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DAMPING OF POWER SWING BY A SSSC BASED POWER SYSTEM STABILIZERS BASED ON HYBRID PSO AND GSA ALGORITHM

H.R. Najafi M. Ebadian R. Ghanizadeh

Department of Electrical and Computer Engineering, University of Birjand, Birjand, Iran
h.r.najafi@birjand.ac.ir, mebadian@birjand.ac.ir, r_ghanizadeh@birjand.ac.ir

Abstract- In this paper, designing and application of an optimal supplementary controller for damping of power swing in a weakly connected power system. The proposed stabilizer is a SSSC based controller that is designed based on a hybrid PSO and GSA algorithm. The behavior of proposed controller under different loading operating conditions is also investigated. The effectiveness of proposed controller on enhancing dynamic stability is tested through modal analysis and time domain simulation. Also, nonlinear and electrical simulation results show the validity and effectiveness of the proposed control schemes over a wide range of loading conditions. It is also observed that the proposed SSSC based damping stabilizers greatly enhance the power system transient stability. The simulation results of coordinated design of stabilizer based on ψ and m is also presented and discussed. The system performance analysis under different operating conditions shows that the ψ-based controller is superior to the m-based controller.

Keywords: Power System Dynamic Stability, SSSC, PSOGSA.

I. INTRODUCTION

The main priorities in a power system operation are its security and stability, so a control system should maintain its frequency and voltage at a fixed level, against any kind of disturbance such as a sudden increase in load, a generator being out of circuit, or failure of a transmission line because of factors such as human faults, technical defects of equipment, natural disasters, etc. Due to the new legislation of electricity market, this situation creates doubled stress for beneficiaries [1-2]. Low frequency oscillations that are in the range of 0.2 to 3 Hz are created by the development of large power systems and their connection. These oscillations continue to exist in the system for a long time and if not well-damped, the amplitudes of these oscillations increase and bring about isolation and instability of the system [3]. Using a Power System Stabilizer (PSS) is technically and economically appropriate for damping oscillations and increasing the stability of power system. Therefore, various methods have been proposed for designing these stabilizers [4-6].

However, these stabilizers cause the power factor to become leading and therefore they have a major disadvantage which leads to loss of stability caused by large disturbances, particularly a three phase fault at the generator terminals [7]. In recent years, using Flexible Alternating Current Transmission Systems (FACTS) has been proposed as one of the effective methods for improving system controllability and limitations of power transfer. By modeling bus voltage and phase shift between buses and reactance of transmission line, FACTS controllers can cause increment in power transfer in steady state. These controllers are added to a power system for controlling normal steady state but because of their rapid response, they can also be used for improving power system stability through damping the low frequency oscillation [1-4], [7-9].

Static Synchronous Series Compensator (SSSC) is one of the important members of FACTS family which can be installed in series in the transmission lines. The SSSC is able to effectively control the power flow in power system. The reason for this effectiveness lies in its capability to change its reactance characteristic from capacitive to inductive, and vice versa [10]. Also, in order to improve the dynamic stability of power system, an auxiliary stabilizing signal can be added to the power flow control function of the SSSC [12]. In several references [10-13] the SSSC is used to stabilize frequency, enhance stability and damp power oscillation. In some other papers [13-14], the effect of compensation degree and operation mode of SSSC on small disturbance and transient stability is reported. Most of the proposals made in these papers are based on small disturbance analysis therefore it is necessary to linearize the system involved. Nevertheless, complex dynamics of the system cannot be fully captured by linear approaches especially during major disturbances. This brings about difficulties in tuning the FACTS controllers because an acceptable performance in large disturbances cannot be guaranteed by controllers tuned to provide desired performance at small signal condition. Therefore, because of its easy online tuning and also lack of assurance of the stability by some adaptive or variable structure techniques, a conventional lead/lag controller structure is usually preferred by the power system utilities.

The tuning problem of FACTS controller parameters is a complex issue. So far, various conventional approaches have been reported in the literature which considers the design problems of conventional power system stabilizers. These methods include: the eigenvalue assignment, mathematical programming, gradient procedure for optimization and also the modern control theory. Unfortunately, due to their iterative nature, conventional methods are time-consuming, require heavy computational burden and show slow convergence. Furthermore, the search process is susceptible to get stuck in local minima and consequently the solution obtained may not be optimal [15].

In this paper, singular value decomposition (SVD) is used to select the control signal which is most suitable for damping the electromechanical (EM) mode oscillations. A single machine infinite bus (SMIB) power system equipped with a SSSC controller is used in this study. Also the damping controllers design is formulated as an optimization problem to be solved using PSOGSA. The effectiveness of the proposed controller is demonstrated through eigenvalue analysis, nonlinear time simulation studies and some performance indices to damp low frequency oscillations under different operating conditions. Results show that the proposed PSOGSA based tuned damping controller achieves good robust performance for a wide range of operating conditions.

II. PROPOSED ALGORITHMS

A. Particle Swarm Optimization (PSO)

PSO is an evolutionary computation technique which is proposed by Kennedy and Eberhart [16]. The PSO was inspired by the social behavior of bird flocking. It uses a number of particles (candidate solutions) which fly around in the search space to find the best solution. Meanwhile, the particles all look at the best particle (best solution) in their paths. In other words, particles consider their own best solutions as well as the best solution found so far.

Each particle in PSO should consider the current position, the current velocity, the distance to *pbest*, and the distance to *gbest* in order to modify its position. PSO was mathematically modeled as follows:

$$v_i^{t+1} = w \times v_i^t + c_1 \times \text{rand} \times (pbest_i - x_i^t) + \\ + c_2 \times \text{rand} \times (gbest_i - x_i^t) \tag{1}$$

$$x_i^{t+1} = x_i^t + v_i^{t+1} \tag{2}$$

where v^t_i is the velocity of particle i at iteration t, w is a weighting function, c_j is an acceleration coefficient, rand is a random number between 0 and 1, x^t_i is the current position of particle i at iteration t, $pbest_i$ is the *pbest* of agent i at iteration t, and *gbest* is the best solution so far. The first part of (1), wv^t_i, provides exploration ability for PSO. The second and third parts, $c_1\times\text{rand}\times(pbest_i - x^t_i)$ and $c_2\times\text{rand}\times(gbest - x^t_i)$, represent private thinking and collaboration of particles respectively. The PSO starts by randomly placing the particles in a problem space. In each iteration, the velocities of particles are calculated using (1). After defining the velocities, the positions of particles can be calculated as (2). The process of changing particles' positions will continue until an end criterion is met.

B. Gravitational Search Algorithm (GSA)

In 2009, Rashedi et al. [17] proposed a new heuristic optimization algorithm called the Gravitational Search Algorithm (GSA) for finding the best solution in problem search spaces using physical rules. The basic physical theory from which GSA is inspired is Newton theory, which says: "Every particle in the universe attracts every other particle with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them". GSA can be considered as a collection of agents (candidate solutions) which have masses proportional to their value of fitness function. During generations all masses attract each other by the gravity forces between them. The heavier of the mass, has the bigger the attraction force. Therefore, the heaviest masses which are probably close to the global minimum attract the other masses in proportion to their distances.

According to [17-18], suppose there is a system with N agents. The position of each agent (masses) which is a candidate solution for the problem is defined as follows:

$$X_i = (x_i^1, \ldots\ldots, x_i^d, \ldots\ldots x_i^n) \quad \text{for } i = 1,2,\ldots N \tag{3}$$

where n is the dimension of the problem and x^d_i is the position of the ith agent in the dth dimension.

The algorithm starts by randomly placing all agents in a search space. During all epochs, the gravitational forces from agent j on agent i at a specific time t are defined as follows:

$$F_{ij}^d = G(t) \frac{M_{pi}(t) M_{aj}(t)}{R_{ij}(t) + \varepsilon} (x_j^d(t) - x_i^d(t)) \tag{4}$$

where M_{aj} is the active gravitational mass related to agent j, M_{pi} is the passive gravitational mass related to agent i, $G(t)$ is the gravitational constant at time t, ε is small constant and $R_{ij}(t)$ is the Euclidian distance between two agents i and j.

The gravitational constant G and the Euclidian distance between two agents i and j are calculated as follows:

$$G(t) = G_0 \times \exp(-\alpha \times iter/\ maxiter) \tag{5}$$

$$R_{ij}(t) = \left\| x_i(t), x_j(t) \right\|_2 \tag{6}$$

where α is the descending coefficient, G_0 is the initial gravitational constant, *iter* is the current iteration, and *maxiter* is the maximum number of iterations. In a problem space with the dimension d, the total force that acts on agent i is calculated by the following equation:

$$F_i^d(t) = \sum_{j=1, j \neq i}^{N} \text{rand}_j F_{ij}^d(t) \tag{7}$$

where rand_j is a random number in the interval [0,1]. According to the law of motion, the acceleration of an agent is proportional to the resultant force and inverse of its mass, so the accelerations of all agents are calculated as follows:

$$a_i^d(t) = \frac{F_i^d(t)}{M_{ii}(t)} \tag{8}$$

where d is the dimension of the problem, t is a specific time, and M_i is the mass of object i.

The velocity and position of agents are calculated as follows:

$$v_i^d(t+1) = \text{rand}_i \times v_i^d(t) + a_i^d(t) \tag{9}$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \tag{10}$$

where d is the problem dimension and rand_i is a random number in the interval [0,1].

As can be inferred from (9) and (10), the current velocity of an agent is defined as a fraction of its last velocity ($0 \le \text{rand}_i \le 1$) added to its acceleration. Furthermore, the current position of an agent is equal to its last position added to its current velocity.

Agents' masses are defined using fitness evaluation. This means that an agent with the heaviest mass is the most efficient agent. According to the above equations, the heavier of the agent, has the higher the attraction force and the slower the movement. The higher attraction is based on the law of gravity (4), and the slower movement is because of the law of motion (8) [17].

The masses of all agents are updated using the following equations:

$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \tag{11}$$

where $fit_i(t)$ represents the fitness value of the agent i at time t, $best(t)$ is the strongest agent at time t, and $worst(t)$ is the weakest agent at time t.

The $best(t)$ and $worst(t)$ for a minimization problem are calculated as follows:

$$best(t) = \min_{j \in \{1..N\}} fit_j(t) \tag{12}$$

$$worst(t) = \max_{j \in \{1..N\}} fit_j(t) \tag{13}$$

The $best(t)$ and $worst(t)$ for a maximization problem are calculated as follows:

$$best(t) = \max_{j \in \{1..N\}} fit_j(t) \tag{14}$$

$$worst(t) = \min_{j \in \{1..N\}} fit_j(t) \tag{15}$$

The normalization of the calculated masses (11) is defined by the following equation:

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_j(t)} \tag{16}$$

In the GSA, at first all agents are initialized with random values. Each agent is a candidate solution. After initialization, the velocity and position of all agents will be defined using (9) and (10). Meanwhile, the other parameters such as the gravitational constant and masses will be calculated by (5) and (11). Finally, the GSA will be stopped by meeting an end criterion. The steps of GSA are represented in Figure 1.

In all population-based algorithms which have social behavior like PSO and GSA, two intrinsic characteristics should be considered: the ability of the algorithm to explore whole parts of search spaces and its ability to exploit the best solution. Searching through the whole problem space is called exploration whereas converging to the best solution near a good solution is called exploitation. A population-based algorithm should have these two vital characteristics to guarantee finding the best solution. In PSO, the exploration ability has been implemented using *pbest* and the exploitation ability has been implemented using *gbest*. In GSA, by choosing proper values for the random parameters (G_0 and α), the exploration can be guaranteed and slow movement of heavier agents can guarantee exploitation ability [17, 19].

Rashedi et al. [17] provided a comparative study between gsa and some well-known heuristic optimization algorithms like PSO. The results proved that GSA has merit in the field of optimization. However, GSA suffers from slow searching speed in the last iterations [20]. In this paper a hybrid of this algorithm with PSO, called PSOGSA, is proposed in order to improve this weakness.

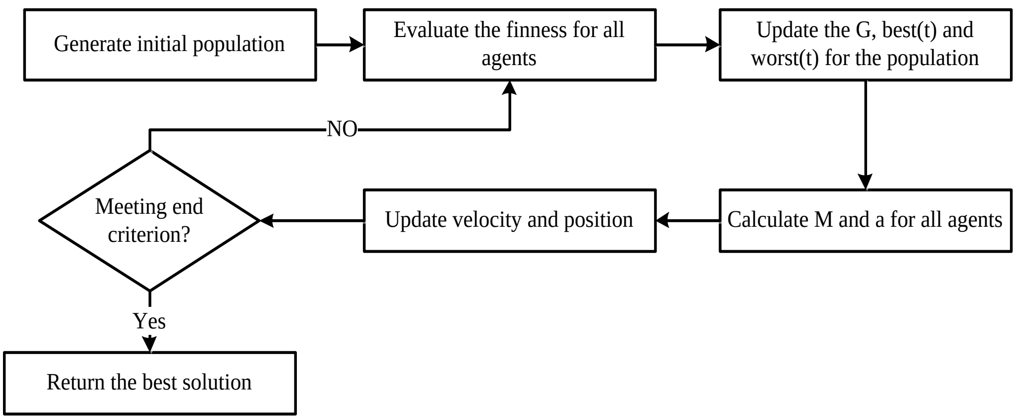

Figure 1. General steps of the gravitational search algorithm [17]

C. The Hybrid PSOGSA Algorithm

The basic idea of PSOGSA is to combine the ability for social thinking (*gbest*) in PSO with the local search capability of GSA. In order to combine these algorithms, (17) is proposed as follows:

$$v_i(t+1) = w \times v_i(t) + c_1' \times \text{rand} \times ac_i(t) + \\ + c_2' \times \text{rand} \times (gbest_i - x_i^t) \tag{17}$$

where $v_i(t)$ is the velocity of agent i at iteration t ; c'_j is an acceleration coefficient, w is a weighting function, rand is a random number between 0 and 1, $ac_i(t)$ is the acceleration of agent i at iterationt, and *gbest* is the best solution so far. In each iteration, the positions of agents are updated as follows:

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{18}$$

In PSOGSA, at first, all agents are randomly initialized. Each agent is considered as a candidate solution. After initialization, the gravitational force, gravitational constant, and resultant forces among agents are calculated using (4), (5) and (7), respectively. After that, the accelerations of particles are defined as (8). In each iteration, the best solution so far should be updated. After calculating the accelerations and updating the best solution so far, the velocities of all agents can be calculated using (17). Finally, the positions of agents are updated by (18). The process of updating velocities and positions will be stopped by meeting an end criterion. The steps of PSOGSA are represented in Figure 2.

To see how PSOGSA is efficient, the following remarks are noted:

- In PSOGSA, the quality of solutions (fitness) is considered in the updating procedure.
- The agents near good solutions try to attract the other agents which are exploring different parts of the search space.
- When all agents are near a good solution, they move very slowly. In this case, *gbest* helps them to exploit the global best.
- PSOGSA uses a memory (*gbest*) to save the best solution found so far, so it is accessible at any time.
- Each agent can observe the best solution (*gbest*) and tend toward it.
- By adjusting c'_1 and c'_2, the abilities of global searching and local searching can be balanced.

The above-mentioned remarks make PSOGSA powerful enough to solve a wide range of optimization problems [21].

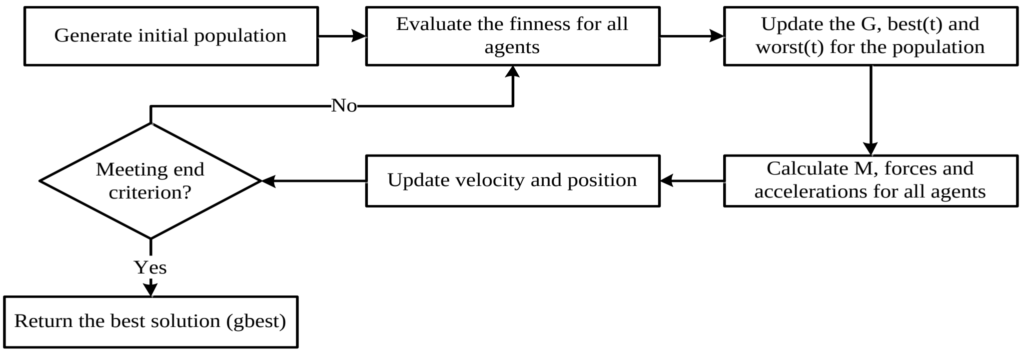

Figure 2. Steps of PSOGSA [21]

III. POWER SYSTEM MODEL

A single-machine infinite-bus (SMIB) power system equipped with SSSC is investigated, as shown in Figure 3 [9]. The SSSC consists of a boosting transformer with a leakage reactance x_{SCT}, a three-phase GTO based voltage source converter (VSC), and a DC capacitor (C_{DC}). The two input control signals to the SSSC are m and ψ. Signal m is the amplitude modulation ratio of the pulse width modulation (PWM) based VSC. Also, signal ψ is the phase of the injected voltage and is kept in quadrature with the line current (inverter losses are ignored). Therefore, the compensation level of the SSSC can be controlled dynamically by changing the magnitude of the injected voltage. Hence, if the SSSC is equipped with a damping controller, it can be effective in improving power system dynamic stability.

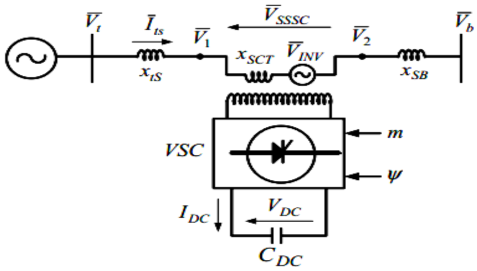

Figure 3. SMIB power system with SSSC

A. Nonlinear Model of Power System Implemented with SSSC

The dynamic model of the SSSC is required in order to study the effect of the SSSC for enhancing the small signal stability of the power system. The system data is given in Appendix. By applying Park's transformation and neglecting the resistance and transients of the transformer, the SSSC can be modeled as [12]:

$$\bar{I}_{ts} = I_{tsd} + jI_{tsq} = I_{ts}\angle\varphi \tag{19}$$

$$\begin{aligned} \bar{V}_{INV} &= mkV_{DC}(\cos\psi + j\sin\psi) = mkV_{DC}\angle\psi \\ \psi &= \varphi \pm 90^\circ \end{aligned} \tag{20}$$

$$\dot{V}_{DC} = \frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} = \frac{mk}{C_{DC}}(I_{tsd}\cos\psi + I_{tsq}\sin\psi) \tag{21}$$

where k is the ratio between AC and DC voltage of SSSC voltage source inverter.

And so:

$$I_{tsq} = \frac{V_B\sin\delta + mkV_{DC}\cos\psi}{X_{ts} + X_{SB} + X_{SCT} + X_q} \tag{22}$$

$$I_{tsd} = \frac{E'_q - V_B\cos\delta - mkV_{DC}\sin\psi}{X_{ts} + X_{SB} + X_{SCT} + X'_d} \tag{23}$$

The nonlinear dynamic model of the power system of Figure 3 is [9]:

$$\dot{\delta} = \omega_b(\omega - 1) \tag{24}$$

$$\dot{\omega} = \frac{1}{M}(P_m - P_e - D\omega) \tag{25}$$

$$\dot{E}'_q = \frac{1}{T'_{do}}(E_{fd} - E_q) \tag{26}$$

$$\dot{E}_{fd} = -\frac{1}{T_A}E_{fd} + \frac{K_A}{T_A}(V_{ref} - V_t) \tag{27}$$

where:

$$P_e = E'_q I_{tsq} + (X_q - X'_d) I_{tsd} I_{tsq}$$

$$E_q = E'_q + (X_d - X'_d).I_{tsd}$$

$$V_t = \sqrt{(X_q I_{tsq})^2 + (E'_q - X'_d I_{tsd})^2}$$

B. Power System Linearized Model

By linearizing the SMIB system nonlinear differential equations including SSSC around the nominal operating point the following equations can be achieved:

$$\Delta\dot{\delta} = \omega_b \Delta\omega \tag{28}$$

$$\Delta\dot{\omega} = (-\Delta P_e - D\Delta\omega)/M \tag{29}$$

$$\Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \tag{30}$$

$$\Delta\dot{E}_{fd} = -\frac{1}{T_A}\Delta E_{fd} - \frac{K_A}{T_A}(\Delta V_t) \tag{31}$$

$$\Delta\dot{V}_{DC} = K_7\Delta\delta + K_8\Delta E'_q + K_9\Delta V_{DC} + +K_{dm}\Delta m + K_{d\psi}\Delta\psi \tag{32}$$

where:

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{pDC}\Delta V_{DC} + +K_{pm}\Delta m + K_{p\psi}\Delta\psi \tag{33}$$

$$\Delta E'_q = K_4\Delta\delta + K_3\Delta E'_q + K_{qDC}\Delta V_{DC} + +K_{qm}\Delta m + K_{q\psi}\Delta\psi \tag{34}$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E'_q + K_{vDC}\Delta V_{DC} + +K_{vm}\Delta m + K_{v\psi}\Delta\psi \tag{35}$$

where K_1, K_2, …, K_9, K_{pu}, K_{qu}, K_{du} and K_{vu} are linearization constants and are dependent on system parameters and the operating condition. The block diagram of the linearized dynamic model of the SMIB power system with SSSC is shown in Figure 4.

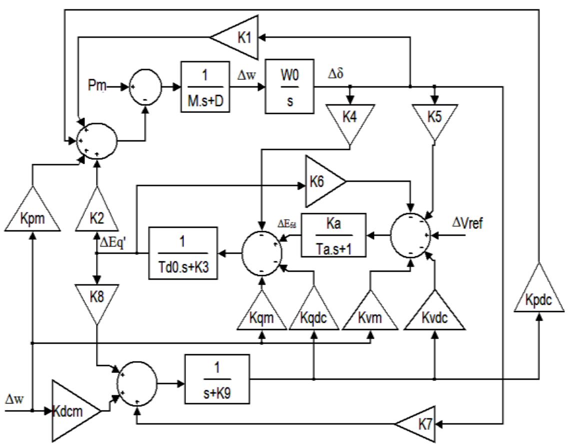

Figure 4. Modified Heffron-Phillips model of a SMIB system with SSSC

$$\dot{X} = Ax + Bu \tag{36}$$

$$A = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & -\frac{K_{pDC}}{M} \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & -\frac{1}{T'_{do}} & -\frac{K_{qDC}}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vDC}}{T_A} \\ K_7 & 0 & K_8 & 0 & K_9 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ -\frac{K_{pm}}{M} & -\frac{K_{p\psi}}{M} \\ -\frac{K_{qm}}{T'_{do}} & -\frac{K_{q\psi}}{T'_{do}} \\ -\frac{K_A K_{vm}}{T_A} & -\frac{K_A K_{v\psi}}{T_A} \\ K_{dm} & K_{d\psi} \end{bmatrix}$$

C. SSSC Based Damping Controller

The damping controller is designed to produce an electrical torque, according to the phase compensation method, in phase with the speed deviation. In order to produce the damping torque, the 2 control parameters of the SSSC (m and ψ) can be modulated. The speed deviation $\Delta\omega$ is chosen as the input to the damping controller. Figure 5 shows the structure of the SSSC based damping controller. This controller may be considered as a lead-lag compensator. However, an electrical torque in phase with the speed deviation is to be produced to improve the damping of the power system oscillations. It consists of a gain block, signal-washout block, and lead-lag compensator. The parameters of the damping controller are obtained using the PSOGSA technique.

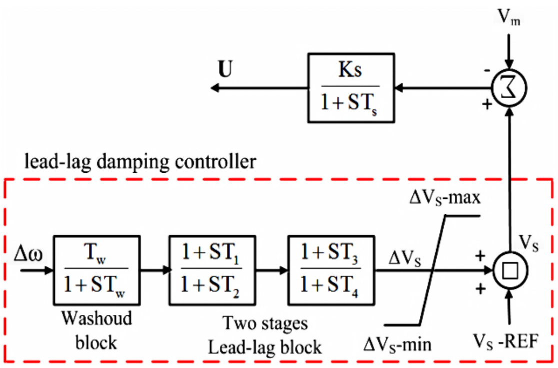

Figure 5. SSSC with lead-lag controller

IV. SSSC CONTROLLER DESIGN USING PSOGSA

In the proposed method, the SSSC controller parameters must be tuned optimally to improve overall system dynamic stability in a robust way. This study employs the PSOGSA to improve optimization synthesis and find the global optimum value of the fitness function in order to acquire an optimal combination. In this study, the PSOGSA module works offline. In other words, the parameters of the SSSC damping controller are tuned for different loading conditions and system parameter uncertainties based on Table 1, and then the obtained optimal parameters of the damping controller are applied to the time-domain simulation.

Table 1. Loading condition

Operating condition	P (pu)	Q (pu)	X_L (pu)
Normal	0.8	0.114	0.3
Light	0.2	0.01	0.3
Heavy	1.2	0.4	0.3
Case 4	The 30% increase of line reactance X_L at normal loading condition		
Case 5	The 30% increase of line reactance X_L at light loading condition		
Case 6	The 30% increase of line reactance X_L at heavy loading condition		

For our optimization problem, an integral time absolute error of the speed deviations is taken as the objective function J, expressed as:

$$J = \int_0^{t_1} |e(t)| \; t \; dt \quad (37)$$

where, 'e' is the error signal ($\Delta\omega$) and t_1 is the time range of simulation. The optimization problem design can be formulated as the constrained problem shown below, where the constraints are the controller parameters bounds.

$$\begin{aligned} &\text{minimize } J \\ &\text{subject to} \\ &K_{\min} \le K \le K_{\max} \\ &T_{1\min} \le T_1 \le T_{1\max},\ T_{2\min} \le T_2 \le T_{2\max} \\ &T_{3\min} \le T_3 \le T_{3\max},\ T_{4\min} \le T_4 \le T_{4\max} \end{aligned} \quad (38)$$

Typical ranges of the optimized parameters are [0-100] for K and [0.01-1] for T_1, T_2, T_3 and T_4. The mentioned approach employs the PSOGSA to solve this optimization problem and search for an optimal or near optimal set of controller parameters. It should be noted that PSOGSA algorithm is run several times and then optimal set of output feedback gains for the SSSC controllers is selected. The final values of the optimized parameters are given in Table 2. Figure 6 shows the illustration of cost versus iteration for both the m- and ψ-based controllers using the PSO, GSA and PSOGSA techniques.

Table 2. The optimal settings of the individual controller

Controller parameters	ψ controller			m controller		
	PSO	GSA	PSOGSA	PSO	GSA	PSOGSA
K	73.8019	62.6673	81.3002	84.3309	76.6433	83.9329
T_1	0.7008	0.3887	0.4363	0.9447	0.9347	0.8017
T_2	0.4822	0.7517	0.6890	0.1334	0.1201	0.3188
T_3	0.9978	0.1944	0.9257	0.3332	0.5180	0.8281
T_4	0.0669	0.0603	0.1119	0.0818	0.2554	0.0171

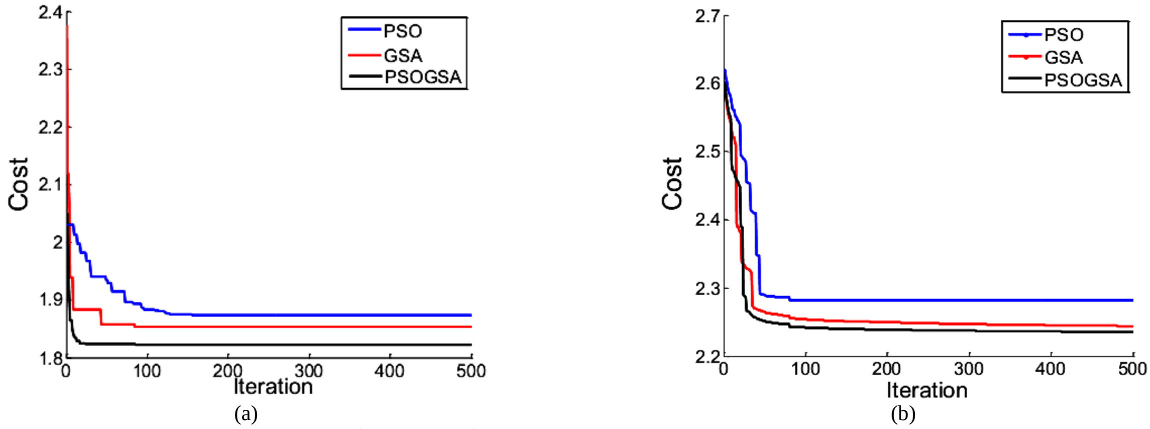

Figure. 6. The convergence for objective function minimization using PSO, GSA and PSOGSA techniques: (a) ψ-based controller, (b) m-based controller

V. SIMULATION RESULTS

In order to demonstrate the effectiveness and robustness of the proposed controller, against severe turbulence and the damping of oscillations caused by it, power system using the proposed model, is simulated in MATLAB software. To make sure that the obtained results are reliable, this simulation is evaluated with eigenvalue analysis method and time domain nonlinear simulation, which is shown as follows.

A. Eigenvalue Analysis

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 3 and 4. Given a complex eigenvalue, the damping ξ is defined as [5]:

$$\xi = -\frac{\sigma}{\sqrt{\sigma^2 + \mu^2}} \quad (40)$$

When SSSC is not installed, it can be seen that some of the modes are poorly damped and in some cases, are unstable (highlighted in Tables 3 and 4).

B. Nonlinear Time-Domain Simulation

The single-machine infinite-bus system shown in Figure 3 is considered for nonlinear simulation studies. The 6-cycle, 3-phase fault at t = 1 sec, on the infinite bus has occurred, at all loading conditions given in Table 1, to study the performance of the proposed controller. The speed deviation and electrical power deviation based on the ψ and m controller in all different loading conditions are shown in Figures 7 and 8. It can be seen that the PSOGSA based SSSC controller tuned using the objective function achieves good robust performance and provides superior damping.

From the above conducted tests, it can be concluded that ψ based damping controller is superior to the m based damping controller and enhance greatly the dynamic stability of power systems.

Table 3. Eigenvalues and damping ratios of electromechanical modes with and without ψ controller

Controller Loading Condition	without controller	PSO controller	GSA controller	PSOGSA Controller
Nominal loading condition Eigenvalue (damping ratio)	-9.18 ± 11.41i, (0.626) **0.0601 ± 4.107i, (-0.014)** -1.5215	-1.76 ± 4.123i, (0.3925) -2.94 ± 11.997i, (0.238) -33.63 ± 23.205i, (0.823) -1.72, -1.62,-107.87	-1.854 ± 4.53i, (0.378) -2.658 ± 11.76i, (0.220) -34.47 ± 25.35i, (0.805) -1.66, -1.34,-109.92	-2.43 ± 5.63i, (0.396) -2.12 ± 10.62i, (0.195) -35.89 ± 26.45i, (0.805) -1.89, -2.78,-109.78
Light loading condition Eigenvalue (damping ratio)	-9.671 ± 13.165i, (0.592) **0.121 ± 4.1758i, (-0.028)** -0.9890	-1.63 ± 5.015i, (0.3091) -4.765 ± 7.56i, (0.5332) -15.65 ± 17.761i, (0.661) -1.765, -1.641, -104.757	-1.55 ± 5.115i, (0.290) -4.615 ± 7.612i, (0.518) -14.34 ± 16.691i, (0.651) -1.635, -1.743, -105.82	-2.23 ± 4.99i, (0.408) -4.563 ± 7.43i, (0.523) -16.64 ± 17.54i, (0.688) -2.43, -3.41, -107.32
Heavy loading condition Eigenvalue (damping ratio)	-8.123 ± 10.77i, (0.602) **0.717 ± 5.211i, (-0.1363)** -1.1290	-1.52 ± 5.876i, (0.2504) -3.768 ± 8.25i, (0.4154) -92.63 ±19.23i, (0.979) -2.109,-16.643, -65.9657	-1.67 ± 5.899i, (0.272) -3.836 ± 8.342i, (0.417) -94.33 ±20.654i, (0.976) -2.22,-16.353, -64.11	-2.56 ± 6.33i, (0.374) -4.34 ± 7.452i, (0.503) -97.23 ±18.46i, (0.982) -2.12,-18.66, -70.81
Case 4 loading condition Eigenvalue (damping ratio)	-9.43 ± 12.32i, (0.607) **0.0531 ± 4.74i, (-0.011)** -1.221	-1.116 ± 4.221i, (0.255) -2.41 ± 11.117i, (0.211) -30.13 ± 20.515i, (0.826) -1.21, -1.12, -101.34	-1.231 ± 4.342i, (0.272) -2.44 ± 11.231i, (0.212) -31.43 ± 21.321i, (0.827) -1.33, -1.213, -100.52	-2.21 ± 4.412i, (0.447) -2.24 ± 11.13i, (0.197) -33.73 ± 23.78i, (0.817) -1.87, -1.19, -109.43
Case 5 loading condition Eigenvalue (damping ratio)	-9.121 ± 12.35i, (0.594) **0.23 ± 4.251i, (-0.054)** -0.933	-1.32 ± 5.154i, (0.248) -4.25 ± 7.123i, (0.512) -13.65 ± 15.361i, (0.664) -1.45, -1.431, -102.357	-1.44 ± 5.425i, (0.256) -4.657 ± 7.543i, (0.525) -14.76 ± 15.987i, (0.678) -1.41, -1.44, -104.33	-2.32 ± 6.112i, (0.354) -6.54 ± 6.65i, (0.701) -16.16 ± 15.47i, (0.722) -1.88, -1.46, -107.82
Case 6 loading condition Eigenvalue (damping ratio)	-8.313 ± 10.14i, (0.633) **0.691 ± 5.131i, (-0.133)** -1.329	-1.22 ± 5.776i, (0.206) -3.166 ± 7.65i, (0.382) -90.54 ±18.73i, (0.979) -2.11,-15.63, -60.887	-1.23 ± 5.778i, (0.208) -3.567 ± 7.89i, (0.411) -91.93 ±19.12i, (0.979) -2.10,-16.22, -58.89	-2.12 ± 5.66i, (0.350) -5.45 ± 7.112i, (0.608) -97.23 ±21.15i, (0.977) -2.76,-18.89, -66.43

Table 4. Eigenvalues and damping ratios of electromechanical modes with and without m controller

Controller Loding Condition	without controller	PSO controller	GSA controller	PSOGSA Controller
Nominal loading condition Eigenvalue (damping ratio)	-9.18 ± 11.41i, (0.626) **0.0601 ± 4.107i, (-0.014)** -1.5215	-1.21 ± 5.654i, (0.2092) -1.64 ± 7.897i, (0.2033) -21.35 ± 19.38i, (0.7404) -1.54, -2.748, -101.65	-1.32 ± 5.76i, (0.223) -1.66 ± 7.817i, (0.207) -21.95 ± 20.11i, (0.737) -1.59, -2.86, -102.15	-2.72 ± 6.16i, (0.403) -1.93 ± 7.88i, (0.237) -23.55 ± 22.34i, (0.725) -1.89, -5.46, -104.44
Light loading condition Eigenvalue (damping ratio)	-9.671 ± 13.165i, (0.592) **0.121 ± 4.1758i, (-0.028)** -0.9890	-1.68 ± 5.374i, (0.2983) -1.592 ± 7.104i, (0.2186) -14.79 ± 15.23i, (0.6966) -1.652, -3.873, -102.13	-1.77 ± 5.734i, (0.294) -1.91 ± 7.34i, (0.251) -15.19 ± 16.11i, (0.686) -1.43, -3.92, -101.32	-2.21 ± 5.334i, (0.382) -1.90 ± 7.31i, (0.251) -18.69 ± 16.54i, (0.748) -1.73, -4.97, -105.22
Heavy loading condition Eigenvalue (damping ratio)	-8.123 ± 10.77i, (0.602) **0.717 ± 5.211i, (-0.1363)** -1.1290	-1.076 ± 4.98i, (0.2111) -3.654 ± 8.89i, (0.3801) -90.11 ± 11.40i, (0.992) -1.18, - 3.754, -30.543	-1.66 ± 5.13i, (0.307) -3.45 ± 8.17i, (0.389) -90.67 ± 11.90i, (0.991) -1.69, - 3.44, -32.16	-2.44 ± 5.323i, (0.416) -5.58 ± 8.87i, (0.532) -90.65 ± 11.94i, (0.991) -1.54, - 4.84, -45.21
Case 4 loading condition Eigenvalue (damping ratio)	-9.43 ± 12.32i, (0.607) **0.0531 ± 4.74i, (-0.011)** -1.221	-1.13 ± 5.504i, (0.201) -1.44 ± 7.67i, (0.184) -20.55 ± 19.11i, (0.732) -1.14, -2.408, -100.15	-1.55 ± 6.41i, (0.235) -2.34 ± 8.87i, (0.255) -22.19 ± 20.51i, (0.734) -1.58, -3.481, -105.45	-1.99 ± 6.71i, (0.284) -2.64 ± 8.88i, (0.284) -28.23 ± 22.68i, (0.779) -1.88, -5.871, -107.25
Case 5 loading condition Eigenvalue (damping ratio)	-9.121 ± 12.35i, (0.594) **0.23 ± 4.251i, (-0.054)** -0.933	-1.47 ± 5.21i, (0.271) -1.33 ± 6.98i, (0.187) -14.99 ± 15.33i, (0.699) -1.89, -3.73, -101.15	-1.47 ± 5.21i, (0.271) -1.33 ± 6.98i, (0.187) -14.99 ± 15.33i, (0.699) -1.89, -3.73, -101.15	-2.37 ± 5.46i, (0.398) -1.99 ± 7.128i, (0.268) -20.63 ± 17.45i, (0.763) -1.77, -5.56, -105.35
Case 6 loading condition Eigenvalue (damping ratio)	-8.313 ± 10.14i, (0.633) **0.691 ± 5.131i, (-0.133)** -1.32	-1.172 ± 4.78i, (0.238) -3.127 ± 8.13i, (0.358) -91.43 ± 12.65i, (0.990) -1.32, - 3.55, -31.23	-1.56 ± 4.898i, (0.303) -3.97 ± 8.43i, (0.426) -94.55 ± 13.94i, (0.989) -1.53, - 3.42, -32.15	-2.35 ± 4.98i, (0.426) -4.37 ± 8.383i, (0.462) -98.65 ± 16.84i, (0.985) -1.66, - 6.62, -50.25

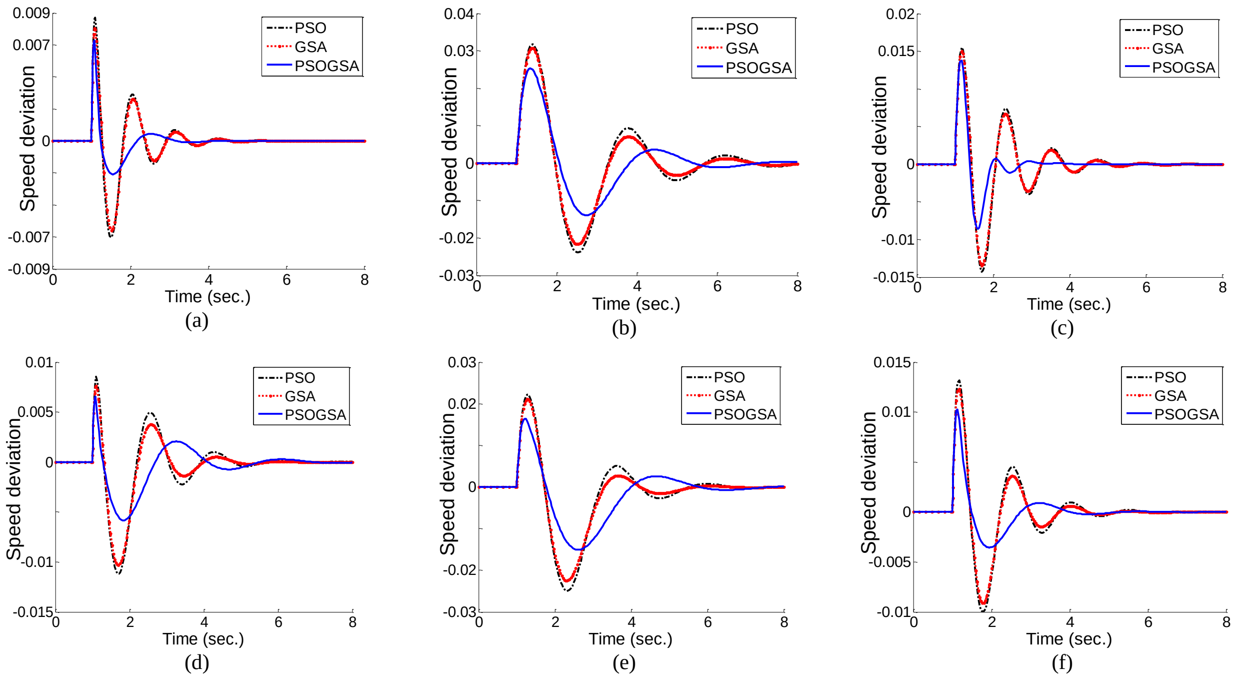

Figure 7. Dynamic responses for $\Delta\omega$, with ψ controller at: (a) normal, (b) light, (c) heavy, (d) case 4, (e) case 5, (f) case 6 loading conditions

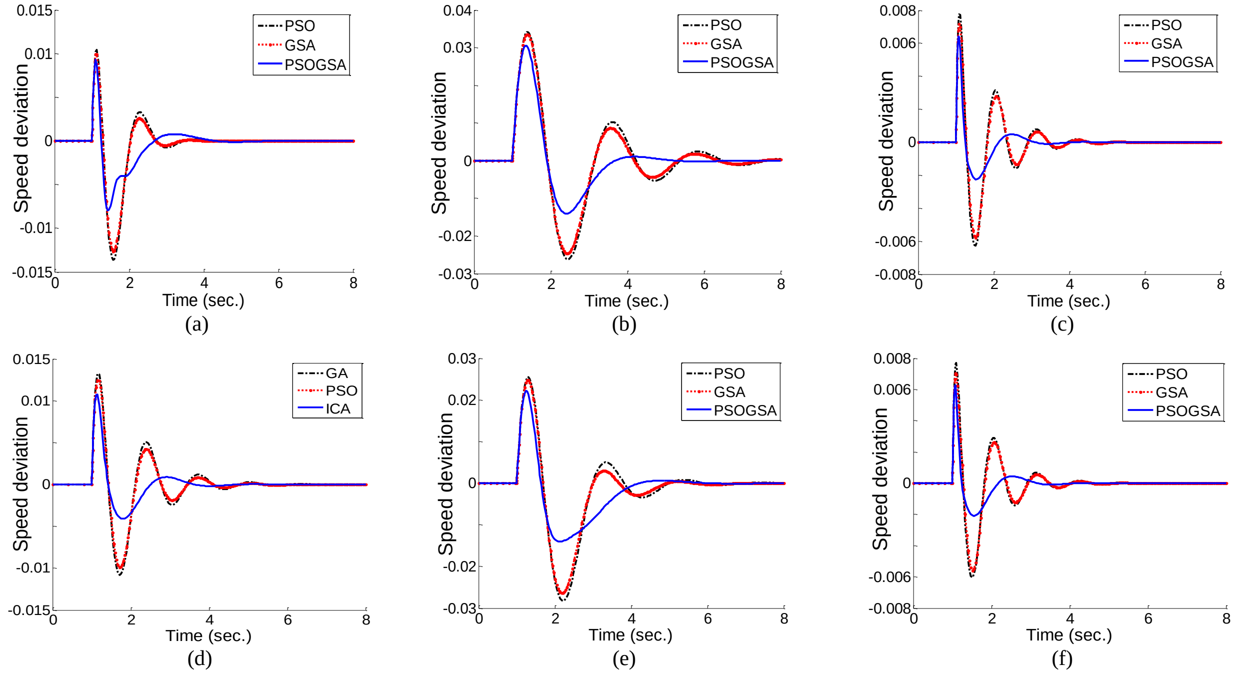

Fig. 8. Dynamic responses for $\Delta\omega$, with m controller at: (a) normal, (b) light, (c) heavy, (d) case 4, (e) case 5, (f) case 6 loading conditions

VI. CONCLUSIONS

In this paper, damping of low-frequency oscillation by using a SSSC controller was investigated. The stabilizer was tuned to simultaneously shift the undamped electromechanical modes of the machine to the left side of the s-plane. An objective problem comprising the damping ratio of the undamped electromechanical modes was formulated to optimize the controller parameters. The design problem of the controller was converted into an optimization problem, The PSOGSA optimization technique has been proposed to design the SSSC controllers individually ψ and m coordinately.

The PSO, GSA and PSOGSA have been utilized to search for the optimal controller parameter settings that optimize a damping ratio based objective function. The effectiveness of the proposed SSSC controller for damping of low-frequency oscillations in a power system were demonstrated by applying to a weakly connected power system subjected to a disturbance. The eigenvalue analysis and time-domain simulation results showed the effectiveness of the proposed controller in damping low-frequency oscillations. The system performance analyses under different operating conditions show that the ψ-based controller is superior to the m-based controller.

APPENDIX

The nominal parameters and operating condition of the system are listed in Table 4.

Table 4. System parameters

Generator	M =8 MJ/MVA X_q=0.6 pu	T'_{do}=5.044 X'_d=0.3 pu	X_d=1 pu D=4
Excitation system	K_A=80	T_A=0.05 s	
Transformers	X_T=0.1 pu	X_{SDT}=0.1 pu	
Transmission line	X_L=0.6 pu		
SSSC parameters	C_{DC}=0.25 T_S=0.05	V_{DC}=1 X_{SCT}=0.15	K_S=1.2

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BIOGRAPHIES

Hamidreza Najafi was born in Mashhad, Iran, on July 10, 1960. He obtained the B.Sc. and M.Sc. degrees from Mashhad University of Ferdowsi, Mashad, Iran in 1981 and 1991, respectively and the Ph.D. degree from Iran University of Science and Technology, Tehran, Iran in 2004. He has been a lecturer at Faculty of Engineering, University of Birjand, Birjand, Iran since 1993, and he works currently as an Assistant Professor in Electric Power Group at the same university. His special fields of interest include power system modeling, HVDC and FACTS, reliability of power system, stability control of power system, application of neural networks and fuzzy system in power system.

Mahmoud Ebadian received his B.Sc. degree in Electrical Engineering from Mashhad University of Ferdowsi, Mashhad, Iran, in 1991, the M.Sc. degree from Kh.N. Toosi University of Technology, Tehran, Iran, in 1996, and the Ph.D. degree from Moscow Power Engineering Institute, Moscow, Russia in 2006. His is an Associate Professor at Department of Power Engineering, University of Birjand, Birjand, South Khorasan, Iran. His areas of interest include voltage collapse, voltage stability and FACTS.

Reza Ghanizadeh was born in Mianeh, Iran, in 1987. He received Associated degree in Electrical Engineering from Tabriz College of Technology, Tabriz, Iran, in 2007, the B.Sc. degree in Electrical Engineering from Ardabil Branch, Islamic Azad University, Ardabil, Iran, in 2009, and the M.Sc. degree from University of Birjand, Birjand, Iran, in 2012. He is currently a Ph.D. student at Department of Power Engineering, University of Birjand. His research interests are power system stability, reactive power control in transmission and distribution systems, power quality studies and FACTS devices.