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Time delay approach for PSS and SSSC based coordinated controller design using hybrid PSO–GSA algorithm

Rajendra Ku Khadanga *, Jitendriya Ku Satapathy

Department of Electrical Engineering, National Institute of Technology (NIT), Raurkela, Odisha 769008, India

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ABSTRACT

In this work we present a novel approach in order to improve the power system stability, by designing a coordinated structure composed of a power system stabilizer and static synchronous series compensator (SSSC)-based damping controller. In the design approach various time delays and signal transmission delays owing to sensors are included. This is a coordinated design problem which is treated as an optimization problem. A new hybrid particle swarm optimization and gravitational search algorithm (hPSO–GSA) algorithm is used in order to find the controller parameters. The performance of single-machine infinite-bus power system as well as the multi-machine power systems are evaluated by applying the proposed hPSO–GSA based controllers (PSS and damping controller). Various results are shown here with different loading condition and system configuration over a wide range which will prove the robustness and effectiveness of the above design approach. From the results it can be observed that, the proposed hPSO–GSA based controller provides superior damping to the power system oscillation on a wide range of disturbances. Again from the simulation based results it can be concluded that, for a multi-machine power system, the modal oscillation which is very dangerous can be easily damped out with the above proposed approach.

Introduction

The major problem associated with an interconnected power system when connected by a weak line is the low frequency oscillation. If the damping of the system is not adequate, then these oscillation leads to system separation. In industries to damp out these oscillations, generally PSS are used [1]. However the application of PSS is insufficient in some cases in order to provide sufficient damping when the loading of a transmission line increases over a long distance. For this purpose other alternatives which may be effective are needed which can be applied in addition with PSS.

Recently the power engineer's uses FACTS controllers for the power system applications. The main objective of the FACTS controller is to control the system parameter at a very fast rate, which can improve the system stability [2]. The SSSC is considered to be a member of the FACTS family. The SSSC has a unique capability that it can change reactance from capacitive to inductive [3]. An auxiliary stabilizing signal is used here which can improve the system stability in a significant manner. This auxiliary signal is basically used in the control function of the SSSC [4]. The application of SSSC to improve stability and to damp out the system oscillation is discussed in [5–9].

The performance of a power system can be enhanced by designing a PSS and a FACTS based damping controller which can be operated in a coordinated manner. A lot of research has been carried out in this coordinated process work [10–14].

Generally a FACTS device is installed far way from the generator. On the other hand PSS is installed near to the generator. Thus a transmission delay is observed due to various signal transmission and sensors used in the powers system [15]. These delays should be included when designing a FACT/PSS based damping controller design. However in the above literature study these time delays have not been considered. Also the literature includes various algorithms such as residue method, linear matrix inequality technique, eigenvalue-distance minimization approach, and multiplemodel adaptive control approach, for the coordinated controller's damping enhancement. The key issue which need to be discussed in the coordinated design technique is to verify the robustness of the design approach. Very efficient and effective techniques are highly beneficial in order to design the robust controller which can change according to the system configurations.

* Corresponding author.
E-mail addresses: rajendra697@gmail.com (R.K. Khadanga), jitendriya@gmail.com (J.K. Satapathy).

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"Heuristics from Nature" is the most promising field in recent years which is basically an area which utilizes the analogies of the nature or some social systems [16]. In the research community these techniques are very popular and can be used as a research tool or design tool or a problem solver because they can optimize or solve the complex multi-modal non-differentiable objective functions.

In order to design a FACT-based damping controller some new approaches or algorithms based on artificial intelligence have been proposed. These algorithms are genetic algorithm [17,18], differential evolution (DE) [19], particle swarm optimization (PSO) [20,21], modified particle swarm optimization [22,23], bacteria foraging optimization [24,25], multi-objective evolutionary algorithm [4,26], etc.

Recently gravitational search algorithm (GSA) have been developed which utilizes the law of gravity and the concept of mass interaction [27]. In this approach a random number of solution is taken as a initial population for the algorithm. Then in order to achieve the optimum solution the generation number is varied/updated [28]. The various advantages of GSA algorithm are, ease of implementation, very simple concept and it is computationally very efficient [29]. Also GSA provides better performance in solving a highly nonlinear function. Some modification has been done to GSA algorithm like adaptive GSA [30], opposition based GSA [31] in order to improve its efficiency. Although GSA provides some adequate result for optimizing a problem, but is often problematic. This causes a large timing in implementation of the algorithm and thus trapped in local optima [32]. In order to avoid the dis-advantages of the particular algorithm, hybridisation of GSA with other algorithm is implemented. The different hybrid algorithm are fuzzy-GSA [33–35], hGSA–GA [36].

In the work the particle swarming principle is used with the GSA frame work and the newly developed algorithm is termed as hybrid PSO–GSA (hPSO–GSA) algorithm [37]. The hPSO–GSA is basically two concepts which combines each other. The first concept is PSO's ability of social thinking (g_{best}) and the second concept is GSA's local search capability [38,39]. Simulation results shows that the approach of swarming in hPSO–GSA increase its convergence efficiency and thus prevents being trapped into the local optima. Again results shows that this hybrid algorithm is superior compared to the conventional GSA, PSO algorithm. Further from the simulation result we can conclude that the proposed hybrid algorithm provides a better performance compared to hBFOA–PSO algorithm. In view of the above advantages, hPSO–GSA algorithm is used in the proposed work in order to find a optimal and coordinated tuned damping controller.

The preent work has been carried out in order to assess the coordination of PSS and SSSC based damping controller. Therefore this design problem which is based in improvement of system stability is considered to be an optimization problem. To tune the PSS and damping controller parameters the hPSO–GSA approach is applied in order to reach the optimal point. The above controller design which is applied for the evaluation of different power system applications.

In this study, a single machine infinite-bus (SMIB) and a multi machine power system is considered and the results are obtained at various disturbances. An example of two area power system is considered in this paper, and the proposed controller is studied on this system. Again all the dynamics associated with the power system have been included and the local signals have been used to obtain the results. Finally from the results a general conclusion is drawn which is presented in the paper in order to prove the robustness of the algorithm.

Power system modeling with SSSC

At the first instant in order to verify the performance of operation, a SMIB power system is taken into consideration. Fig. 1 shows the structure of a SMIB power system. This system is mainly composed of a synchronous generator, an infinite bus and an SSSC.

Modeling of generator

In this analysis all the dynamics associated with the stator, field and damper windings have been considered. The two axis reference frames (two-axis d–q frame) is used to express the quantity associated with the stator and the rotor.

The system equation of the above power system is given by [15]:

$$V_d = R_s i_d + \frac{d}{dt}\phi_q - \omega_R \phi_q \tag{1}$$

$$V_q = R_s i_q + \frac{d}{dt}\phi_q + \omega_R \phi_d \tag{2}$$

$$V'_{fd} = R'_{fd} i'_{fd} + \frac{d}{dt}\phi'_{fd} \tag{3}$$

$$V'_{kd} = R'_{kd} i'_{kd} + \frac{d}{dt}\phi'_{kd} \tag{4}$$

$$V'_{kq1} = R'_{kq1} i'_{kq1} + \frac{d}{dt}\phi'_{kq1} \tag{5}$$

$$V'_{kq2} = R'_{kq2} i'_{kq2} + \frac{d}{dt}\phi'_{kq2} \tag{6}$$

where

$$\phi_d = L_d i_d + L_{md}(i_{fd} + i_{kd}), \quad \phi_q = L_q i_q + L_{mq} + i'_{kq},$$
$$\phi'_{fd} = L'_{fd} i'_{fd} + L_{md}(i_d + i'_{kd}), \quad \phi'_{kd} = L'_{kd} i'_{kd} + L_{md}\left(i_d + i'_{fd}\right),$$
$$\phi'_{kq1} = L'_{kq1} i'_{kq1} + L_{mq} i_q \phi'_{kq2} = L'_{kq2} i'_{kq2} + L_{mq} i_q$$

The different subscripts of the above equation are: d represents d-axis and q represents q-axis quantities; R represents rotor and S represents stator quantities; f represents field and k represents damper winding; l represents leakage and m magnetizing inductance.

Now the mechanical equations of the above sytem is given by:

$$\frac{d}{dt}\omega_r = \frac{1}{J}(P_e - F\omega_r - P_m) \tag{7}$$

$$\frac{d}{dt}\theta = \omega_r \tag{8}$$

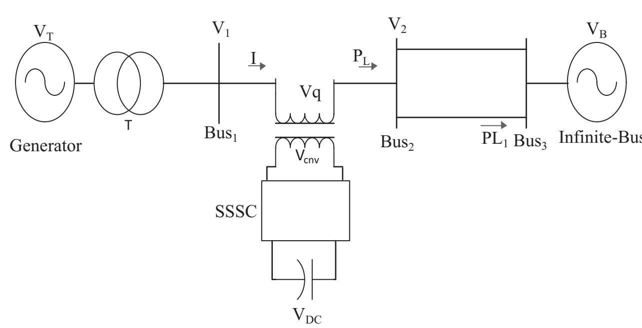

Fig. 1. SMIB system installed with SSSC.

where ω_r represents the rotor angular velocity and θ represents the angular position, P_e is the electrical power and P_m represents and mechanical power, J is the inertia of rotor and F is the friction of rotor.

The proposed approach

Structures of the PSS and SSSC-based damping controller

Fig. 2 shows a damping controller structure which is basically used to control the voltage injected (V_q) by the SSSC. The change in speed deviation ($\Delta\omega$) is considered to be the input of the controllers and V_q is considered to be the output of the controller. The damping structure considered here consists of three blocks [9], namely gain block with gain K_s, signal washout block and two-stage phase compensation block as shown in Fig. 2. The signal washout block will serve as a high-pass filter and the appropriate phase-lead characteristics will be provided by the phase compensation block, with time constants T_{1S}, T_{2S}, T_{3S} and T_{4S}. Now another structure is shown in Fig. 3 which represents the PSS. The output of the PSS (V_s) will be added to V_{ref} where V_{ref} is the excitation system reference voltage.

As far as the optical fiber communication is concern, there is continues phasor measurement by the wide-area measurement system and these phasor measurement can be deliver to the control centers in real time. Thus there is chance of using remote signals in order to design the efficient control schemes. The biggest problem associated with these type of signal is the delay involved in the channel of the transmission line. Generally a dedicated communication channel provides not more than 50 ms delay in any condition during transmission [14]. This time delay can cause the significance degradation in the performance of a particular transmission line. Therefore these delays should be taken care of during the controller design. For PSS 15 ms delay in time constant is considered and 50 ms delay in time is considered for the damping controller with a 15 ms sensor delay in time constant [15].

Optimization problem

In the proposed work, $T_w = T_{wp} = 10$ is taken which is generally prespecified. In the steady state condition ΔV_q is seems to be zero and therefore V_{qref} is constant, and during the dynamic condition, in order to damp out system oscillation the injected voltage V_q is varied by applying some algorithm. In our study V_{qref} is assumed to constant as the power flow loop during steady state operation is very slow. Thus the effective value of V_q in dynamic condition is formulated as,

$$V_q = V_{qref} + \Delta V_q \tag{9}$$

The oscillation of a system can be seen through the speed deviation of rotor, the power angle deviation or tie-line power. To minimize any one of the above deviation can be viewed as the research objectives. For the SMIB system an integral time absolute error (J) of the speed deviations ($\Delta\omega$) is considered to be the objective

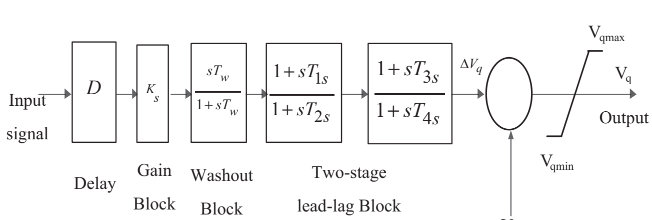

Fig. 2. Structure of SSSC based damping controller.

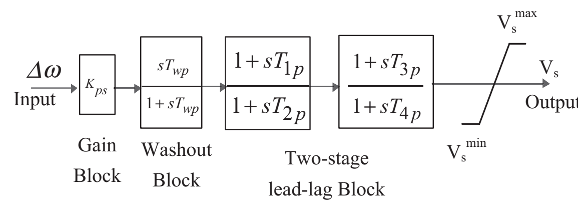

Fig. 3. Structure of power system stabilizer.

function and for the multi-machine, the same error of the speed signals of the local ($\Delta\omega_L$) and inter-area modes ($\Delta\omega_1$) of oscillations are considered. The above explanation can be summarized as:

single-machine infinite-bus power system [32]:

$$J = \int_{t=0}^{t=t_{sim}} |\Delta\omega| \cdot t \cdot dt \tag{10}$$

Multi-machine power system:

$$J = \int_{t=0}^{t=t_{sim}} \left(\sum |\Delta\omega_L| + \sum |\Delta\omega_1|\right) \cdot t \cdot dt \tag{11}$$

where

t_{sim} = simulation time range.

For a stipulated period of time, the time domain simulation of the above power system is worked out and from the simulation the calculation for the objective function is calculated. The prescribed range of the PSS and damping controller are limited in a boundary. Thus the following optimization problem is formulated from the above design approach.

$$\text{Minimize J} \tag{12}$$

$$\begin{aligned} \text{Subject to } & K_i^{min} \leqslant K_i \leqslant K_i^{max} \\ & T_{1i}^{min} \leqslant T_{1i} \leqslant T_{1i}^{max} \\ & T_{2i}^{min} \leqslant T_{21i} \leqslant T_{2i}^{max} \\ & T_{3i}^{min} \leqslant T_{3i} \leqslant T_{3i}^{max} \\ & T_{4i}^{min} \leqslant T_{4i} \leqslant T_{4i}^{max} \end{aligned} \tag{13}$$

where K_i^{min} is the lower bound of the gain; K_i^{max} is the upper bounds of the gain for the controllers (PSS and damping controller). T_{ji}^{min} is the lower bound of the time constants; T_{ji}^{max} are the upper bounds of the time constants for the controllers (PSS and damping controller).

Again the SMIB system is composed of a PSS and a damping controller. Therefore the two gains and eight no. of constants parameters needs to be optimized. Again in case of a multi-machine power system, parameter needs to be optimized are one damping controller gain and multiple PSSs which is equal to the no. of generators and the corresponding time constants.

Hybrid particle swarm optimization and gravitational search algorithm

Particle swarm optimization

For solving an optimization problem the PSO method is generally used. In this algorithm each individual can be represented by a particle which represent a candidate solution [20]. In PSO each particle moves with a velocity and this velocity is modified in accordance with the own velocity and the velocity of other particles. Here p_{best} is the position corresponds to the best fitness and g_{best} is the best in the population out of all particle. Fig. 4 represents the flow chart for the PSO algorithm.

The PSO search procedure is summerized as [21]:

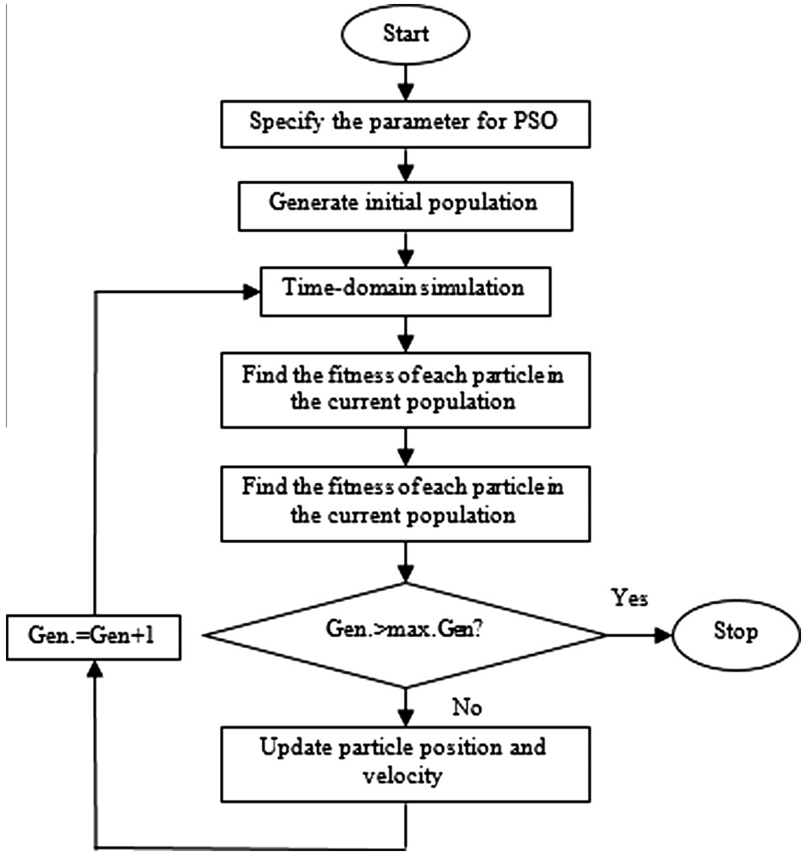

Fig. 4. Flow chart for particle swarm optimization.

A. Initially there is difference in the initial positions of p_{best} and g_{best}. And gradually the closeness between the particles increases and they reaches to a global optimum using different direction of p_{best} and g_{best}.
B. This modification of particle position is a continuous one. Using a technique known as grids of *XY* position and velocity, the positions are verified.
C. Again the new and modified velocity an individual particle can be modified by the current velocity and the new position can be calculated as a distance from p_{best} to g_{best}.

The above procedure can be summerized by the following equations:

$$V_i^{t+1} = wv_i^t + c_1 * rand * (p_{best} - x_i^t) + c_2 * rand * (g_{best} - x_i^t) \quad (14)$$

$$x_i^{t+1} = x_i^{t+1} + v_i^{t+1} \quad (15)$$

with $j = 1, 2, \ldots, n$ and $g = 1, 2, \ldots, m$; n = total amount of particle in a particular Swarm; m = total amount of components in a particular particle; t = iterations/generations number; $v_{g,j}^{(t)}$ = represents *g*th velocity component of particle *j* at *t*th iteration, $v_g^{\min} \leqslant v_{j,g}^{(t)} \leqslant v_g^{\max}$. w = A factor represents inertia of weight; $c1$, $c2$ = factors which represents to cognitive and social acceleration; $r1$, $r2$ = represents a numbers which is uniformly distributed with a random initialization in the range $(0, 1)$; $x_{j,g}^{(t)}$ = represents *g*th component of particle *j* at *t*th iteration; $p_{best\ j} = p_{best}$ of particle *j*; $g_{best\ g} = g_{best}$ of the group.

Gravitational search algorithm (GSA)

For finding an optimal solution, gravitational search algorithm (GSA) is an alternative approach. This algorithm has been compared with other algorithms and seems to be an exciting method and gives better performance which can be viewed from the various literatures [27]. The algorithm is mainly based on the Newtonian law, which states that, "There is a force of attraction between each particle of the world. The force of attraction can be calculated by directly multiplying the masses and by dividing the product of square of distance between the particles [28]. Fig. 5 represents the flow chart for the GSA.

The algorithm for GSA can be stated as:

Assuming *N* number of objects in the dimension of m, then the position of *i*th object is defined as:

$$X_i = (x_i^1, \ldots, x_i^d, \ldots, x_i^n) \quad \text{for } i = 1, 2, \ldots, N \quad (16)$$

where X_i^d represents the position of *i*th agent the *d*th dimension.

The force which acts on the *i*th mass due to *j*th mass defined as:

$$F_{ij}^d(t) = G(t)\frac{M_{pi}(t) * M_{aj}(t)}{R_{ij}(t) + \in}(x_j^d(t) - x_i^d(t)) \quad (17)$$

where M_{aj} = agent *j*'s active gravitational mass; M_{pi} = agent *i*'s passive gravitational mass; $G(t)$ = Gravitational constant at any time t; $\in$ = A constant which is very small; $R_{ij}(t)$ = Euclidian distance = $\|X_i(t), X_j(t)\|_2$.

Then the force acting on agent 'i' which is varied in the dimension d is given by:-

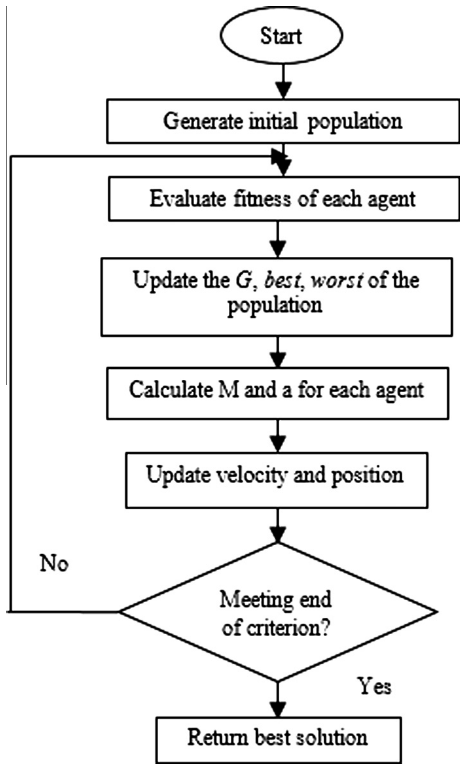

Fig. 5. Flow chart for gravitational search algorithm.

$$F_i^d(t) = \sum_{j=1, j\neq i}^{N} rand_j F_{ij}^d(t) \tag{18}$$

where rand$_j$ = Represents a random number varied between [0,1].

Hence, the acceleration of the agent i, is given as follows:

$$a_i^d(t) = \frac{F_i^d(t)}{M_{ii}(t)} \tag{19}$$

where $M_{ii}(t)$ = Mass of the object i, d = Dimension of the agents, t = Specific Time.

The calculation of different gravitational masses and the inertia masses are carried out, from the fitness evaluation. It is generally concluded that a heavier mass will lead to an efficient agent and these higher mass agents have a larger force of attractions and they move very slowly. The masses like gravitational mass and inertia masses are calculated using the concept of map of fitness. The equality principle is also used for this application. The updation of these masses are done by using the following equation [29].

$$M_{ai} = M_{pi} = M_{ii} = M_i, \quad i = 1, 2, \ldots, \mathrm{N}. \tag{20}$$

$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \tag{21}$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_j(t)} \tag{22}$$

where $fit_i(t)$ represents, at time t the agent i's fitness value and $Best(t)$ and $Worst(t)$ can be defined as a minimization problem which can be represented as follows:

$$Best(t) = \min_{j\in(1\ldots n)} fit_j(t) \tag{23}$$

$$Worst(t) = \max_{j\in(1\ldots n)} fit_j(t) \tag{24}$$

Hybrid particle swarm optimization and gravitational search algorithm (hPSO–GSA)

The hybrid PSO and GSA algorithm uses the concept of PSO and GSA algorithm, thus holds the advantages of both the algorithms. This technique deals with the ability of social thinking of PSO and local search ability of GSA algorithm [37].

The combination of these two algorithm can be summarized as follows:

$$V_i(t+1) = w * V_i(t) + c_i' * rand * ac_i(t) + c_2' * rand * (g_{best} - X_i(t)) \tag{25}$$

where $V_i(t)$ represents i agent velocity at t iteration, w is a weighting function, c_j' is a weighting factor, $ac_i(t)$ is the acceleration of agent i at iteration t, rand is a random number between 0 and 1, g_{best} is the best solution so far.

To update the positions of each individual particles, the following expression can be used:

$$X_i(t+1) = X_i(t) + V_i(t+1) \tag{26}$$

In the first step of hPSO–GSA, there is a random initialization of all agents and these agent is treated to be a candidate solution [38]. Once the initialization is completed, the calculation of different forces and constants among the agents is carried out. The different constants which need to calculate are gravitational constant, gravitational force, resultant forces etc. Then each particle's accelerations is calculated using the GSA algorithm. The best solution so far achieved should be updated in each iteration. Finally the velocity and the position of all the agents can be calculated using Eqs. (25) and (26). The updating process will stop after the criteria for the velocities and position satisfy the end criterion. Fig. 6 shows the flow chart for the proposed hPSO–GSA algorithm.

In order to improve of the efficiency of the hPSO–GSA algorithm some remark has to be carried out. For the updating process the fitness is taken into account. The agents which are near to the good solution attract the other agents. In this way the search space explores. The agents move very slowly which are mainly near to a good solution. The g_{best} is mainly responsible to exploit the global best. The g_{best} is a memory which is used to save the best solutions so that it can be accessible at any moment of time. A balance can be obtained by adjusting the c_1' and c_2' between the global search and the local search ability.

In order to find the optimal values of the parameters for the controllers under some constraints, the hybrid particle swarm optimization algorithm and gravitational search algorithm (hPSO–GSA) can be described as follows:

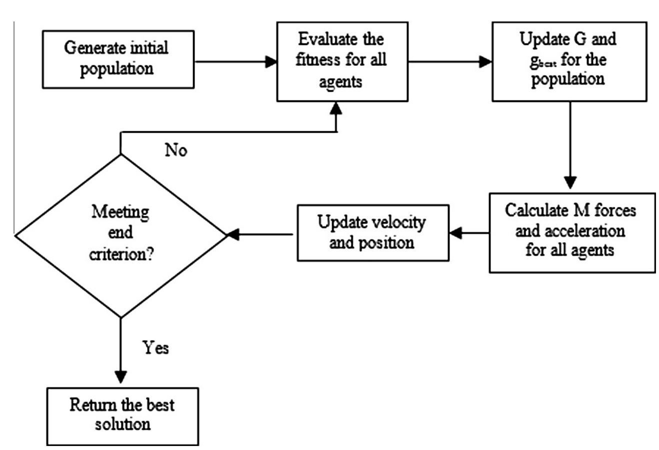

Fig. 6. Flow chart for the proposed hybrid PSO–GSA algorithm.

Step 1: in this step input data including the HPSO–GSA Parameters are defined and then randomly initialize the position of each particle $X_i = \{x_{i1}, x_{i2}, \ldots, x_{im}\}$. under the above constraints (Eq. (13)). Here, m is the dimension of each particle.
Step 2: Evaluate the fitness function of each particle $F_i(t)$ at t iteration.
Step 3: Calculate the inertial mass by using (Eqs. (21) and (22)).
Step 4: Evaluate the gravitational force and acceleration as per (Eqs. (17) and (21)) respectively.
Step 5: Update the velocity and position of each particle as per (Eqs. (25) and (26)) respectively.
Step 6: At each iteration the position of the particle should be maintained within the prescribed range.
Step 7: Increase the iteration counter.
Step 8: Repeat step 2 to step 6 until the termination condition is satisfied.

Therefore the control parameters for the above system are generated randomly and these values lies within some prescribed ranges, which can be updated successfully by using PSO–GSA algorithm to minimize the error (J).

Results and discussion

To design and simulate the PSS and damping controller, the Sim-Power Systems (SPS) tool box has been used [40]. In order to design the Simulink model of any power system, SPS is generally used which is basically a MATLAB-based platform. A block called 'Powergui' of SPS provides a graphical user interface (GUI) tool which can analyze the developed models. The purpose of this block is, to carry out the load flow analysis of the system and again it initializes the initial parameters of the machine in steady state.

Single-machine infinite-bus power system

The developed MATLAB/SIMULINK SMIB power system model with SSSC (shown in Fig. 1) is shown in Fig. 7. This said power system is composed of a generating unit which is connected to a transmission line. This transmission line is basically a double-circuit parallel line. A 3-phase step-up transformer and a SSSC is connected in between the generator unit and transmission line. All the components ratings are given in Appendix A. The SPS of the MATLAB/SIMULINK environment is used in order to develop the said power system example. Again using an.m file the hPSO–GSA algorithm is written. Considering a disturbance the above developed model is simulated and simultaneously the objective function calculation is carried out. For finding the parameters of the controller, Eq. (10) is considered by minimizing its fitness value. For fitness calculation, the simulation study is carried out on an Intel (R) Core (TM) 2 Duo 2.93 GHz, 2 G.B RAM computer, with the MATLAB 7.10.0 environment by considering the above algorithms. In order to optimize Eq. (10), the hPSO–GSA algorithm is used.

In this proposed simulation work for the application of PSO, GSA, and PSOGSA different parameters has been initialized. For the application of PSO, GSA and PSOGSA the following settings has been used. For PSO: swarm size = 30, $c1 = 2$, $c2 = 2$, w is decreased linearly from 0.9 to 0.2, maximum iteration = 50, and stopping criteria = maximum iteration. For GSA and PSOGSA $c1' = 0.5$, $c2' = 1.5$, population size = 30, max. Iteration = 50, w = is a random number varied in the range of 0–1. $G_0 = 1$, $\alpha = 20$, and when the iteration reaches to maximum iteration, simulation stops [38]. Tables 1–3 represent the best optimized value using hPSO–GSA, GSA and PSO. From the tables it can concluded that statistically the hPSO–GSA provides a better result in terms of objective function and optimized parameters value. The abbreviation K_T, T_1–T_4, Min, Max and Avg. of the tables are the gain, time constants of the controller, minimum fitness, maximum fitness, and an average fitness of the system respectively. Further it can be concluded as, by adopting this hybrid algorithm the probability of trapping in local optimum can be reduced to a great extent. This new algorithm is good at finding the global minimum point. Moreover it shows good convergence speed near minimum points since it utilizes the social concept the best individual at each generation.

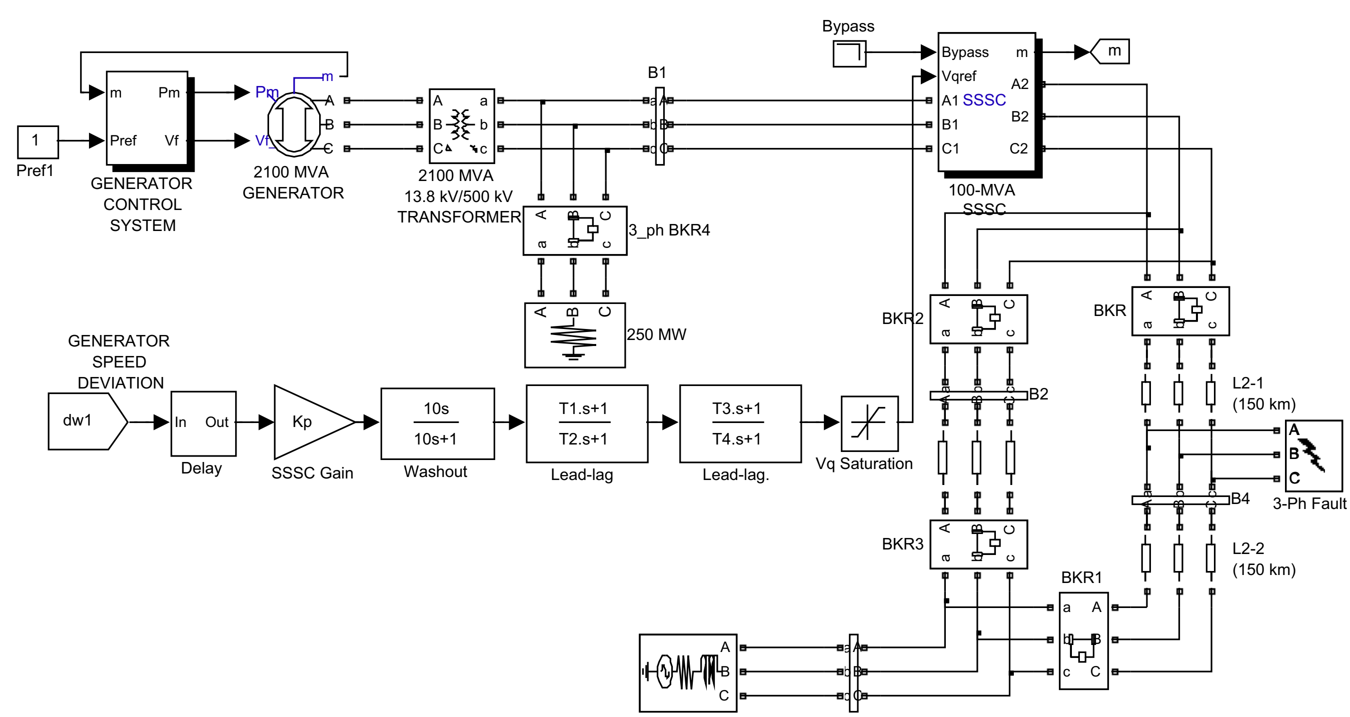

Fig. 7. MATLAB/SIMULINK model of SMIB power system with SSSC.

Table 1
Optimized controller parameters using hPSO–GSA.

	K_T	T_1, T_2	T_3, T_4	Min	Max	Avg.
Damping controller	67.871	0.4232, 0.146	0.296, 0.349	$1.275 * 10^{-4}$	$1.881 * 10^{-4}$	$1.564 * 10^{-4}$
Power system stabilizer	4.0771	0.496, 0.109	0.101, 0.740			

Table 2
Optimized controller parameters using GSA.

	K_T	T_1, T_2	T_3, T_4	Min	Max	Avg.
Damping controller	55.772	0.798, 0.503	0.984, 0.566	$1.529 * 10^{-4}$	$1.981 * 10^{-4}$	$1.726 * 10^{-4}$
Power system stabilizer	11.904	0.907, 0.998	0.862, 0.678			

Table 3
Optimized controller parameters using PSO.

	K_T	T_1, T_2	T_3, T_4	Min	Max	Avg.
Damping controller	53.052	0.741, 0.424	0.556, 0.657	$1.745 * 10^{-4}$	$1.956 * 10^{-4}$	$1.812 * 10^{-4}$
Power system stabilizer	12.655	0.637, 0.245	0.956, 0.574			

From Table 3 it can be concluded that the hPSO–GSA algorithm compared to PSO and GSA algorithm provides minimum fitness and thus justifying the application of the hPSO–GSA algorithm. For one particular system disturbance, the above controller is designed at a nominal operating condition. Different loading and operating conditions is considered to test the potency of the algorithm. The optimized controller values are tabulated in Table 1 which can be obtained from 30 independent runs at the nominal operating condition. Tables 2 and 3 shows the comparison results of GSA and PSO algorithms simultaneously which are considered as conventional algorithms for the stabilizer design. Some different loading conditions are taken into account for the study and the simulation is carried out by considering some fault clearing sequences. The dotted line with legend 'No Control' represents the response of the system without any controller and the legend 'hPSO–GSA' with a solid line represents the system response for the above coordinated design. For the sake of comparison the response of the system is compared with a previous publish hBFOA–PSO algorithm which is represented by a heading 'hBFOA–PSO' with a dashed line [15].

3-Phase self-clearing fault created with Nominal loading condition

At nominal loading i.e. $P_e = 0.8$ pu and $\delta_0 = 48.4°$, the behavior of the controller is tested by considering a severe disturbance. At $t = 1$ s in the line connecting between bus-2 and bus-3 of a 3 cycle, 3 phase fault is applied and after the fault is cleared the system is restored. The various system responses like, speed deviation $\Delta\omega$ in pu, tie-line power P_L in MW, SSSC injected voltage V_q is shown in Fig. 8(a–c). From the responses as shown in the figures it can be concluded that, the system goes to an oscillatory stage without any controller under this disturbance.

Further from Fig. 8(b and c) it can be seen that the above said controller represents a better performance as far as the real power flow and the injected voltage to the system is concerned, as compared to the hBFOA–PSO algorithm as in [15], which rationalize the application of hPSO–GSA algorithm for further study.

Fig. 9 shows the system variation with time delays. A wide range of delay is taken into consideration. It can be concluded that the response slightly deteriorates when there is an increase in transport delays with the above proposed controller and when there is a decrease in delay then the response improves.

3-Phase fault is created and cleared by line tripping with light loading condition

Again the loading condition is changed from nominal to light loading i.e. $P_e = 0.5$ pu and $\delta_0 = 29.47°$ and a 3-cycle, 3-phase fault is considered near to bus-3. The faulty line is opened and after 3-cycles the fault is cleared. Fig. 10 shows the system response under this contingency. This figure clearly shows that the proposed controller is very effective for the change in operating system and the new fault location. Again Fig. 10 clearly demonstrates that the controller applying hPSO–GSA algorithm provides better result as compared to the published hBFOA–PSO algorithm.

Small disturbance applied at heavy loading condition

Now finally at the heavy loading condition i.e. $P_e = 1.0$ pu and $\delta_0 = 60.730$ for the existence of the controller is verified. In this condition the load at bus-1 is disconnected at $t = 1$ s for a period of 100 ms. Here in order to test the robustness of the algorithm, a new comparison is made. The proposed algorithm is compared with the conventionally developed algorithms particle swarm optimization (shown in the legend 'PSO') and gravitational search algorithm (Shown in legend 'GSA'). Fig. 11 show the system speed deviation response under this condition. From this figure it is observed that the proposed controller is very much effective for the new operating condition and the change in the power system configuration. Further the hPSO–GSA based controller provides more stable performances compared to other controllers.

Extension to three-machine six-bus power system

Fig. 12 shows the extension of the above coordinated approach to a multi-machine power system. This power system is similar to the power system as in Refs. [4,6,15]. This system mainly consists of three no. of generators. These three generators are arranged in such a manner that two subsection will be created. These two sections are connected to each other through a tie-line. When any disturbance occur, then there will be a swinging of the two systems, which causes an instability. At the mid-point of the tie-line a SSSC is installed which can improve the system stability and with each of the generator one PSS is connected. Appendix A represents all the data related to the above system.

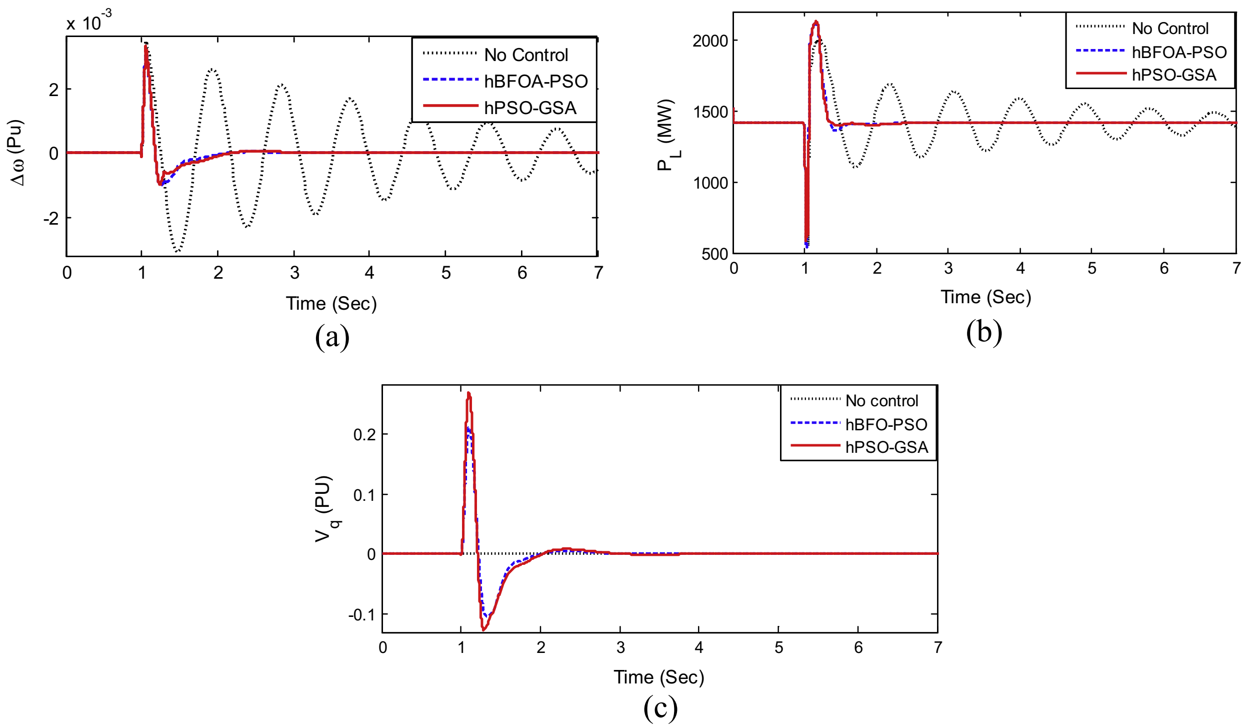

Fig. 8. System response for the case A.1. (a) Speed deviation, (b) tie-line power and (c) SSSC injected voltage.

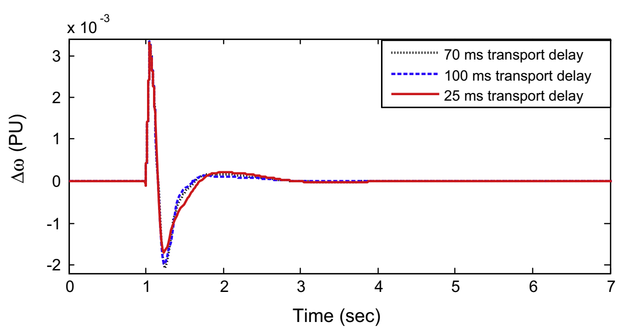

Fig. 9. Speed deviation response of the system with variation of signal transmission delays.

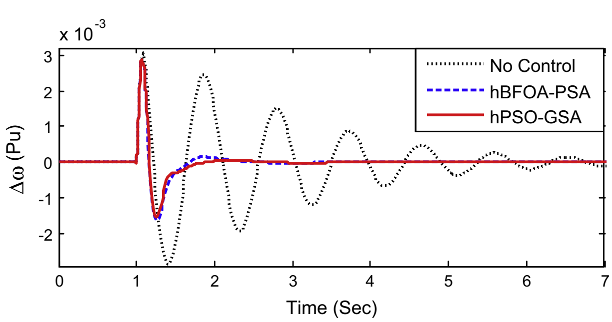

Fig. 10. Speed deviation response for the case A.2.

As explained in Section 'Single-machine infinite-bus power system' for a SMIB case, the same approach is continued in order to optimize the coordinated PSS and damping controller for the multi machine case. The speed deviations of generators G1 and G3 is considered as the input for the PSS as well as damping controller. The MATLAB/SIMULINK based multi machine power system modeling is shown in Fig. 13. Different optimized values of the damping controller and PSS, by applying the hPSO–GSA algorithm is shown in Table 4. The abbreviation of this table is same as Tables 1–3 and represents the same quantities.

Three-phase fault disturbance

In this case at $t = 1$ s, in between bus 1 and bus 6 a 3-cycle, 3-phase self-clearing fault is applied with near to bus 6. After the fault is cleared the previous original section is restored. Fig. 14(a–c) represents the system responses with this type of disturbance. These figures clearly demonstrate that, both the responses are oscillatory in nature if the controllers are not present in the system. The system response without any controller is represented in a dotted line with legend 'No Control' and in order to represent the proposed hPSO–GSA optimized PSS and damping controller a solid line with legend 'hPSO–GSA' is given.

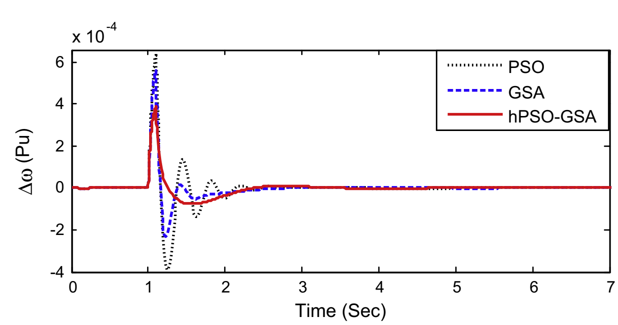

Fig. 11. Speed deviation response for case A.3.

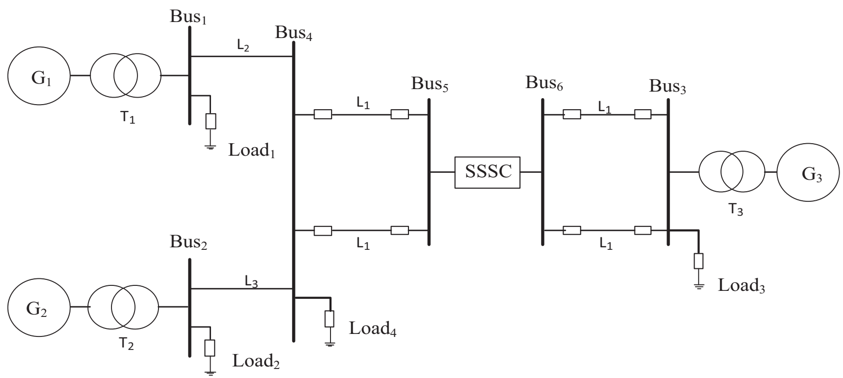

Fig. 12. An example of a multi-machine power system.

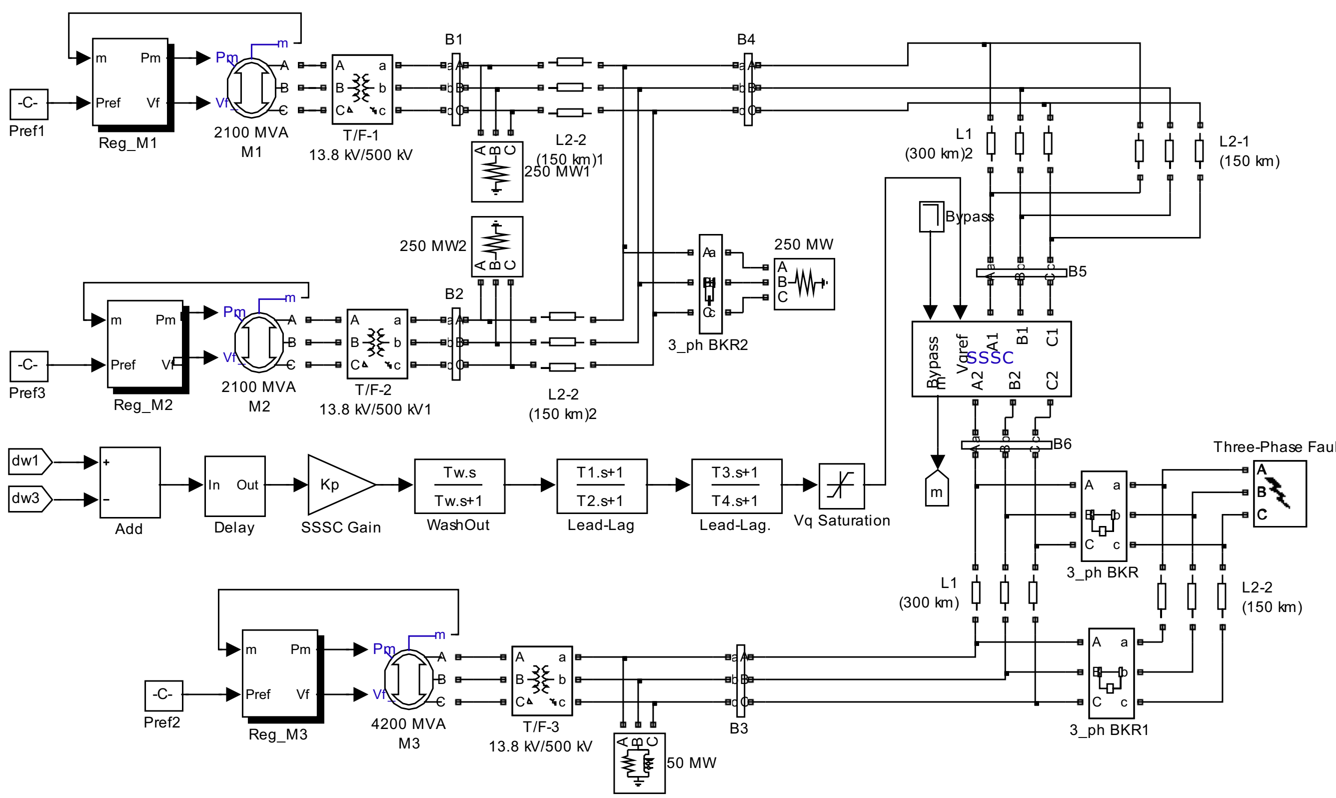

Fig. 13. Developed multi-machine MATLAB/SIMULINK model power system with SSSC.

Table 4
Optimized controller parameters using hPSO–GSA.

	K_T	T_1, T_2	T_3, T_4	Min	Max	Avg.
Damping controller	101.0779	0.0744, 0.1120	0.7999, 0.4878	$10.1535 * 10^{-2}$	$24.1508 * 10^{-2}$	$18.4645 * 10^{-2}$
Power system stabilizer-1	8.1304	0.2972, 0.110	0.7196, 0.1130			
Power system stabilizer-2	4.0127	0.7439, 0.4546	0.3608, 0.7990			
Power system stabilizer-3	5.1381	0.1123, 0.1112	0.8839, 0.1905			

By modifying the stabilizing signals and injected voltage of PSS and SSSC simultaneously, the response of the power system is significantly improved. Again using signal time delays the effectiveness of the CPSS is verified for the above disturbance. A wide range of time delay is taken into consideration like in previous case. Fig. 15(a and b) shows the responses of the system and it can be concluded that the effect is almost negligible with the variation of the time delays.

Line outage disturbance

The 2nd disturbance considered is that, at $t = 1$ s. between bus 1 and bus 6 one of the parallel transmission line is tripped off. After

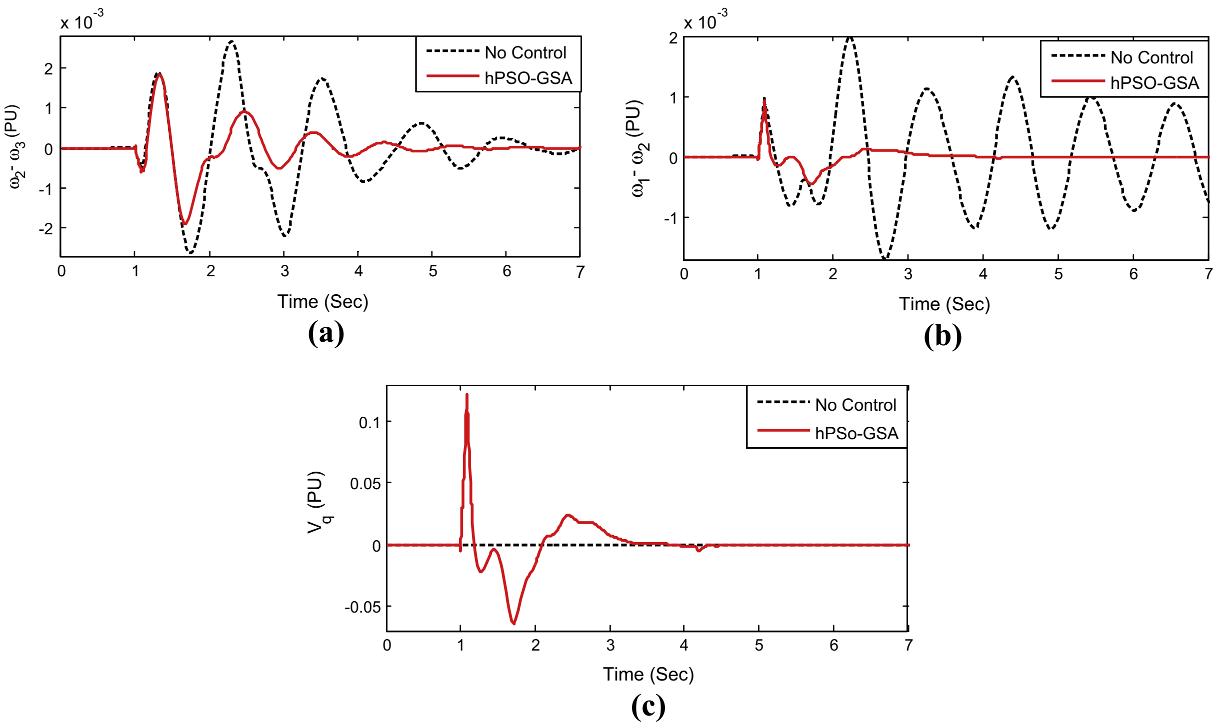

Fig. 14. (a) Inter-area mode of oscillations, (b) local mode of oscillations and (c) SSSC injected voltage, response of the system for B.1 case.

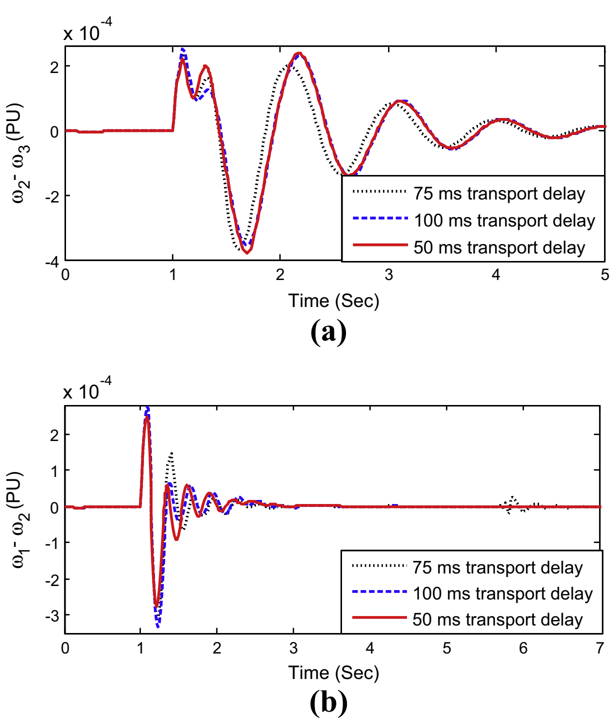

Fig. 15. (a) Inter-area mode of oscillations and (b) local mode of oscillations response of the system in variation with signal transmission delays.

operation of the line reclosure, the previous system is restored in almost 3-cycles. The response of the above system is shown in Fig. 16(a and b).

Small disturbance

The last disturbance considered for the above power system is that at $t = 1$ s, the load at bus 4 is taken out for a period of 100 ms. This disturbance can be treated as small disturbance. The

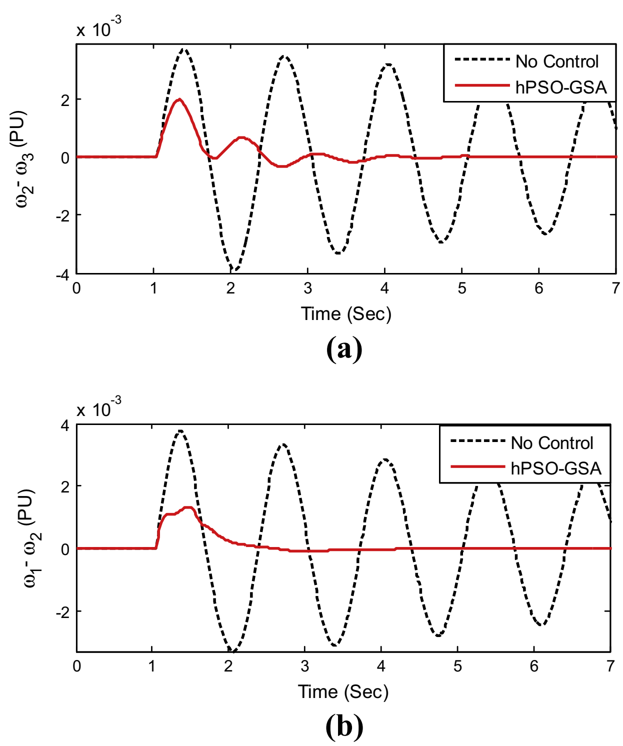

Fig. 16. (a) Inter-area mode of oscillations and (b) local mode of oscillations response of the system for B.2 case.

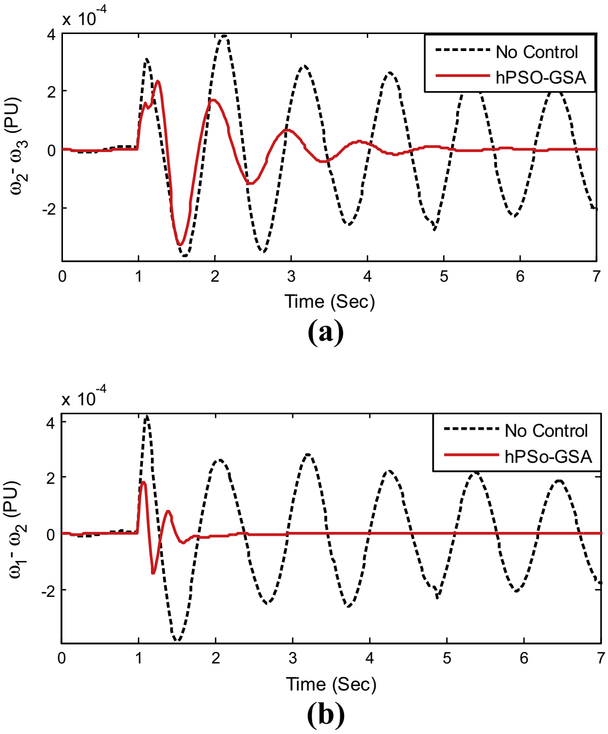

Fig. 17. (a) Inter-area mode of oscillations and (b) local mode of oscillations response of the system for B.3 case.

responses are shown in Fig. 17(a and b). From the figures it can be concluded that the proposed controller provides efficient and robust damping under small and all other disturbances.

Conclusion

In the above study, an investigation is carried out for the stability improvement of the power system. A time domain simulation based on minimization of an objective function for the controllers is carried out. Then for the coordinated PSS and damping controller structure parameter tuning a hybrid algorithm (hPSO–GSA) is applied. To prove the effectiveness of the coordinated structure different results and simulation figures are demonstrated for various disturbance. It can be observe from the simulation results that the controllers are very robust and effective as far as some change in the operating condition is concerned. Finally the extension of the above design approach to multi-machine power system is carried out. Simulation results concludes that the above proposed control mechanism is very much adaptive for the application to power system.

Appendix A

The default User's Manual [40] of Sim-Power Systems represents a complete list of parameters used for our study. Unless otherwise specified all the data are in pu only.

A.1. Single-machine infinite bus power system

Generator: $S_B = 2100$ MVA, $H = 3.7$ s, $V_B = 13.8$ kV, $f = 60$ Hz, $R_S = 2.8544e{-}3$, $X_d = 1.305$, $X'_d = 0.296$, $X''_d = 0{:}252$, $X_q = 0.474$, $X'_q = 0.243$; $X''_d = 0.18$, $T_d = 1.01$ s, $T'_d = 1.01$ s, $T''_{q0} = 0.1$ s.

Load at Bus2: 250 MW.

Transformer: 2100 MVA, 13.8/500 kV, 60 Hz, $R_1 = R_2 = 0.002$, $L_1 = 0$, $L_2 = 0.12$, D_1/Y_g connection, $R_m = 500$, $L_m = 500$.

Transmission line: 3-Ph, 60 Hz, Length = 300 km each, $R_1 = 0.02546$ X/km, $R_0 = 0.3864$ X/km, $L_1 = 0.9337e{-}3$ H/km, $L_0 = 4.1264e{-}3$ H/km, $C_1 = 12.74e{-}9$ F/km, $C_0 = 7.751e{-}9$ F/ km.

Hydraulic turbine and governor: $K_a = 3.33$, $T_a = 0.07$, $G_{min} = 0.01$, $G_{max} = 0.97518$, $V_{gmin} = -0.1$ pu/s, $V_{gmax} = 0.1$ pu/s, $R_p = 0.05$, $K_p = 1.163$, $K_i = 0.105$, $K_d = 0$, $T_d = 0.01$ s, $\beta = 0$, $T_w = 2.67$ s.

Excitation system: $T_{LP} = 0.02$ s, $K_a = 200$, $T_a = 0.001$ s, $K_e = 1$, $T_e = 0$, $T_b = 0$, $T_c = 0$, $K_f = 0.001$, $T_f = 0.1$ s, $E_{fmin} = 0$, $E_{fmax} = 7$, $K_p = 0$.

Conventional power system stabilizer parameters: gain $K_{PS} = 30$, washout time constant $T_W = 10$ s.

Lead-lag structure time constants: $T_{1CP} = 0.05$ s, $T_{2CP} = 0.02$ s, $T_{3CP} = 3$ s, $T_{4CP} = 5.4$ s.

Output limits of $V_S = \pm 0.15$.

A.2. Three-machine power system

Generators: $S_{B1} = S_{B2} = 2100$ MVA, $S_{B3} = 4200$ MVA, $H = 3.7$ s, $V_B = 13.8$ kV, $f = 60$ Hz, $R_S = 2.8544e{-}3$, $X_d = 1.305$, $X'_d = 0.296$, $X''_d = 0.252$, $X_q = 0.474$, $X'_q = 0.243$, $X''_d = 0.18$, $T_d = 1.01$ s, $T'_d = 1.01$ s; $T''_{q0} = 0.1$ s.

Loads:

Load1 = Load2 = 25 MW, Load3 = 7500 MW + 1500 MVAR, Load4 = 250 MW.

Transformers: $S_{BT1} = S_{BT2} = 2100$ MVA, $S_{BT3} = 4200$ MVA, 13.8/500 kV, $f = 60$ Hz, $R_1 = R_2 = 0.002$, $L_1 = 0$, $L_2 = 0.12$, D_1/Y_g connection, $R_m = 500$, $L_m = 500$.

Transmission lines: 3-Ph, 60 Hz, line lengths: $L_1 = 175$ km, $L_2 = 50$ km, $L_3 = 100$ km, $R_1 = 0.02546$ Ω/km, $R_0 = 0.3864$ Ω/km, $L_1 = 0.9337e{-}3$ H/km, $L_0 = 4.1264e{-}3$ H/km, $C_1 = 12.74e{-}9$ F/km, $C_0 = 7.751e{-}9$ F/km.

SSSC: converter rating: $S_{nom} = 100$ MVA; system nominal voltage: $V_{nom} = 500$ kV; frequency: $f = 60$ Hz; maximum rate of change of reference voltage (V_{qref}) = 3 pu/s.

Converter impedances: $R = 0.00533$, $L = 0.16$; DC link nominal voltage: $V_{DC} = 40$ kV; DC link equivalent capacitance $C_{DC} = 375 * 10^{-6}$ F.

Injected voltage regulator gains: $K_P = 0.00375$, $K_i = 0.1875$.

DC voltage regulator gains: $K_P = 0.1 * 10^{-3}$, $K_i = 20 * 10^{-3}$.

Injected voltage magnitude limit: $V_q = \pm 0.2$.

Initial operating conditions:

Machine 1: $Pe_1 = 1280$ MW (0.6095 pu); $Qe_1 = 444.27$ MVAR (0.2116 pu), Machine 2: $Pe_2 = 880$ MW (0.419 pu); $Qe_2 = 256.33$ MVAR (0.1221 pu).

Machine 3: $Pe_3 = 3480.6$ MW (0.8287 pu); $Qe_3 = 2577.2$ MVAR (0.6136 pu).

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