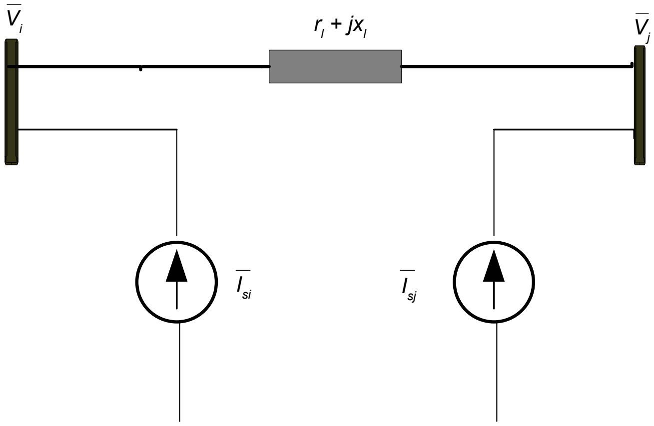

Figure 4: The GCSC current injection model.

In the nominal operation, there is a power transfer flow within 413 MW from area 1 to area 2. The GCSC is assumed to be installed through the current injection model between buses 8 and 9. In the considered test power system, in order to better simulation, the loads are assumed to treat as constant impedance loads. The PSSs' control signals in both areas are neglected in this study. The detailed power system data are given in [1].

3. TUNING THEORY AND METHODOLOGY

The structure of the assumed lead-lag damping controller is displayed in Figure 6. In this Figure, γ_0 is the initial value of the blocking angle. The series variable reactance of the GCSC is modulated using the damping controller. The input control signal of the controller is considered as the power transfer signal between the two areas in the test power system. This is because that the FACTS controllers are mostly operated in the transmission networks and thus the tie-line power signal demonstrates more dynamic data, especially in the case of the inter-area modes. T_{GCSC} is the time-constant of the GCSC blocking angle control system which is assumed here as in 15 *ms*.

In this study, the process of the GCSC-based damping controller design is transmitted into an optimization problem which is solved by the PSO algorithm. Application of PSO algorithm in power systems has been reported in several papers and its effectiveness has been proven [14-17]. Figure 7 shows the flowchart of the PSO algorithm. In this flowchart, the update velocities and positions of particles are done by (12) and (13) [14]:

$$\begin{aligned} v_{id}(t+1) = {} & \omega v_{id}(t) + c_1 rand_1(pbset(t) - x_{id}(t)) \\ & + c_2 rand_2(gbest(t) - x_{id}(t)) \end{aligned} \tag{12}$$

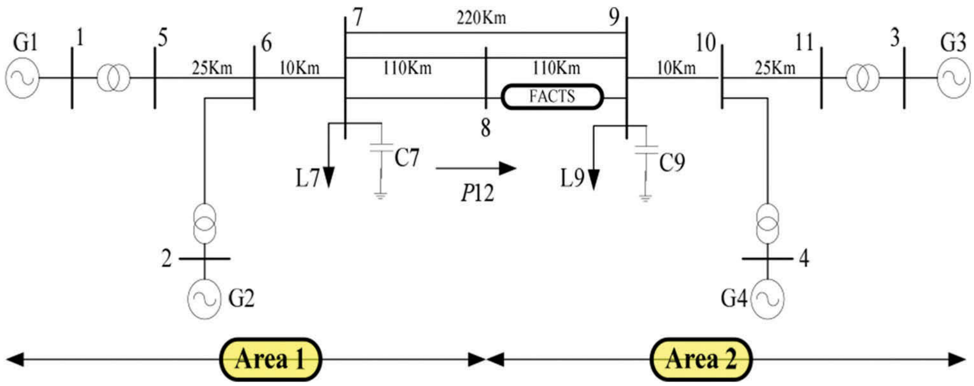

Figure 5: The two area four machine power system equipped with the GCSC.

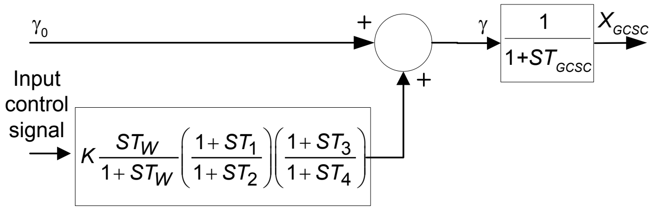

Figure 6: The structure of the proposed damping controller.

$$\vec{x}(t+1)=\vec{x}(t)+\vec{v}(t+1) \tag{13}$$

The PSO parameters are particle numbers, particle size, iteration numbers, and the significant cognitive (c_1) and social (c_2) coefficients which are set as 50, 5, 100, 2, and 2, respectively. Also, to be certain of not trapping in the local-optimums, the PSO algorithm is run several times. All the simulations are performed in the MATLAB/SIMULINK environment. To provide a more robust and stable power system operation, the fitness function is formulated in such a way that both inter-area and local oscillatory modes are taken into account. The operating points are given in Table 1.

The parameters of damping controller, i.e. K, T_1, T_2, T_3, and T_4 are optimized via the PSO algorithm in order to provide an efficient power system stability operation. Thus, the following fitness function (F) is written considering to the operating conditions in the Table 1.

$$\begin{gathered} J=\int_0^{tsim} t.\left(|\omega_1-\omega_2|+|\omega_1-\omega_3|+|\omega_2-\omega_3|+|\omega_2-\omega_4|\right)dt \\ F=\sum_{i=1}^{NP} J_i \end{gathered} \tag{14}$$

In Eq. (14), ω_i is the i-th generator speed signal. *NP* and *tsim* are the total number of operation points and the performed simulation time, respectively. Furthermore, the optimization problem is solved subject to some boundary constraints as in Equation. (16).

$$\begin{gathered} 0<K<200 \\ 0.01<T_x<3, x=1,2,3,4. \end{gathered} \tag{15}$$

The optimized values of the GCSC-based damping controller are listed in Table 2. To assess the robustness of the designed damping controller, it is assumed that two severe disturbances are imposed to the test power system as expressed in scenarios 1 and 2.

3.1 Scenario 1

In this scenario, it is considered that in the middle of one of the transmission line between the buses 7 and 8, a severe three-phase fault occurred. The fault is cleared without any changes in the system configuration. It should be noted that the fault is initiated at $t = 1s$ and took 100 ms to be cleared.

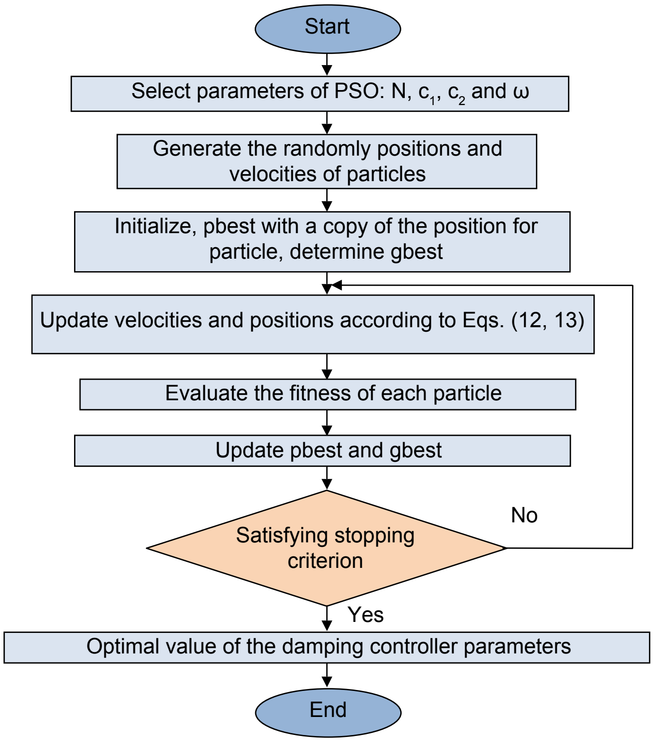

Figure 7: The particle swarm optimization algorithm flowchart.

3.2 Scenario 2

In this scenario, it is tried to investigate the system performance under more difficult disturbance. Thus, addition to the given conditions in the scenario 1, another three-phase fault is assumed to occur at $t = 5s$ and in the middle of the transmission line between the buses 7 and 9. It is considered the fault is cleared after 250 ms and by permanently tripping the faulted line.

4. SIMULATION RESULTS

Figures 8-10 demonstrate the time domain simulation results regarding to the implemented scenarios under the operating points given in Table 1. Although it is clearly seen in the Figures 8-10, the system stability is greatly enhanced against the critical scenarios, but for further assurance from the efficiency of the proposed damping controller, two performance indices are employed in terms of the ITAE and FD indices.

$$ITAE=\int t.\left(|\omega_1-\omega_2|+|\omega_1-\omega_3|+|\omega_2-\omega_4|+|\omega_3-\omega_4|\right)dt \tag{16}$$

$$FD=(0.02\times OS)^2+(0.01\times US)^2+T_s^2 \tag{17}$$

Where, ω is the generator rotor speed and *OS*, *US*, and T_s are representing the overshoot, undershoot, and the settling

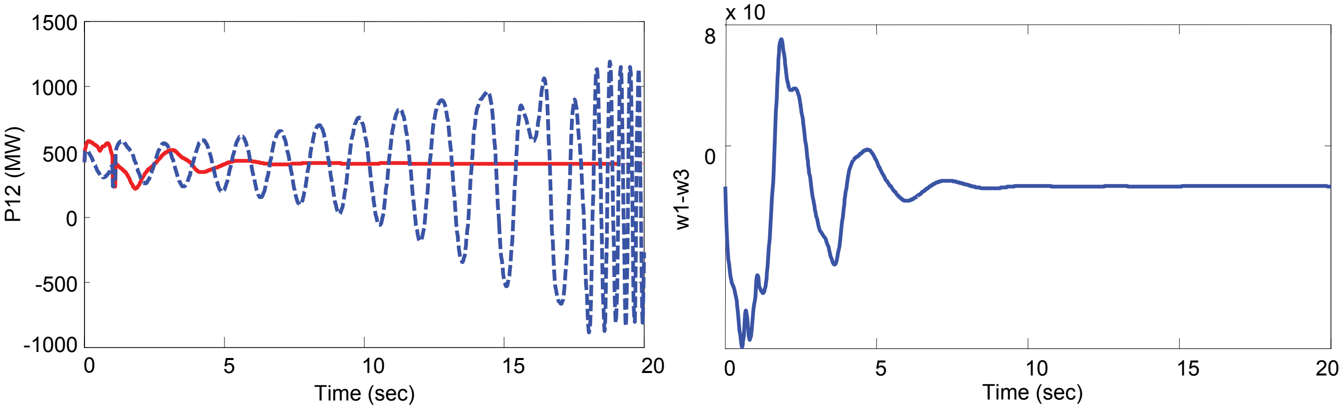

Figure 8: The dynamic response of the power system to scenario 1 in the Case 1.

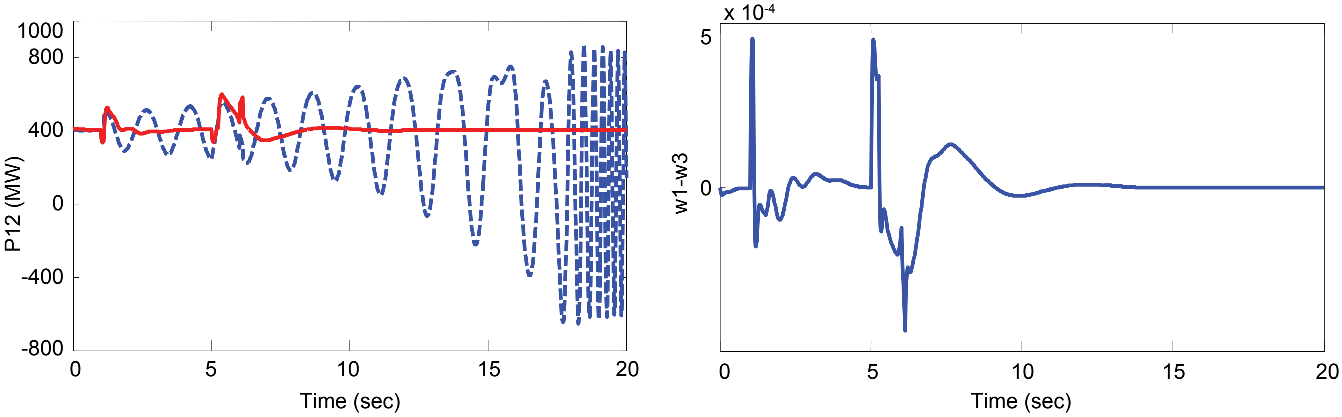

Figure 9: The dynamic response of the power system to scenario 2 in the case 1.

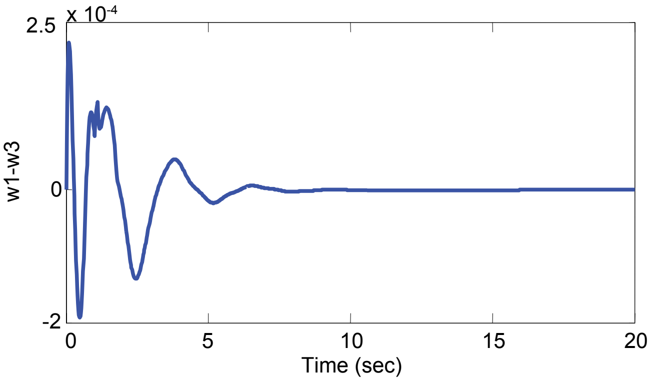

Figure 10: The dynamic response of the power system to scenario 1 in the case 2.

time of the tie-line (*P12*) signal dynamic response. Note that better performance of the designed controller in each considered scenario brings lower values of the performance indices. The numerical results of the indices in all operating points and assumed scenarios are shown in Figure 11.

5. CONCLUSIONS

In this paper, to investigate the GCSC's series compensation capability in enhancing the power system stability a supplementary damping controller was proposed to be designed under a wide range of operation conditions. Furthermore, to have an appropriate modeling of the GCSC stabilizing behavior, the current injection model was drawn out. The problem of adjusting the controller parameter set was transmitted into an optimization problem which was considered to be optimized using the PSO algorithm. The time domain simulation was performed and the consequent results reveal the suitable damping function of the PSO-based designed controller and also verify the efficiency of the proposed current injection model in providing more

Table 1: The considered power system operating points

Operating point	P_1	Q_1	P_2	Q_2	P_3	Q_3	P_4	Q_4
Case 1	0.762	0.083	0.717	0.067	0.822	0.133	0.792	0.136
Case 2	1.151	0.153	0.462	0.033	0.766	0.075	0.766	0.069
Case 3	0.505	0.051	0.906	0.115	0.888	0.116	0.877	0.106

Table 2: The optimized parameters of the damping controller using the PSO algorithm

K	T_1	T_2	T_3	T_4
167.83	1.0234	0.0762	2.4481	0.9965

PSO – Particle swarm optimization

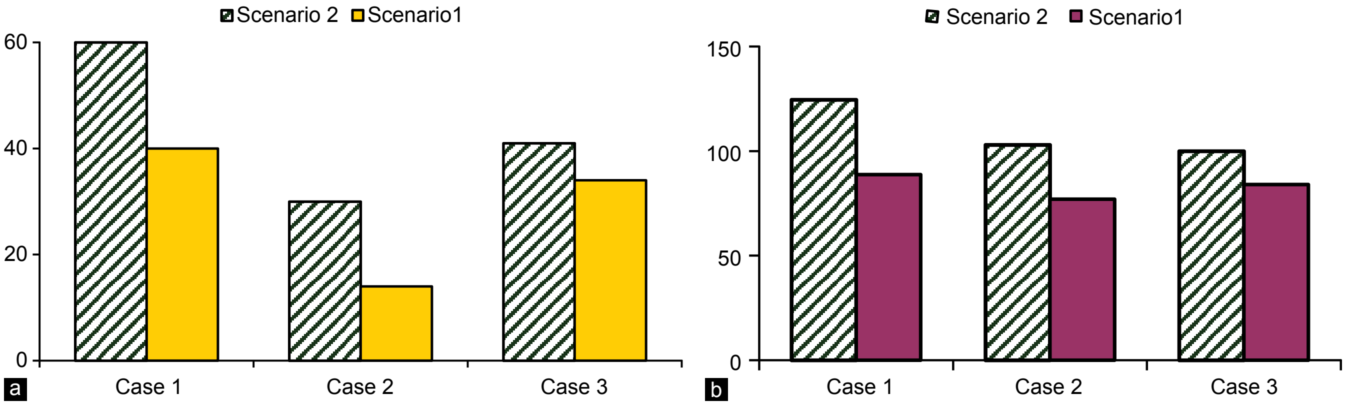

Figure 11: (a) ITAE index values and (b) FD index values.

robust stability margins. Moreover, the numerical results of the two performance indices in terms of ITAE and FD clearly demonstrate the stable and secure operation of the multi-machine power system.

REFERENCES

1. K R Padiyar, "FACTS controllers in power transmission and distribution," India: New age publishers; 2007.
2. N Hingorany, and L Gyugyi, "Understanding FACTS: Concepts and technology of Flexible AC Transmission Systems," IEEE Press, New York, 1999.
3. R Sadikovic, "Use of FACTS devices for power flow control and damping of oscillations in power systems," Ph. D. Thesis, Swiss federal institute of technology, 2006.
4. H Shayeghi, H A Shayanfar, S Jalilizadeh, and A Safari, "TCSC robust damping controller design based on particle swarm optimization for a multi-machine power system," *Energy Conversion and management,* Vol. 51, no. 10, pp. 1873-82, 2010.
5. N Johanson, L Angquist, and H P Nee, "An adaptive controller for power system stability improvement and power flow control by means of a thyristor switched series capacitor (TSSC)," *IEEE Transactions on Power Systems*, Vol. 25, no. 1, pp. 381-91, 2010.
6. G G Karady, T H Ortmeyer, B R Pilvelait, and D Maratukulam, "Continuously regulated series capacitor," *IEEE Transaction on Power Delivery*, Vol. 8, no. 3, pp. 1384-54, 1993.
7. L F De Souza, E Wantanabe, and J E Alves, "Thyristor and Gate- Controlled series capacitor: A comparison of components ratings," *IEEE Transaction on Power Delivery,* Vol. 23, no. 2, pp. 899-906, 2008.
8. L F De Souza, E Wanatabe, and D De Jesus, "SSR and power oscillation damping using gate-controlled series capacitors," *IEEE Transaction on Power Delivery,* Vol. 22, no. 3, pp. 1806-12, 2007.
9. S Ray, G K Venayagamoorthy, and E H Watanabe, "A computational approach to optimal damping controller design for a GCSC," *IEEE Transaction on Power Delivery,* Vol. 23, no. 3, pp. 1673-81, 2008.
10. M Ardes, C Portela, E L Emmerik, and R F Da Silva Dias, "Static series compensators applied to very long distance transmission lines," *Electrical Engineering,* Vol. 86, no. 2, pp. 69-76, 2004.
11. M R Alizadeh Pahlavani, and H A Mohammadpour, "Damping of sub-synchronous resonance and low frequency power oscillations in a series-compensated transmission line using gate-commutated series capacitor," *Electric Power System Research,* Vol. 81, no. 2, pp. 308-17, 2011.
12. E H Wanatabe, M Aredes, P G Barbosa, G Santos, F K De Lima, and R F Da Silva Dias, "Flexible AC Transmission System," Power Electronics Handbook, Elsevier, Netherlands, pp. 797-822, 2007.
13. A Safari, A Ameli, and H A Shayanfar, "Nonlinear Time Response Optimization Using Imperialist Competitive Algorithm for Tuning Robust Power System Stabilizers," *IETE Journal of Research*, Vol. 59, no. 5 , pp. 631-39, 2013.
14. R Eberhart, and J Kennedy, "A new optimizer using particle swarm theory," *Micro machine and Human Science,* pp. 39-43**,** 1995**.**
15. X Y Shi, "Introduction to mathematical optimization from linear programming to meta-heuristics," Cambridge International Science Publishing, Berlin; 2008**.**
16. Y Del Valle, G K Venayagamoorthy, S Mohagheghi, J Carlos, and R G Harlry, "Particle swarm optimization: Basic concepts, variants and application in power systems," *IEEE Transactions on Evolutionary Computation,* Vol. 12, no. 2, pp. 171-95, 2008**.**
17. A Ratnaweera, S K Halgamuge, and H S Watson, "Self organizing hierarchical particle swarm optimization with time varying acceleration coefficients," *IEEE Transactions on Evolutionary Computation,* Vol. 8, no. 3, pp. 240-55, 2004**.**

AUTHORS

Amin Safari received the B.Sc. and M.Sc. degrees in Electrical Engineering in 2007 and 2009, respectively. Currently, he is a Ph.D. student of Power Electrical Engineering, Iran University of Science and Technology, Tehran, Iran. His areas of interest in research are Application of Artificial Intelligence to Power System Control Design, FACTS device and fuzzy sets and systems. He has published more than 50 papers in international journals and conference proceedings.

E-mail: asafari1650@yahoo.com

Navid Rezaei received the B.Sc. and M.Sc. degrees in Electrical Engineering in 2009 and 2011, respectively. He is a Ph.D. student of Power Electrical Engineering, Iran University of Science and Technology, Tehran, Iran. His areas of interest in research are Application of Artificial Intelligence, Power System Dynamics and FACTS Devices.

E-mail: navirezaei@yahoo.com

DOI: 10.4103/0377-2063.126962; Paper No JR 23_13; Copyright © 2013 by the IETE