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A PARTICLE SWARM OPTIMIZER TO DESIGN A GCSC-BASED DAMPING CONTROLLER OF POWER SYSTEM

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Abstract- In recent years, FACTS devices are recognized as one of the most effective ways to improve power system operation controllability and increase power transfer limits. Gate-Controlled Series Capacitor (GCSC) is one of these FACTS devices which is installed in series with the transmission line. In turn, the supplementary controllers are applied to FACTS technology to boost the produced damping torque. Recently, evolutionary and meta-heuristic algorithms have been extensively used to optimize the parameters of damping controllers. In this paper, on the basis of the linearized Heffron-Phillips model of a single machine power system with GCSC, the Particle Swarm Optimization (PSO) algorithm is used to design a lead-lag damping controller for the GCSC. A time domain and an undamped eigenvalue based objective functions are employed as two different fitness. To verify the robustness of the proposed controllers, various operating conditions are simulated due to a severe disturbance. Observing and analyzing the results reveals appropriate performance of this controller in damping the power system oscillations and enhancing the dynamic stability. Moreover, the undamped eigenvalue based fitness is superior to time domain based one.

Keywords: GCSC, PSO, ITAE, Eigenvalue Analysis, Enhancing Dynamic Stability.

I. INTRODUCTION

Power system instability, can appear in different ways and be affected from many various factors. Evaluation of the main factors in generation such conditions and utilizing the control methods for the improving of the power system stability performance has a great importance in the system studies [1]. Besides, in recent years, due to the fast progress in design, manufacture and application of power-electronics devices, consequently, FACTS technology has been an advanced process. Operation of FACTS devices according to their versatile capabilities in improvement of different aspects of a power system like power flow control, congestion management, enhancing the stability margins and etc., has attracted the researcher's attentions [2]. Optimum utilization of different FACTS devices in damping power systems oscillations, naturally causes system to stand in a more authentic operational condition. Recently, Gate-Controlled Series Capacitor (GCSC) is discussed as a FACTS device which is also installed in series with the transmission line. Indeed, GCSC is a Thyristor Controlled Reactor (TCR), in which a capacitor parallel with a dozen anti-parallel GTO switches is used instead of the reactor. In other words, GCSC and TCR are dual circuit to each other [1].

A GCSC can control the series compensation degree by regulating the blocking angle γ. Because of simpler structure and ability of better control, GCSC can be considered as an effective alternative for damping the power system oscillations. From a longer perspective, due to the power system nonlinear nature and constant unpredictable load changes, FACTS devices may not provide adequate damping torque for system oscillatory modes. As a result, supplementary controllers with high flexibility and adjustable parameters are needed to strengthen the generated damping torque by FACTS devices. In the last two decades, the evolutionary and meta-heuristic methods have been mentioned as the robust tools for optimizing the engineering problems. Vast range of application, ease of use and ability to achieve close to the absolute optimal answers are including reasons for the increasing success of these techniques [11].

In the literature, many researchers have focused on GCSC's different aspect into the power systems. Jesus et al [4], represented that the GCSC with a simple controller, can damp both SSR and Low Frequency Oscillations (LFOs). However their concentration is on mitigating the SSR rather those LFOs damping and the controller parameters are designed by trial and error. In 2008, De Souza et al [5], in addition to introduce the structure of the GCSC, in a comparative work, showed some advantages of the GCSC with respect to the TCSC, such as smaller size of GCSC's capacitor and lower current rating in the GCSC's switches. They mentioned that although the GCSC has a better performance with respect to the TCSC, especially in power oscillation damping purposes, TCSC is more practical because of its simpler protection scheme and being an already established technology. Watanabe et al [6] introduced principle of operation and some prospective applications of the GCSC and proved by simulation that in most situations, GCSC can be more attractive than TCSC. Ardes et al in 2004 [7], by presenting a new, simple and robust control strategy for the GCSC, controlled the active power transmitted by very long lines. The GCSC was proved to be very effective, in controlling the power-flow of the transmission lines that are little longer than half the wavelength of the system frequency, even comparative to the HVDC systems [8].

Ray et al [9], by developing an optimal controller, using the Heuristic Dynamic Programming (HDP) approach, investigated the GCSC's role in enhancing the power system stability. The eigenvalue analysis and time-domain responses, confirmed the robustness of the HDP based controller of the GCSC. In 2009 [10], Mohammadpour et al, studied the impacts of GCSC in migrating the SSR and investigated how can reduce the generated harmonics by a multi-module GCSC. In this work, according to the advantages of the GCSC, as one of the simplest and most capable FACTS generations and the effectiveness of the PSO technique, we focus on the POD ability of the GCSC, on the basis of the LFO damping, using a PSO-based designed supplementary controller. In this paper, due to the Particle Swarm Optimization algorithm's higher computing power, easier coding and more rapidly converging than many other optimization methods [12], this algorithm is exerted to better design of the GCSC's supplementary lead-lag damping controller. We compare the Integral of Time multiplied Absolute value of Error (ITAE) as a time-domain based objective function to an undamped eigenvalue based fitness to assess better damping of power system.

The PSO simultaneously shifts the lightly damped and undamped electro-mechanical modes to a prescribed zone in the s-plane such that the relative stability is guaranteed and the time domain specifications concurrently secured. The Heffron-Phillips model of GCSC in a SMIB power system is considered to simulation and then the robustness of the simulations is represented by the two proposed fitness in different operational conditions, under a severe disturbance, satisfying the ITSE performance index. Observing and analyzing the results reveals appropriately performance of this controller in damping the power system oscillations and enhancing the dynamic stability. Moreover, the undamped eigen-value based fitness is superior to time domain based one.

In this paper, the following sections we have: in section II, an overview to the GCSC, section III, PSO technique survey, section IV, problem formulation, section V, designing the GCSC damping controller using PSO, section VI, the simulation results are shown and in section VII the conclusion is described.

II. AN OVERVIEW TO THE GCSC

In 1993 Karady et al [3] introduced a GTO-controlled series capacitor as a generation of FACTS devices. In later years, with the development of semiconductor technology, in addition to the GTO, other gate-commutated switches, such as IGCT or IGBT applied in the structure of the GCSC. Thus today, the letter "G" in GCSC investment term stands for "Gate" rather than "GTO" [5]. In Figure 1, a GCSC consisting of a fixed capacitor in parallel with a bidirectional GTO switches is shown.

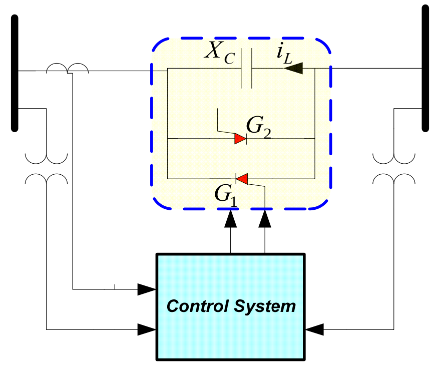


Figure 1. Gate-Controlled Series Capacitor (GCSC)

The main purpose of the GCSC is the capacitor voltage control in crossing current of the inserted line. By switching off the GTOs in the blocking angle γ, the line current passes through the capacitor and the series injected voltage is produced. After blocking in angle γ, the switches remain closed during the angle φ. This angle is named the hold off angle and is given by Equation (1) [1]:

$$\varphi = \pi - 2\gamma \tag{1}$$

If the blocking angle γ is measured with respect to the peak value of the line current, it will be changed between 0^o and 90^o. Thus, the hold off angle φ ranges from 0^o to 180^o [1]. By changing the φ, the reactance of the GCSC is changed in the range between 0 to X_C. Equations (2) and (3) are representing the changes of GCSC reactance versus to the blocking (γ) and hold off (φ) angles, respectively [1]:

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

$$X_{GCSC}(\varphi) = \frac{X_C}{\pi}(\varphi - \sin\varphi) \tag{3}$$

The hold off angle value of 0^o means the capacitor is bypassed and no compensation is occurred while the hold off angle value of 180^o corresponds to fully insertion of the capacitor and maximum compensation. Thus, the great role of the gate-commutated switches is to control the amount of current that is injected in the capacitor by regulating the hold off angle. In comparison to TCSC, due to the lack of the reactor, GCSC can be operated in the whole of its control limitation and so have a wider continuous compensation range and has not the problem of the resonance area, which restricts the compensation capability of the TCSC [7]. Another advantage of the GCSC over the TCSC is its smaller size [5] and its better dynamic response [6].

On the other hand, when the GCSC is compared with SSSC which is also privileged from gate-commutated technology, although the GCSC is less capable, but SSSC seems to be less applicant due to its relatively high cost and lack of previous experience in practical conditions [8]. According to the above comparisons, GCSC could be considered as an effective series FACTS device, mainly for power flow control and oscillation damping purposes. In the GCSC, it is important how to control the series injection capacitive voltage, considering the duality relationship between the GCSC and TCR reveals us the control strategy. It is worth mentioning that the firing angle in a TCR is corresponds to the blocking angle in a GCSC, while the conduction angle in the TCR and the hold off angle in the GCSC are similar [1]. Thus, by controlling the blocking or hold off angle in the GCSC, it can reach to the desired compensation in the line.

III. PSO TECHNIQUE

As a highly nonlinearity, nonstationary system with uncertainties, a power network can have a large number of states and parameters. Implementing any of the classical analytical optimization might not be feasible in most of the cases. But, PSO can be a suitable solution. It utilize a population called particles, which flows through the problem hyperspace with given velocities; in each iteration, velocities are stochastically adjusted considering the historical best position for the particle itself and the neighborhood best position. Then, the movement of each particle naturally evolves to an optimal solution [11-12].

The most important features of this optimization algorithm are easy implementation, fewer adjustable parameters, suitable for the nature of the problem, efficiency in maintaining the diversity of the swarm for improvement of the particle information and simplicity and easy to be coded. Another advantage of the PSO is that the initial population is maintained and so, there is no need for applying operators to the population, a process that is time and memory-storage-consuming. In addition, PSO is based on constructive cooperation between particles, in contrast with the genetic algorithms, which are based on the survival of the fittest. The PSO is initialized with a group of random particles and searches for the optimal point by updating generations.

In each iteration, particles are updated by the best values of itself and the group. The ith particle is represented by $X_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$. 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 $P_i = (p_{i1}, p_{i2}, \ldots, p_{iD})$. The global version of the PSO keeps track of the overall best value (*gbest*), and its location, obtained thus far by any particle in the population. The PSO consists of, at each step, changing the velocity of each particle toward its *pbest* and *gbest* according to Equation (4). The velocity of particle i is represented as $V_i = (v_{i1}, v_{i2}, \ldots, v_{iD})$. The position of the ith particle is then updated according to Equation (5) [11].

$$x_{id} = x_{id} + c v_{id} \tag{4}$$

$$v_{id} = w \times v_{id} + c_1 \times \text{rand}(\,) \times (P_{id} - x_{id}) + c_2 \times \text{rand}(\,) \times (P_{gd} - x_{id})$$

where, P_{id} and P_{gd} are *pbest* and *gbest*. In the PSO, the tradeoff between the local and global exploration abilities is mainly controlled by inertia weights (ω). The inertia weight which is formulated as in Equation (2) varies linearly from 0.4 to 0.9 during the run [11].

$$\omega = \omega_{\max} - \left[\frac{\omega_{\max} - \omega_{\min}}{iter_{\max}} \right] .iter \tag{5}$$

where, $\omega_{\max}$ is the initial value of the inertia weight, $\omega_{\min}$ is the final value of the inertia weight, $iter_{\max}$ is the maximum iteration number and $iter$ is the current iteration number. Figure 2 shows the flowchart of the PSO algorithm.

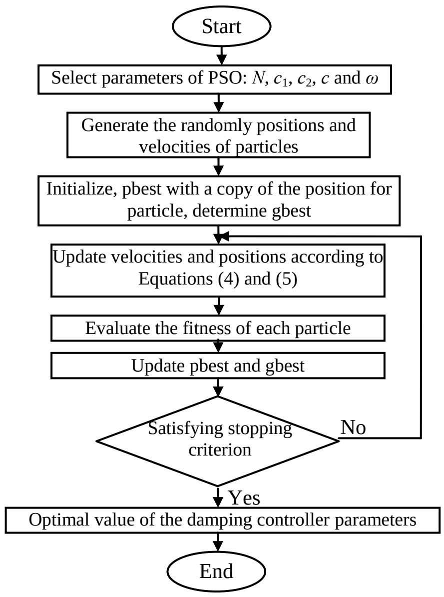


Figure 2. Flowchart of the proposed PSO technique

IV. PROBLEM FORMULATION

A. Modeling the SMIB Power System with the GCSC

Figure 3 shows a single machine infinite bus power system equipped with a GCSC block. V_t and V_b are the generator terminal and infinite bus voltage and X_L, X_C and X_t represent the reactance of the transmission line, the fixed capacitor in the GCSC block and the transformer, respectively.

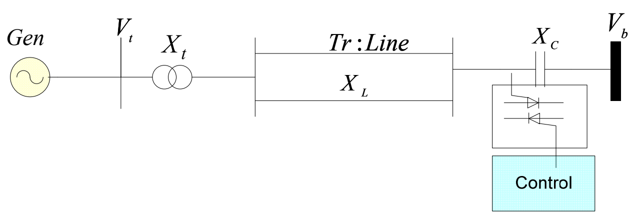


Figure 3. SMIB power system equipped with a GCSC

B. Power System Nonlinear Model with the GCSC

In order to study the small-signal stability of a power system, the GCSC's dynamic model can be modeled as the following [13]:

$$\dot{\omega} = [P_m - P_e - D(\omega - 1)] / M$$
$$\dot{\delta} = \omega_0 (\omega - 1)$$
$$V_t = V_{td} + jV_{tq}$$
$$I = i_d + ji_q$$
$$E_q = E'_q + (X_d - X'_d) i_d$$
$$V_{td} = X_q i_q \qquad (6)$$
$$V_{tq} = E'_q - X'_d i_d$$
$$P_e = V_{td} i_d + V_{tq} i_q$$
$$i_d = \frac{E'_q - V_b \cos\delta}{X_B}$$
$$i_q = \frac{E'_q + V_b \sin\delta}{X_P}$$
$$X_B = X_L - X_{GCSC}(\varphi) + X_q$$
$$X_P = X_L - X_{GCSC}(\varphi) + X'_d$$

where X_d, X'_d and X_q which are the d-axis reactance, d-axis transient reactance, and q-axis reactance, respectively.

C. Power System Linearized Model with GCSC

The Heffron-Phillips model of the power system with the GCSC block is obtained by linearizing the set of Equation (6) around the operating conditions of the power system [14]:

$$\Delta\dot{\delta} = \omega_0 \Delta\omega$$
$$\Delta\dot{E}_{fd} = (K_A(\Delta V_{ref} - \Delta V_t) - \Delta E_{fd}) / T_A$$
$$\Delta P_e = K_1 \Delta\delta + K_2 \Delta E'_q + K_P \Delta\varphi \qquad (7)$$
$$\Delta E_q = K_4 \Delta\delta + K_3 \Delta E'_q + K_q \Delta\varphi$$
$$\Delta V_t = K_5 \Delta\delta + K_6 \Delta E'_q + K_v \Delta\varphi$$

where K_1, K_2, …, K_6, K_p, K_q and K_v are the linearization constants. The block diagram of the linearized dynamic model of the SMIB power system with the GCSC is shown in Figure 4. Power system parameters are shown in the Appendix.

D. GCSC based damping controller

The task of damping controller, in order to improve good damping for the electromechanical oscillations, is producing an in-phase electrical torque, with the speed deviation $\Delta\omega$, considering as the input for the damping controller. This controller's structure which comprising gain block, signal-washout block and lead-lag compensator is shown in Figure 5, where φ_0 the hold off angle reference value is corresponds to the initial power flow condition, which is usually considered to be constant. Thus, for modulating the series compensation, the output variable of the controller equals X_{GCSC}, which is obtained by putting the $\varphi = \varphi_0 + \Delta\varphi$ angle through a first order lag controller. The T_W and T_{GCSC} are considered as 10 (sec) and 15 (ms), respectively. The parameters of lead-lag compensator are obtained using PSO algorithm.

V. GCSC CONTROLLER DESIGN USING PSO

A. Time Domain based Fitness

Due to that the power system oscillations after a disturbance are reflected in the generator rotor speed. Thus, in this paper we use the integral of time absolute value error of the speed deviations as the objective function J_1, expressed as [15]:

$$J_1 = \sum_{i=1}^{NP} \int_0^{t_{sim}} t \left|\Delta\omega_i\right| dt \qquad (8)$$

In Equation (8), N_P is the total number of operating points to carry out the optimization, t_{sim} is the time range of simulation and $\Delta\omega$ is the deviation of the rotor speed of the generator in the SMIB.

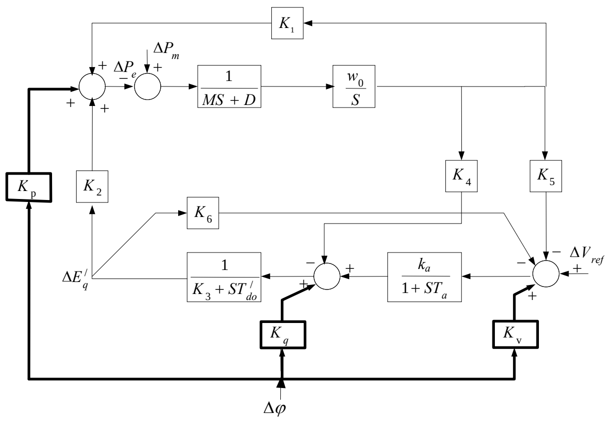


Figure 4. The linearized Heffron-Phillips model of a SMIB power system with a GCSC

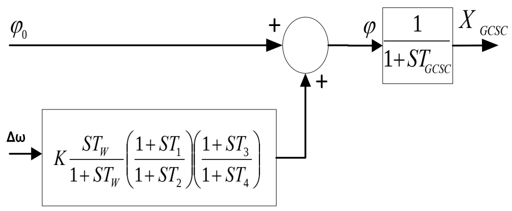


Figure 5. Structure of the GCSC damping controller

B. Eigenvalue based Fitness

An eigenvalue based objective function reflecting the combination of the damping factor and damping ratio is considered as follows [16]:

$$J_2 = \sum_{j=1}^{N_P} \sum_{\sigma_i \ge \sigma_0} (\sigma_0 - \sigma_i)^2 + a \sum_{j=1}^{N_P} \sum_{\zeta_i \le \zeta_0} (\zeta_0 - \zeta_i)^2 \qquad (9)$$

where, $\sigma_{i,j}$ and $\zeta_{i,j}$ are the real part and the damping ratio of the ith eigenvalue of the jth operating point. The value of α is chosen at 10. N_P is the total number of operating points for which the optimization is carried out. The values of σ_0 and ξ_0 determine the relative stability in terms of damping factor margin and the desired minimum damping ratio which are to be achieved, respectively.

Thus, in this study, the values of σ_0 and ξ_0 are -2 and 0.4, respectively. When optimized with J_2, the eigenvalues are restricted within a D-shaped area as shown shaded in Figure 6. The optimization purpose is minimizing the objective function bounded to following constraints.

minimize J subject to:

$$K^{\min} \le K \le K^{\max}$$
$$T_1^{\min} \le T_1 \le T_1^{\max}, T_2^{\min} \le T_2 \le T_2^{\max} \quad (10)$$
$$T_3^{\min} \le T_3 \le T_3^{\max}, T_4^{\min} \le T_4 \le T_4^{\max}$$

The PSO algorithm searches for an optimal or near optimal set of controller parameters, with typical ranges are [0.01-100] for K and [0.01-1] for T_1, T_2, T_3 and T_4 of the optimized parameters. To evaluate optimization of the J_1 and J_2 objective functions, the non-linear time domain simulation of the power system is carried out for the simulation period 10 seconds. In this work, the value of N_P is 4 corresponding to the considered cases as follows:

- Base case: P=0.75 pu, Q=0.1 pu, X_{L1}=0.4 pu and φ=100^o (Nominal loading)
- Case 1: P=1.2 pu, Q=0.25 pu, X_{L1}=0.4 pu and φ=100^o (Heavy loading)
- Case 2: P=0.25 pu, Q=0.02 pu, X_{L1}=0.4 pu and φ=100^o (Light loading)
- Case 3: P=0.75 pu, Q=0.10 pu, X_{L1}=0.5 pu and φ=80^o

The P, Q and X_L values are in the per-unit system. In order to acquire better performance, number of particle, particle size, number of iteration, c_1, c_2 and c is chosen as 40, 5, 150, 2, 2 and 1, respectively.

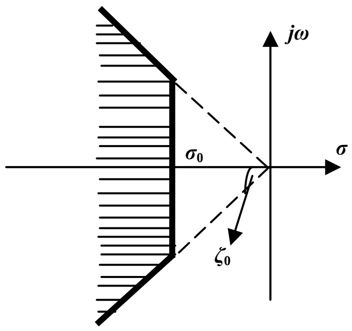


Figure 6. D-shaped optimization area with J_2

The final values of the optimized parameters with both objective functions, J_1 and J_2, are given in Table. 1. The electromechanical modes and the damping ratios obtained for all operating conditions both with and without proposed controllers in the system are given in Tables 2. When GCSC is not installed, it can be seen that some of the modes are poorly damped. It is also clear that the system damping with the proposed J_2 based tuned GCSC controller are significantly better damped. The comparison between J_1 and J_2 convergence ratios is represented in Figure 7. It is shown that J_2 converges to a minor fitness value.

Table 1. Optimized parameters of proposed controllers

Controller Parameters	K_p	T_1	T_2	T_3	T_4
J_1	124.0967	0.8632	0.4143	0.8198	0.5072
J_2	189.2114	0.0110	0.1437	0.6123	0.5124

VI. SIMULATION RESULTS

A. Description the Considered Scenario

To assess robustness and effectiveness of the proposed controllers and the coordinated design approach, a severe disturbance is considered for different loading conditions; that is, a 6-cycle, three-phase fault is occurred at $t=1$ sec at the middle of the one transmission lines. The fault is cleared with a permanent line tripping.

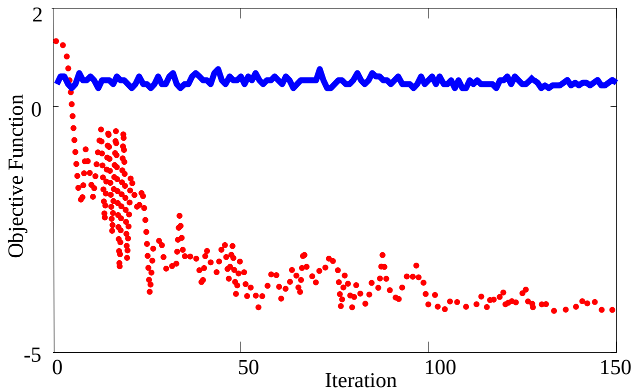


Figure 7. The objective function convergence ratios with the iterations: Solid (J_1) and Dotted (J_2)

In order to verify the robustness of proposed PSO optimized GCSC-based damping controller, the results of the performed non-linear time-domain simulation, the deviations of GCSC reactance (ΔX_{GCSC}) and the terminal voltage (ΔV_t) and the rotor speed signals ($\Delta\omega$) are illustrated in Figures 8-10.

B. Performance Index assessment

To demonstrate the effectiveness of the proposed approach, the Integral Time multipled Square value of Error ($ITSE$) based on the speed deviations of the system response is defined as:

$$ITSE = 100 \int_0^{tsim} t\left(\left|\Delta\omega_i\right|^2 + \left|\Delta V_{ti}\right|^2 + \left|\Delta X_{GCSC}\right|^2\right)dt \quad (11)$$

where, the speed deviations of the machine are represented by $\Delta\omega$. It is worth mentioning that the lower the value of $ITSE$ index is the better the system response in terms of time-domain characteristics. To investigate the effect of changing capacitance and the hold-off angle of GCSC. Some variations in the capacitor and the hold-off angle are assumed and the corresponding $ITSE$ index is measured. Numerical results of the performance robustness for all system loading cases and corresponding to system parameters are represented in Figure 11. It can be seen that J_2 objective function has better performance in damping power system and enhancing the dynamic stability. This demonstrates that the overshoot, undershoot, settling time and speed deviations of the machine are greatly reduced by applying the proposed J_2 objective function.

Table 2. The electromechanical modes and the damping ratios obtained for all operating conditions both with and without proposed controllers

Operating Cases	Nominal Loading	Heavy Loading (Case 1)	Light Loading (Case 2)	Case 3
Without Controller	**-0.1193±3.5007i, 0.03** -83.0271, -17.7917	**-0.3309±4.0044i, 0.08** -80.6929, -19.6956	**-0.2595±1.5085i, 0.17** -85.2953, -15.2217	**-0.3034±2.2172i, 0.13** -79.5972, -20.6968
J_1	**-0.8216±2.3077i, 0.33** -81.9182, -20.5798, -1.7232, -4.3342	**-0.9242±2.6767i, 0.32** -79.0072, -26.5340, -3.4917, -1.7577	**-0.3769±0.9655i, 0.36** -85.5589, -15.2506, -5.6350, -1.5995	**-0.5801±1.9902i, 0.27** -79.5017, -21.6447, -3.4467,-1.7471
J_2	**-2.8583±0.3779i, 0.99** **-2.2246±3.7337i, 0.51** -82.2858, -17.8003	**-2.1514±3.5724i, 0.51** -80.5471, -17.5435, -5.8041, -2.2024	**-2.0707±0.3875i, 0.88** **-3.8122±3.2774i, 0.75** -85.5903, -14.8233	**-2.7639±1.4623i, 0.88** **-2.3646±1.9241i, 0.77** -79.8535, -19.9301

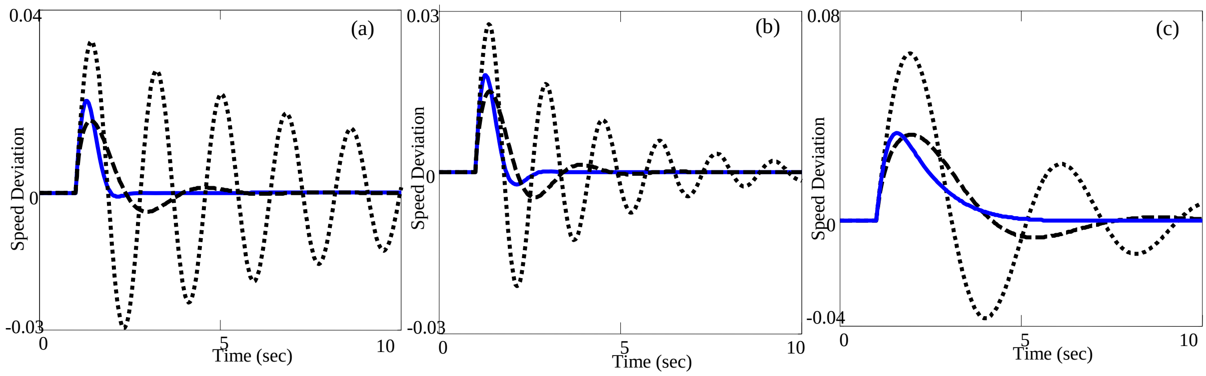


Figure 8. Dynamic response of Speed Deviation: (a) Nominal, (b) Heavy, (c) Light loading conditions within Solid (J_2), Dashed (J_1) and Dotted (without control)

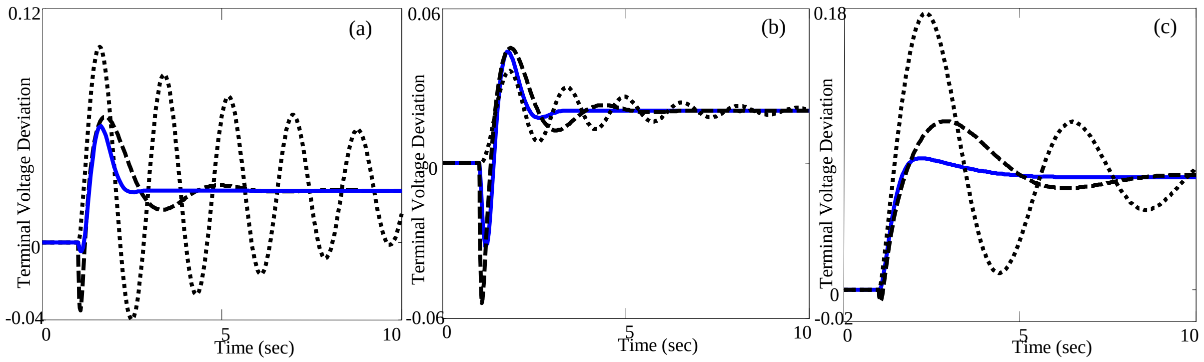


Figure 9. Dynamic response of Terminal Voltage Deviation: (a) Nominal, (b) Heavy, (c) Light loading conditions within Solid (J_2), Dashed (J_1) and Dotted (without control)

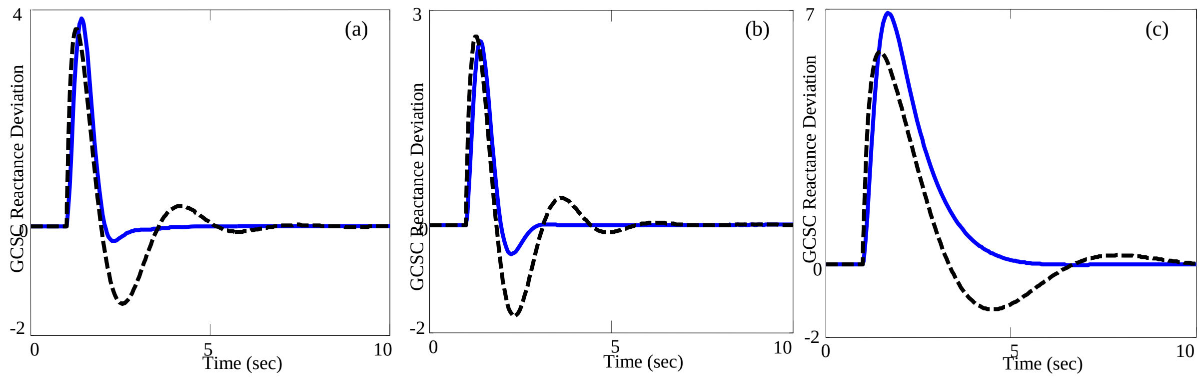
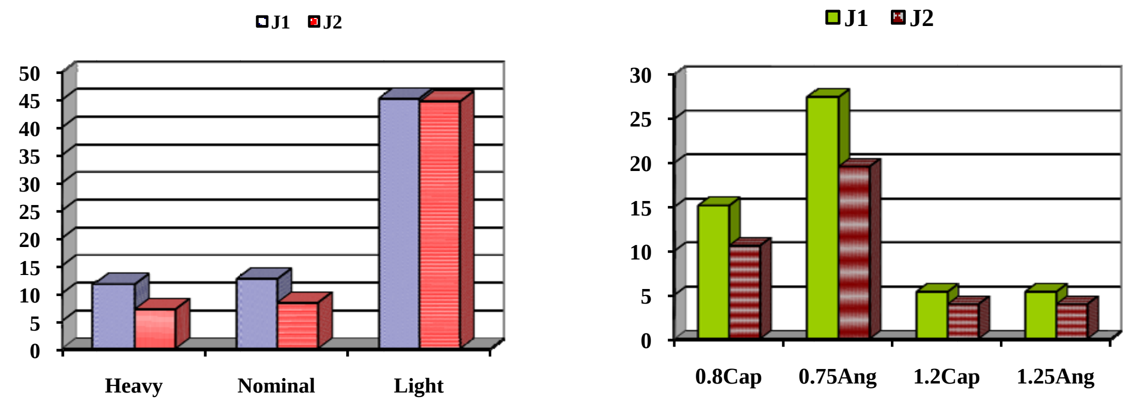


Figure 10. Dynamic response of GCSC Reactance Deviation: (a) Nominal, (b) Heavy, (c) Light loading conditions within Solid (J_2), Dashed (J_1)



(a) (b)

Figure 11. *ITSE* performance index values in: (a) Loading conditions, (b) changing the system parameters (Capacitor and Hold off Angle)

VII. CONCLUSIONS

In this paper, the PSO-based design of a GCSC damping controller is investigated. Parameters of the proposed controllers are well optimized using two different objective functions. The ITAE objective as the time-domain based fitness is compared to an eigenvalue based fitness which shifts the undamped electromechanical modes of the single machine power system to a D-shaped area in the s-plane. Various operating conditions and a severe disturbance is employed to reveal the efficiency of the proposed controllers. Assessment the time domain simulation results and analyzing the shifted eigenvalues and their verification through the '*ITSE*' performance index, supported the robustness of the designed damping controllers and show the superior performance of the eigenvalue based objective function in enhancing the dynamic stability of the power system.

APPENDIX

The Nominal Parameters of the System

Generator: M = 8 MJ/MVA, D = 0

T_d' = 5.044 s, X_d = 1 p.u., X_q = 0.6 p.u., X_d' = 0.3 p.u.

Excitation system: K_a = 100, T_a = 0.01 s

Transformer: X_t = 0.4 p.u.

Transmission lines: X_L = 0.4 p.u.

Operational conditions: P = 0.7 p.u., V_b = 1 p.u., V_t=1 p.u.

GCSC parameters: X_C = 0.4 X_L, φ_0=100^o, T_s =0.05, K_s =1

NOMENCLATURES

E'_q: Internal voltage behind transient reactance
FACTS: Flexible AC Transmission System
GTO: Gate Turn-Off
GCSC: Gate-Controlled Series Capacitor
IGBT: Insulated Gate Bipolar Thyristor
IGCT: Integrated Gate Commutated Thyristor
ITAE: Integral of the Time multiplied Absolute value of the Error
ITSE: Integral of the Time multiplied Square value of the Error
K: Proportional gain of the controller
LFO: Low Frequency Oscillation
P_e: Active power
P_m: Mechanical input power
POD: Power Oscillation Damping
PSO: Particle Swarm Optimization
SMIB: Single Machine Infinite Bus
SSSC: Static Synchronous Series Compensator
SSR: Sub-Synchronous Resonance
T_1: Lead time constant of controller
T_2: Lag time constant of controller
T_3: Lead time constant of controller
T_4: Lag time constant of controller
T_e: Electric torque
T_s: Settling time of speed deviation
T_w: Washout time constant
TCR: Thyristor Controlled Reactor
TCSC: Thyristor Controlled Series Capacitor
TSSC: Thyristor Switched Series Capacitor
T'_{do}: Time constant of excitation circuit
V_b: Voltage of infinite bus
V_{ref}: Reference voltage
V_t: Terminal voltage
δ: Rotor angle
γ: Blocking angle
φ: Hold off angle
ω: Rotor speed

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