



A New Robust Control Design Based on Feedback Compensator for SSSC

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Abstract— *In this paper, the modified linearized Phillips-Heffron model is utilized to theoretically analyze a single-machine infinite-bus (SMIB) installed with SSSC. Then, the results of this analysis is used for assessing the potential of an SSSC supplementary controller to improve the dynamic stability of a power system. This is carried out by measuring the electromechanical controllability through singular value decomposition (SVD) analysis. This controller is tuned for simultaneously shifting the undamped electromechanical modes to a prespecified area in the s-plane. The issue of designing a robustly SSSC- based controller is considered and formulated as an optimization problem according to the eigenvalue-based multi-objective function consisting of the damping ratio of the undamped electromechanical modes and the damping factor. Next, considering its high capability to find the most optimistic results, the Gravitational Search Algorithm (GSA) is used to solve this optimization problem. A wide range of operating conditions are considered in design process of the proposed damping controller in order to guarantee the its robustness. The effectiveness of the proposed controller is demonstrated through eigenvalue analysis, controllability measure, nonlinear time-domain simulation and some performance indices studies. The results show that the tuned GSA based SSSC controller which is designed by using the proposed multi-objective function has an outstanding capability in damping power system low frequency oscillations, also it significantly improves the power systems dynamic stability.*

Keywords— *Power system dynamic stability, SSSC, Gravitational Search Algorithm*

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 equipments, 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].

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 verse[8]. Also, in order to improve the oscillation stability of power system, an auxiliary stabilizing signal can be added on the power flow control function of the SSSC [9]. In several references [8-10] the SSSC is used to stabilize frequency, enhance stability and damp power oscillation. In some other papers [11-12], 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 complex issue. So far, various conventional approaches have been reported in the literature which consider the to 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 [13].

In this paper, GSA technique is used for the optimal tuning of SSSC based damping controller in order to enhance the damping of power system low frequency oscillations and achieves the desired level of robust performance under different operating conditions.

II. GRAVITATIONAL SEARCH ALGORITHM

In 2009, Rashedi et al. [14] 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 the mass, 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 [14-15], 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:

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

where N is the dimension of the problem and x_i^d is the position of the i th agent in the d th 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:

$$(2)$$

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, $R_{ij}(t)$ 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:

$$G(t) = G_0 \times \exp(-\alpha \times \text{iter} / \text{maxiter}) \quad (3) \quad R_{ij}(t) = \|x_i(t), x_j(t)\|_2 \quad (4)$$

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:

$$F_i^d(t) = \sum_{j=1, j \neq i}^N \text{rand}_j F_{ij}^d(t) \quad (5)$$

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:

$$a_i^d(t) = \frac{F_i^d(t)}{M_{ii}(t)} \quad (6)$$

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:

$$v_i^d(t+1) = \text{rand}_i \times v_i^d(t) + a_i^d(t) \quad (7) \quad , \quad x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \quad (8)$$

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

As can be inferred from (7) and (8), the current velocity of an agent is defined as a fraction of its last velocity ($0 \leq \text{rand}_i \leq 1$) 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 the agent, the higher the attraction force and the slower the movement. The higher attraction is based on the law of gravity (2), and the slower movement is because of the law of motion (6) [14].

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

$$m_i(t) = \frac{\text{fit}_i(t) - \text{worst}(t)}{\text{best}(t) - \text{worst}(t)} \quad (9)$$

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

$$best(t) = \min_{j \in \{1..N\}} fit_j(t) \quad (10) \quad , \quad worst(t) = \max_{j \in \{1..N\}} fit_j(t) \quad (11)$$

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

$$best(t) = \max_{j \in \{1..N\}} fit_j(t) \quad (12) \quad , \quad worst(t) = \min_{j \in \{1..N\}} fit_j(t) \quad (13)$$

The normalization of the calculated masses (9) is defined by the following equation:

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^N m_j(t)} \quad (14)$$

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 (7) and (8). Meanwhile, other parameters such as the gravitational constant and masses will be calculated by (3) and (9). Finally, the GSA will be stopped by meeting an end criterion. The steps of GSA are represented in Fig. 1.

In all population-based algorithms which have social behaviour 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 the exploitation ability [14, 16].

Rashedi et al [14] 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 [17].

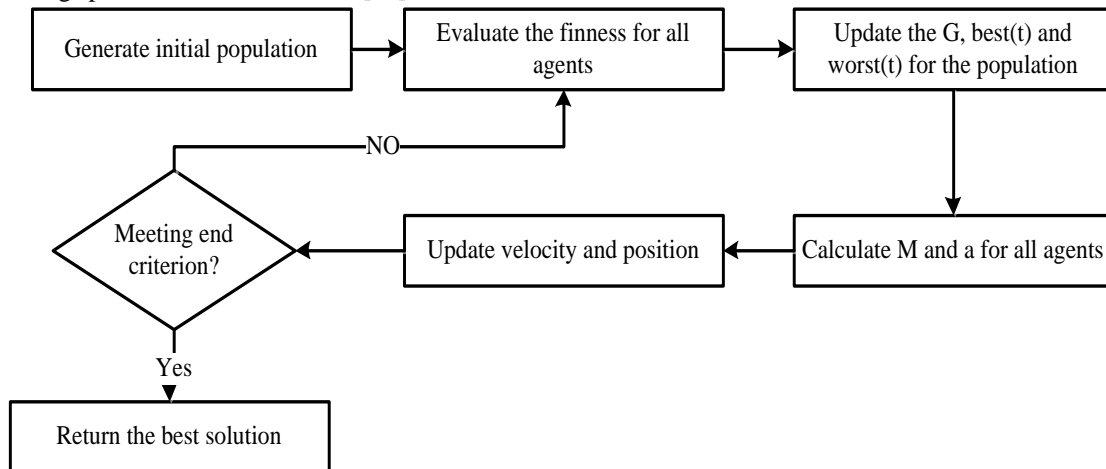


Fig.1 General steps of the gravitational search algorithm [14]

III. DYNAMIC MODEL OF SMIB POWER SYSTEM WITH SSSC

Fig. 2 shows a simple single-machine infinite-bus power system installed with a SSSC that has been chosen to investigate its dynamic modeling.

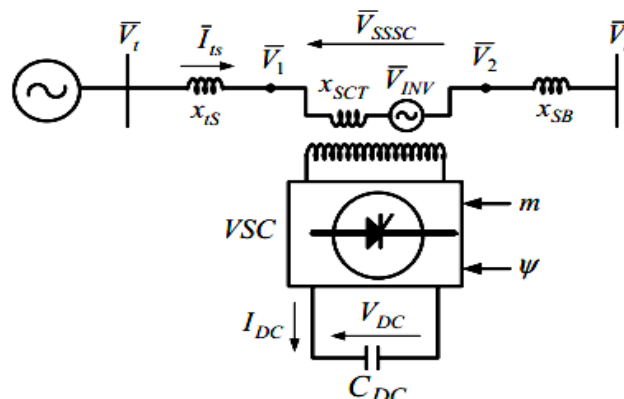


Fig. 2 SMIB power system equipped with SSSC

The SSSC consists of a, a three-phase voltage source converter (VINV), a boosting series coupling transformer with a leakage reactance of XSCT and a DC capacitor (CDC). Signal ψ is the phase of the injected voltage and is kept in quadrature with the line current (losses of are inverter has been ignored), and Signal m is the amplitude modulation ratio of the Pulse Width Modulation(PWM) based VSC, that determines the magnitude of the inserted voltage. If Pulse Width Modulation (PWM) waveform synthesis is used, PWM magnitude modulation ratio, m, can be the damping control signal to provide the dynamicvariation of SSSC compensation. Therefore if SSSC is equipped with a damping controller it can be effective in improving power system dynamic stability. In order to find the modified Heffron-Fillips model of selected power system, the dynamic model of SSSC to study power system stability is as follows [9]:

$$I_{TS} = I_{tsd} + jI_{tsq} = I_{TS} \angle \varphi \quad (15)$$

$$\overline{V}_{INV} = mkV_{DC} (\cos \psi + j \sin \psi) = mkV_{DC} \angle \psi \quad (16)$$

$$\psi = \varphi \pm 90^\circ$$

$$\dot{V}_{DC} = \frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} = \frac{mk}{C_{DC}} (I_{tsd} \cos \psi + I_{tsq} \sin \psi) \quad (17)$$

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

And so:

$$I_{tsq} = \frac{V_B \sin \delta + mkV_{DC} \cos \psi}{X_{ts} + X_{SB} + X_{SCT} + X_q} \quad (18)$$

$$I_{tsd} = \frac{E'q - V_B \cos \delta - mkV_{DC} \sin \psi}{X_{ts} + X_{SB} + X_{SCT} + X_d'} \quad (19)$$

It must be mentioned that this model of SSSC may not be valid for unsymmetrical conditions and transient events [8-9]. By linearizing the SMIB system nonlinear differential equations including SSSC around the nominal operating point the following equations can be achieved:

$$\Delta \dot{\delta} = \Delta \omega_s \omega \quad (20) \quad , \quad \Delta \dot{\omega} = (-\Delta P_e - \Delta D \omega) / M \quad (21)$$

$$\Delta \dot{E}'_q = (-\Delta E_q + \Delta E_{fd}) / T'_{do} \quad (22) \quad , \quad \Delta \dot{E}_{fd} = -\frac{1}{T_A} \Delta E_{fd} - \frac{K_A}{T_A} (\Delta V_i) \quad (23)$$

$$\Delta \dot{V}_{DC} = K_7 \Delta \delta + K_8 \Delta E'_q + K_9 \Delta V_{DC} + K_{dm} \Delta m \quad (24)$$

Where:

$$\Delta P_e = K_1 \Delta \delta + K_2 \Delta E'_q + K_{pDC} \Delta V_{DC} + K_{pm} \Delta m \quad (25)$$

$$\Delta E'_q = K_4 \Delta \delta + K_3 \Delta E'_q + K_{pDC} \Delta V_{DC} + K_{qm} \Delta m \quad (26)$$

$$\Delta V_i = K_5 \Delta \delta + K_6 \Delta E'_q + K_{vDC} \Delta V_{DC} + K_{vm} \Delta m \quad (27)$$

In order to calculating the Ki constants, first the equations (25 -27) must be replaced in equations (20-24) and then by using (18 -19) in linearized equations of (15-17) these constants can be obtained. For example by linearizing of ΔV_{DC} equation in (17), it is obtained that:

$$\Delta \dot{V}_{DC} = \frac{K \Delta m}{C_{DC}} (I_{tsd} \cos \psi + I_{tsq} \sin \psi) + \frac{mk}{C_{DC}} (\Delta I_{tsd} \cos \psi + \Delta I_{tsq} \sin \psi) \quad (28)$$

Now by using ΔI_{tsd} , ΔI_{tsq} that comes from linearizing the equations of (21-24), in (28) we can reach to K_7 , K_8 , K_9 and K_{dm} as follows:

$$K_7 = \frac{mK}{C_{DC}} \left(\frac{V_B \sin \delta \cos \psi}{X_{ts} + X_{SB} + X_{SCT} + X_d'} + \frac{VB \cos \delta \sin \psi}{X_{ts} + X_{SB} + X_{SCT} + X_q} \right) \quad (29)$$

$$K_8 = \frac{mK}{C_{DC}} \left(\frac{1}{X_{ts} + X_{SB} + X_{SCT} + X_d'} \right) \quad (30)$$

$$K_9 = \frac{mK}{C_{DC}} \left(\frac{-Km \sin \psi \cos \psi}{X_{ts} + X_{SB} + X_{SCT} + X_d'} + \frac{Km \cos \psi \sin \psi}{X_{ts} + X_{SB} + X_{SCT} + X_q} \right) \quad (31)$$

$$K_{dm} = \frac{mK}{C_{DC}} \left(\frac{-KV_{DC} \sin \psi \cos \psi}{X_{ts} + X_{SB} + X_{SCT} + X_d'} + \frac{KV_{DC} \cos \psi \sin \psi}{X_{ts} + X_{SB} + X_{SCT} + X_q} \right) \quad (32)$$

Finally the state equations of power system with SSSC are:

$$\begin{bmatrix} \dot{\Delta\delta} \\ \dot{\Delta\omega} \\ \dot{\Delta E'_q} \\ \dot{\Delta E_{fd}} \\ \dot{\Delta V_{DC}} \end{bmatrix} = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & -\frac{K_{pDC}}{M} \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & -\frac{1}{T'_{do}} & -\frac{K_{qDC}}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vDC}}{T_A} \\ K_7 & 0 & K_8 & 0 & K_9 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta V_{DC} \end{bmatrix} + \begin{bmatrix} 0 \\ -K_{pu} \\ -K_{qu} \\ -K_{vu} \\ -K_{dm} \end{bmatrix} [\Delta u] \quad (33)$$

Where

$$K_{pu} = \left[\frac{K_A K_{vm}}{T_A} \right], \quad K_{qu} = \left[\frac{K_{qm}}{T_{do}} \right], \quad K_{vu} = \left[\frac{K_{pm}}{M} \right]$$

And

$$[\Delta y] = \begin{bmatrix} K_1 & 0 & K_2 & 0 & K_{pDC} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta V_{DC} \end{bmatrix} + [\Delta_{pm}] [\Delta u] \quad (34)$$

According to the state equations, the block diagram of a SMIB system installed with a SSSC transfer function for small signal distortions have been demonstrated in Figure 3. Constants of the model depend on system parameters and the operating condition.

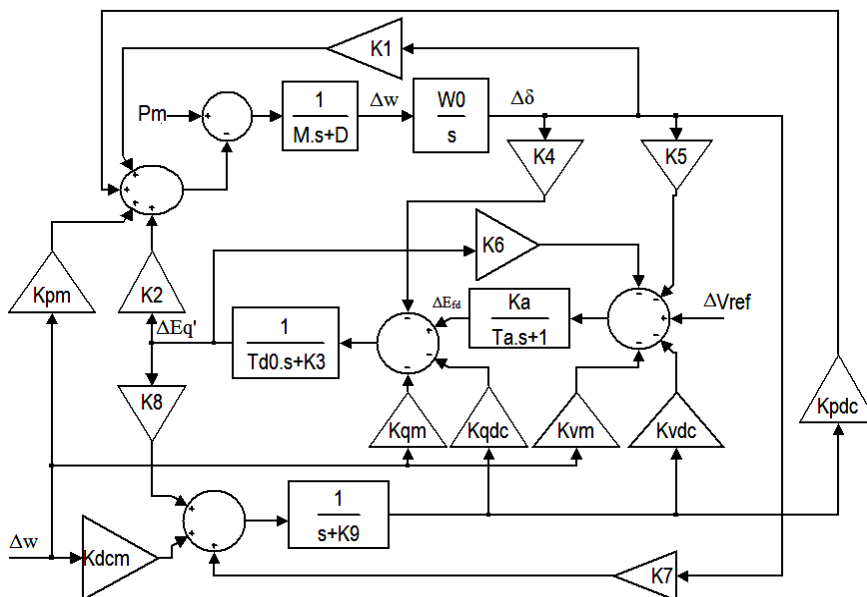


Fig. 3 Modified Heffron-Phillips model of a SMIB system with SSSC.

IV. SSSC CONTROLLER DESIGN USING THE GSA

In this proposed method, parameters of SSSC controller are optimally adjusted for dynamic stability of entire system considering the fact that the selection of gains of output feedback for SSSC as a damping controller is a complicated optimization problem, thus to increase the system damping for electromechanical modes, a multi- objective function based on eigenvalues is considered which includes two separate objective functions that form a compound objective function with an appropriate weight ratio. The GSA algorithm is used to obtain optimum values for the objective function. The multi- objective function with an appropriate weight ratio is considered as following:

$$\begin{aligned} J_1 &= \sum_{j=1}^{NP} \sum_{\sigma_i \geq \sigma_0} (\sigma_0 - \sigma_i)^2, \\ J_2 &= \sum_{j=1}^{NP} \sum_{\xi_i \leq \xi_0} (\xi_0 - \xi_i)^2, \\ J_3 &= J_1 + \alpha J_2 \end{aligned} \quad (35)$$

Where $\sigma_{i,i}$ and $\zeta_{i,i}$ are real part and damping ratio of i^{th} eigenvalue in j^{th} operating point respectively. The value of α is equal to 10 and NP is equal to the number of operating points in optimization problem. By considering J_1 , the dominant eigenvalues are transferred to the left side of the line $s = \sigma_0$ in the S-plane according to Figure 4 (a). This provides relative stability in the system. Similarly, if we consider objective function J_2 , the maximum overshoot of eigenvalues becomes limited and eigenvalues are transmitted to the specified area which is shown in Figure 4 (b). Multi-purpose objective function J transmits the eigenvalues of the system to the specified area shown in Figure 4 (c).

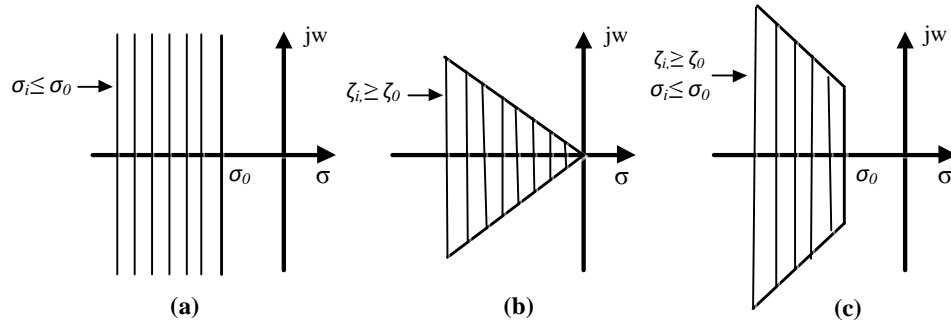


Fig. 4 Region of eigenvalue location for the objective function

The designing problem is formulated as a constrained optimization problem where the constraints are as follows:

$$\begin{aligned}
 K_{\min} &\leq K \leq K_{\max} \\
 T_{1\min} &\leq T_1 \leq T_{1\max} \\
 T_{2\min} &\leq T_2 \leq T_{2\max} \\
 T_{3\min} &\leq T_3 \leq T_{3\max} \\
 T_{4\min} &\leq T_4 \leq T_{4\max}
 \end{aligned}$$

The proposed method uses GSA intelligent algorithm to solve optimization problem to obtain the optimal set of controller parameters. The objective function given in equation (35) takes place in different performance conditions of system, the desired performance conditions are considered as in Table I.

TABLE I: LODING CONDITION

Operating conditions	$P (pu)$	$Q (pu)$	$X_L(pu)$
Normal	0.8	0.26	0.4
Light	0.4	0.134	0.4
Heavy	1.2	0.36	0.4

In this work the range of optimization parameters is selected between [1-100] for k, also the range of parameters for T_1, T_2, T_3 and T_4 is selected between [0.01-1]. The proposed optimization algorithms have been implemented several times then; set of optimal values is selected. The final values of the optimized parameters with both single objective functions J_1, J_2 and the multi-objective function J are given in Table II.

TABLE II: THE OPTIMAL SETTINGS OF THE PROPOSED CONTROLLERS BASED ON THE DIFFERENT OBJECTIVE FUNCTION

Controller parameters	J_1	J_2	J
K	98.65	73.33	80.21
T_1	0.96	0.61	0.91
T_2	0.012	0.056	0.041
T_3	0.107	0.801	0.99
T_4	0.173	0.401	0.602

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 Table. III 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 Table III). It is also clear that the system damping with the proposed J based tuned SSSC controller are significantly improved.

TABLE III: EIGENVALUES AND DAMPING RATIOS OF ELECTROMECHANICAL MODES WITH AND WITHOUT CONTROLLER

Operating conditions	Type of controller			
	Without controller	J ₁ (damping ratio)	J ₂ (damping ratio)	J (damping ratio)
Nominal loading condition		-1.41 ± 5.176i, (0.262)	-1.21 ± 5.654i, (0.2092)	-1.76 ± 4.123i, (0.3925)
	-9.18 ± 11.41i, (0.626)	-1.52 ± 7.603i, (0.196)	-1.64 ± 7.897i, (0.2033)	-2.94 ± 11.997i, (0.2380)
	0.0601 ± 4.107i, (-0.014)	-43.17 ± 22.13i, (0.889)	-21.35 ± 19.38i, (0.7404)	-33.63 ± 23.205i, (0.8230)
	-1.5215	-1.59, -6.42	-1.54, -2.748	-1.72, -1.62
		-106.43	-101.65	-107.87
Light loading condition		-1.49 ± 7.63i, (0.1916)	-1.68 ± 5.374i, (0.2983)	-1.63 ± 5.015i, (0.3091)
	-9.671 ± 13.165i, (0.592)	-1.42 ± 5.214i, (0.2627)	-1.592 ± 7.104i, (0.2186)	-4.765 ± 7.56i, (0.5332)
	0.121 ± 4.1758i, (-0.028)	-15.75 ± 16.84i, (0.683)	-14.79 ± 15.23i, (0.6966)	-15.655 ± 17.761i, (0.661)
	-0.9890	-1.49, -2.63	-1.652, -3.873	-1.765, -1.641
		-101.44	-102.13	-104.757
Heavy loading condition		-1.29 ± 6.165i, (0.2048)	-1.076 ± 4.98i, (0.2111)	-1.52 ± 5.876i, (0.2504)
	-8.123 ± 10.77i, (0.602)	-2.353 ± 7.85i, (0.2871)	-3.654 ± 8.89i, (0.3801)	-3.768 ± 8.25i, (0.4154)
	0.717 ± 5.211i, (-0.1363)	-91.19 ± 13.43i, (0.989)	-90.11 ± 11.40i, (0.992)	-92.63 ± 19.23i, (0.979)
	-1.1290	-1.56, -2.43	-1.18, -3.754	-2.109, -16.643
		-31.8645	-30.543	-65.9657

B. Nonlinear time-domain simulation

The single-machine infinite-bus system shown in Fig. 2 is considered for nonlinear simulation studies. 6-cycle 3-phase fault at t = 1 s, on the infinite bus has occurred, at all loading conditions given in Table.I, to study the performance of the proposed controller. The performance of the controller when the multi-objective function is used in the design is compared to that of the controllers designed using the single objective functions J₁ and J₂. The speed deviation and electrical power deviation based on the ψ controller in three different loading conditions are shown in Figs. 5, 6 and 7. It can be seen that the GSA based SSSC controller tuned using the multi-objective function achieves good robust performance, provides superior damping in comparison with the other objective functions and enhance greatly the dynamic stability of power systems.

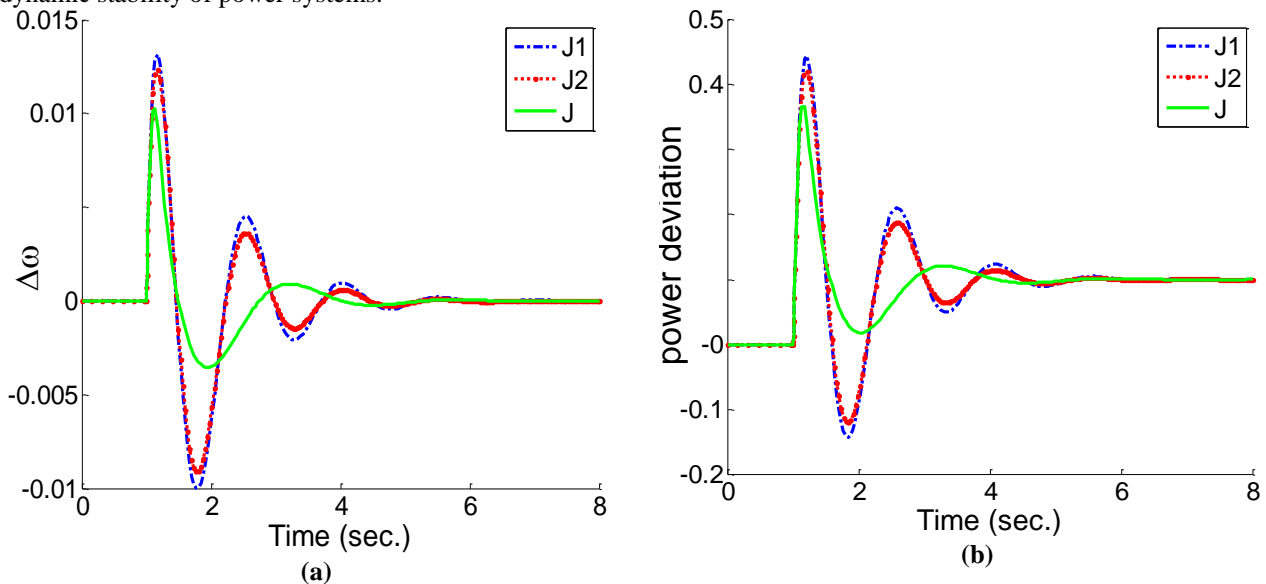


Fig. 5 Dynamic responses for (a) Δω, (b) ΔP with ψ controller at normal loading condition

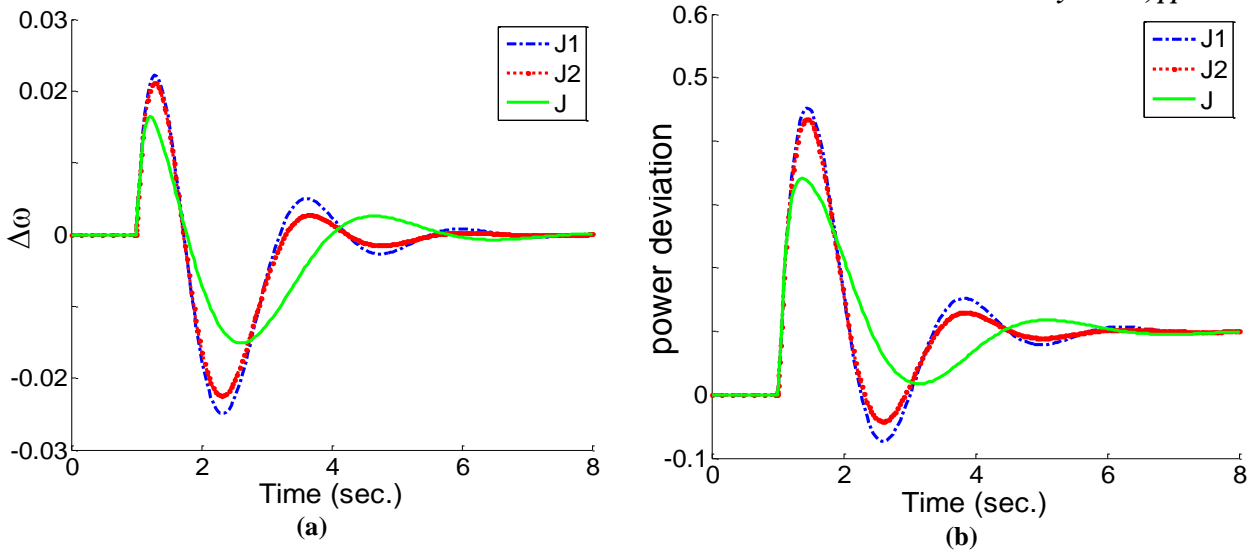


Fig. 6 Dynamic responses for (a) $\Delta\omega$, (b) ΔP with ψ controller at light loading condition

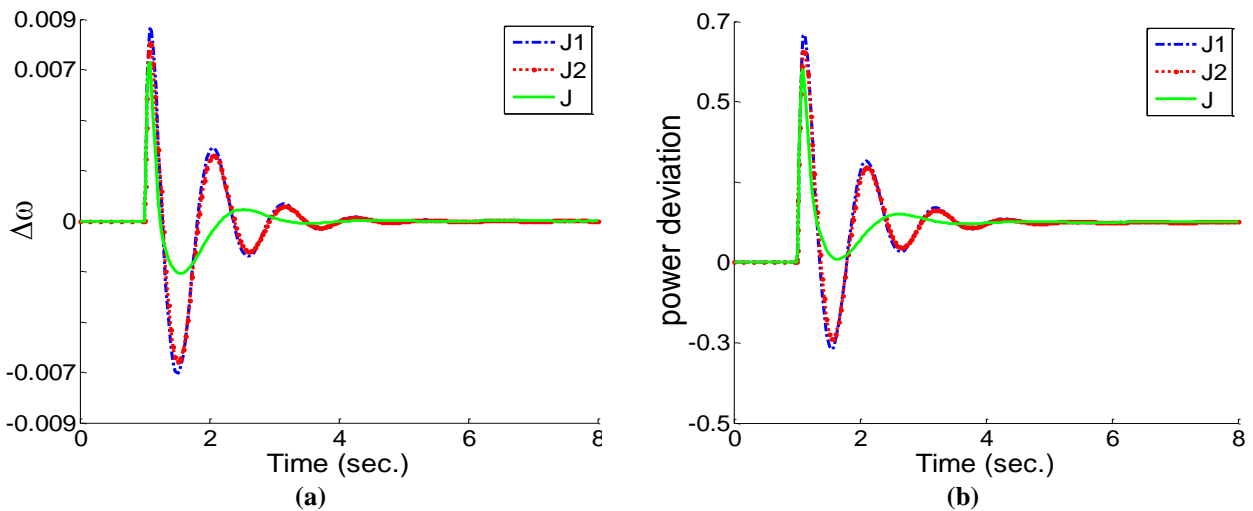


Fig. 7 Dynamic responses for (a) $\Delta\omega$, (b) ΔP with ψ controller at heavy loading condition

V. CONCLUSION

In this paper, transient stability performance improvement by a SSSC controller has been investigated. The stabilizers are tuned to simultaneously shift the undamped electromechanical modes of the machine to a prescribed zone in the s -plane. A multi-objective problem is formulated to optimize a composite set of objective functions comprising the damping factor, and the damping ratio of the undamped electromechanical modes. The design problem of the controller is converted into an optimization problem which is solved by GSA technique with the eigenvalue-based multi-objective function. The effectiveness of the proposed SSSC controllers for improving transient stability performance of a power system is demonstrated by a weakly connected example power system subjected to different severe disturbances. The eigenvalue analysis and nonlinear time-domain simulation results show the effectiveness of the proposed controller using multi-objective function and their ability to provide good damping of low frequency oscillations.

APPENDIX

The nominal parameters and operating condition of the system are listed in table IV.

TABLE IV: SYSTEM PARAMETERS

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

NOMENCLATURE

Nomenclature

E'_q	internal voltage behind transient reactance	VSC	voltage source converter
E_{fd}	equivalent excitation voltage	C_{DC}	DC capacitor
K	proportional gain of the controller	PWM	pulse width modulation
K_A	regulator gain	T_1	lead time constant of controller
M	machine inertia coefficient	T_2	lag time constant of controller
P_e	electric torque	T_3	lead time constant of controller
P_m	mechanical input power	T_4	lag time constant of controller
GSA	Gravitational Search Algorithm	T_A	regulator time constant
GA	genetic algorithm	T'_{do}	time constant of excitation circuit
FACTS	flexible alternating current transmission systems	T_w	washout time constant
PSS	power system stabilizer	T_s	settling time of speed deviation
SMIB	single machine infinite bus	V_{ref}	reference voltage
SSSC	static synchronous series compensator	ω	rotor speed
SVD	singular value decomposition	δ	rotor angle
GTO	gate turn off thyristor	ΔP_e	electrical power deviation

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