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OPTIMAL TUNING OF PID TYPE STABILIZER AND AVR GAIN USING GSA TECHNIQUE

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Abstract- In this paper, a Problem of simultaneous and coordinated tuning of the PID type Power System Stabilizer (PSS) and Automatic Voltage Regulators (AVR) gains in a Single-Machine connected to Infinite-Bus (SMIB) power system is invastigated. The problem of robustly stabilizer parameters and AVR gain tunning is formulated as a nonlinear optimization problem according to the time domain-based objective function for a wide range of operating conditions and is solved by the Gravitational Search Algorithm (GSA) for improvement of power system low frequency oscillations. The GSA optimization technique is simple, robust and capable to solve difficult combinatorial optimization problems. It simulates the masses cooperate using a direct form of communication through gravitational force and has a strong ability to successful control the local search and convergence to the global optimum solution. The effectiveness of the proposed method is tested on a SMIB power system through the nonlinear time domain simulation and some performance indices in comparison with the some version of PSO based approaches to illustrate its robust performance. Results evaluation indicate that the proposed GSA based coordinated PID type stabilizer and AVR achieves good robust performance for wide range of system operation conditions and is superior to the other methods.

Keywords: PSS Design, Gravitational Search Algorithm, Low Frequency Oscillations, Coordinated PSS and AVR.

I. INTRODUCTION

The dynamic stability of power systems is an important issue for secure system operation. By the development of interconnection of large electric power systems, there have been spontaneous system oscillations at very low frequencies in order of 0.2-3.0 Hz [1]. Once started, they would continue for a long period of time. In some cases, they continue to grow, causing system separation if no adequate damping is available. Furthermore, low frequency oscillations present limitations on the power-transfer capability. To improve system damping, the generators are equipped with Power System Stabilizer (PSS) that provides supplementary feedback stabilizing signals in the excitation system.

The action of the PSS is to extend the angular stability limits of a power system by providing supplemental damping to the oscillation of the synchronous machine rotors through the generator excitation. This damping is provided by an electric torque applied to the rotor that is in phase with the speed variation. Power system instabilities can arise in certain circumstances due to the negative damping effects of the PSS on the rotor, which is based on tuning PSSs around a steady-state operating point; their damping effect is only valid for the small excursions around this operating point. During severe disturbances, a PSS may actually cause the generator under its control to lose synchronism in an attempt to control its excitation field [2].

Many conventional techniques have been reported in the literature pertaining to design widely used conventional lead-lag compensator based PSS namely: the eigenvalue assignment, mathematical programming, gradient procedure for optimization and also the modern control theory [2-5]. Unfortunately, the conventional techniques are time consuming as they are iterative and require heavy computation burden and slow convergence. In addition, the search process is susceptible to be trapped in local minima and the solution obtained may not be optimal [4]. Also, a set of controller parameters which stabilize the system under a certain operating condition may no longer yield satisfactory results when there is a drastic change in power system operating conditions and configurations [5].

A more reasonable design of the PSS is based on the gain scheduling and adaptive control theory as it takes into consideration the nonlinear and stochastic characteristics of the power systems [6-7]. This type of stabilizer can adjust its parameters on-line according to the operating condition. Many years of intensive studies have shown that the adaptive stabilizer can not only provide good damping over a wide operating range but more importantly, it can also solve the coordination problem among the stabilizers. Many random heuristic methods, like genetic algorithms, chaotic optimization algorithm, rule based bacteria foraging, honey bee mating optimization and particle swarm optimization [8-13] have been represented for achieving high efficiency and search global optimal solution in the problem space.

However, in these studies non-smooth parameters of the stabilizer such as saturation limits and Automatic Voltage Regulators (AVR) gain has not been optimized, Also, it should be noted that the performance of the above methods greatly depends on its control parameters adjustments, and it often suffers the problem of being trapped in the local optima so as to be premature convergence.

In spite of the potential of the modern control methods with different strategies, PID type controller is still widely used for industrial applications such as power systems control [14-16]. This is because it performs well for a wide class of plants. In addition, they give robust performance for different operating points and easy to implement. On the other hand, Shayeghi et al [16] reported a comprehensive analysis of the effects of the different PID controller gains on the overall dynamic performance of the PSS problem. It is shown that the appropriate selection of PID controller parameters results in satisfactory performance during system upsets. Thus, the optimal tuning of a PID gains is required to get the desired level of robust performance.

In this paper, the Gravitational Search Algorithm (GSA) is proposed for optimal tunning of the coordinated PID type stabilizers as well as the AVRs gains simultaneously. The GSA algorithm is a novel agent-based approach to optimization, in which the search algorithm is inspired by the law of gravity and mass interactions. Unlike the other optimization techniques such as PSO, it executes both global search and local search in each iteration process to determine optimal solution quality and efficiently avoiding local optimum to a large extent [17]. The main advantage of the GSA method is simple concept, easy implementation, robustness to control parameters and computational effort.

In this study, the tuning problem of the coordinated PID type stabilizer parameters and AVR gain and saturation limits are automatically optimized according to a time domain based objective function by GSA technique. Multiple operation conditions are considered in synthesis process to guarantee the relative stability and concurrently secure the time domain specifications. To illustrate the robustness of the proposed coordinated PID type PSS and AVR their ability to provide efficient damping of low frequency oscillations it is tested on a weak connected power system for a wide range of operating conditions.

To show the superiority of the proposed design approach, the simulations results are compared with the with the PSO with Time Variant Acceleration Coefficients (PSO-TVAC) [18] and standard PSO based designed stabilizer through nonlinear simulation results and some performance indices. The results evaluation reveals that the proposed GSA based tuned coordinated PSS and AVR achieves good robust performance for wide range of load changes in the presence of very highly disturbance and is superior to the other stabilizers.

II. POWER SYSTEM DESCRIPTION

Figure 1 shows a schematic diagram of a Single Machine connected to an Infinite Bus (SMIB) power system through a circuit transmission. The generator is equipped with a thyristor exciter with high gain and a power system stabilizer. System data are given in Appendix.

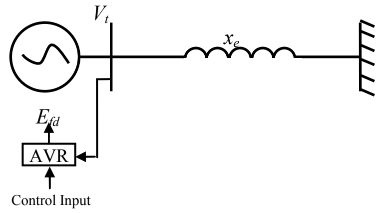

Figure 1. SMIB power system

The model 1.1, i.e. with field circuit and one equivalent damper winding on q axis is used to describe synchronous generator. The dynamic equations of the SMIB system considered can be summarized as follows [19]:

$$\begin{aligned}
\dot{\delta} &= \omega_B S_m \\
\frac{dS_m}{dt} &= \frac{1}{2H}(-DS_m + T_m - T_e) \\
\dot{E}'_q &= \frac{1}{T'_{do}}(E_{fd} + (x_d - x'_d)i_d - E'_q) \\
\dot{E}_{fd} &= \frac{1}{T_A}(K_A(v_{ref} - v_t + V_s)) - E_{fd})
\end{aligned} \quad (1)$$

$$T_e = E'_q i_q + (x'_d - x'_q) i_d i_q \quad (2)$$

A. PSS Structure

The operating function of a PID type PSS is to produce a proper torque on the rotor of the machine involved in such a way that the phase lag between the exciter input and the machine electrical torque is compensated. The structure of the PID type stabilizer to modulate the excitation voltage is shown in Figure 2. The structure consists of a signal washout block, a PID controller as opposed to the traditional lead-lag controller and a saturation limiter.

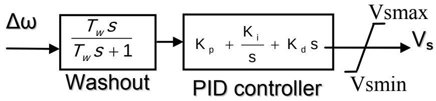

Figure 2. Structure of the PID type stabilizer

$\Delta\omega$ is the speed deviation of the generator and V_s is the output signal fed as a supplementary input signal to the regulator of the excitation system. The washout filter, which really is a high pass filter, is regarded as to reset the steady-state offset in the output of the stabilizer. The value of the time constant T_w is usually not critical and it can range from 1 to 20 s. It should be noted that the PSS output must be limited to V_s^{max} and V_s^{min} for avoiding actuator system damaging.

All stabilizer parameters were regarded as adjustable. Stabilizer performance robustness is satisfied by considering several operating conditions and the system configurations, simultaneously. Thus, the optimized parameters of the coordinated PID type stabilizer and AVR are K_P, K_I and K_D (PID gains); T_W, V_s^{max} and V_s^{min} (PSS output saturations) and K_A (AVR gain).

III. GSA TECHNIQUE

Heuristic algorithms are stochastic global optimization methods which mimic biological or physical processes. One of the newest heuristic algorithms that have been inspired by the physical laws is Gravitational Search Algorithm (GAS) which was first introduced by Rashedi et al [17]. It is a new member of swarm intelligence based on the metaphor of gravitational interaction between masses to solve multi-variable, multi-modal and difficult combinatorial optimization problems. This algorithm describes the mass interactions behavior, learning and information sharing characteristics of masses. It is a very simple, robust and population based stochastic optimization algorithm [20].

This algorithm provides an iterative approach that simulates mass interactions, and moves through a multi-dimensional search space under the influence of gravitation. In GSA, the swarms, called agents, are a collection of masses which interact with each other by the Newtonian laws of gravity and the laws of motion. The swarms share information using a direct form of communication, through gravitational force to guide the search toward the best position in the search space process. The high performance and the global search ability of GSA in solving various nonlinear functions infers from the results of experiments undertaken previously [21].

In GSA, the effectiveness of the swarms is measured by their masses. All the swarms are likely to move toward the global optima attract each other by the gravity force, while this force causes a global movement of all swarms toward the swarms with heavier masses. The heavy masses correspond to best solutions of the problem. In other words, each mass place represents a solution, and the algorithm is navigated by properly adjusting the gravitational and inertia masses. By lapse of time, the masses will be attracted by the heaviest mass which it represents an optimum solution in the search space. Thus, in GSA, all swarms move to a new place by updating their direction and distance determined by their velocities. Consequently, the swarms are likely to move toward the global optima by changing the velocities over the time. This algorithm is an iterative process similar to the other swarm intelligence based approaches. It starts with N agents (masses) in a d-dimension space, where N and d denote the size of population and the number of optimization parameters, respectively. The ith agent is represented by:

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

where, x_i^d is the position of agent i in dimension d and n is the search space dimension.

After evaluating the current population cost (fitness), the mass of each swarm is determined as follows:

$$M_i(k) = \frac{q_i(k)}{\sum_{j=1}^{N} q_j(k)}, \quad q_i(k) = \frac{f_i(k) - f_{worst}(k)}{f_{best}(k) - f_{worst}(k)} \quad (4)$$

where, $f_i(k)$ represent the fitness value of the swarm i at iteration k. $f_{best}(k)$ and $f_{worst}(k)$ is the best and worst fitness of all swarms, respectively and defined as follows:

$$f_{best}(k) = \min_{j=[1,...,N]} f_j(k), \quad f_{worst}(k) = \max_{j=[1,...,N]} f_j(k) \quad (5)$$

To calculate the acceleration of a swarm, total forces from a set of heavier masses applied on it should be regarded as based on a combination of the law of gravity as follows:

$$F_i^d(k) = \sum_{j=T_{best}, j \neq i} r_j G(k) \frac{M_i(k) M_j(k)}{R_{ij}(k) + \varepsilon} (x_j^d(k) - x_i^d(k)) \quad (6)$$

where r_j is a random number in the range [0,1], $G(k)$, M_i and M_j is the gravitational constant, M_i and M_j are masses of swarms i and j at iteration k, respectively; ε is a small value and $R_{ij}(k)$ is the Euclidean distance between two swarms i and j and calculated as follows:

$$R_{ij}(k) = \left\| X_i(k), X_j(k) \right\|_2 \quad (7)$$

T_{best} is the set of first T swarms with the best fitness value and biggest mass, which is a function of iteration (time), initialized to T_0 at the beginning and decreased with iteration. It is used to improve the performance of GSA by controlling exploration and exploitation at search process. This strategy is known as *elitist* selection [19]. Here, T_0 is set to N (total number of swarms) and is decreased linearly to one. Thus, the algorithm uses the exploration at beginning and by lapse of iterations, exploration fades out and exploitation fades in. Using the law of motion, the acceleration of the ith swarm at iteration k and in direction d is given by:

$$a_i^d(k) = \frac{F_i^d(k)}{M_i(k)} = \sum_{j=Tbest, j \neq i} r_j G(k) \frac{M_j(k)}{R_{ij}(k) + \varepsilon} (x_j^d(k) - x_i^d(k)) \quad (8)$$

$$d = 1, 2, ..., n; \quad i = 1, 2, ..., N$$

In the next step, the velocity of a swarm is computed as a fraction of its current velocity added to its acceleration as follows:

$$v_i^d(k+1) = r_i v_i^d(k) + a_i^d(k) \quad (9)$$

Then, swarm position is updated in each search strategy according to Equation (9).

$$x_i^d(k+1) = x_i^d(k) + v_i^d(k+1) \quad (10)$$

where, x_i^d, v_i^d and a_i^d are the position, velocity acceleration of swarm i in dimension d, respectively. r_i is a uniform random variable in the range [0, 1]. This random number is applied to give a randomized characteristic to the search process.

It should be noted that the gravitational constant $G(t)$ is an important control parameter in determining the performance of GSA and adjusting its accuracy. Thus, it is generally reduced with iteration k as follows:

$$G(k) = G_0 \exp(\alpha k / K_{\max}) \quad (11)$$

where, G_0 is the initial value, α is a constant and K_{max} is the maximum iteration number.

It is obvious that from the above clarification the control parameters used in the GSA algorithm are the number of population size N, the value of initial gravitational constant G_0, α and the maximum iteration number (generation).

Using the above concepts, the whole GSA algorithm can be described as follows:

1. Intilize the control parameters of GSA algorithm (N, G_0, d, α and K_{max})
2. For each individual, the position and velocity vectors will be randomly initialized with the same size as the problem dimension within their allowable ranges.
3. Evaluate the fitness of each agent.
4. Update the G, f_{best} and f_{worst} of the population according to Equations (5) and (11).
5. Compute M and a for each agent.
6. Update velocity and position for each agent using Equations (9) and (10).
7. Repeat steps 2-6 until a termination criterion is satisfied.

IV. GSA BASED STABILIZER AND AVR DESIGN

For the PSS structure shown in Figure 2, the PID and AVR gains, time constant T_w and V_s^{max} and V_s^{min} (PSS output saturation limits) are to be optimized. It is worth mentioning that the stabilizer and AVR parameters are tuned to minimize the power system oscillations after a large disturbance so as to improve the power system stability. These oscillations are reflected in the deviations of the power angle, rotor speed and line flow power. Minimization of any one or all of the above deviations could be selected as the objective function (fitness). Here, an Integral of the Squared Time of the Squared Error (ISTSE) of the speed deviations is taken as the objective function into account which is given by [18]:

$$F = \sum_{i=1}^{NP} \int_{t=0}^{t=tsim} t^2 (\Delta\omega)^2 \, dt \quad (12)$$

where, $\Delta\omega$ shows the rotor speed deviation, t_{sim} is the time range of the simulation and NP is the total number of operating conditions for which the optimization is carried out. It is aimed to minimize this objective function in order to enhancement the system response in terms of the settling time and overshoots under different operating condition. The optimal tuning of the coordinated stabilizer parameters and AVR gain can be formulated as the following constrained optimization problem, where the constraints are the stabilizers parameters and AVR gain bounds:

minimize F subject to

$$\begin{aligned} & T_w^{\min} \le T_w \le T_w^{\max}, \; K_P^{\min} \le K_P \le K_P^{\max} \\ & K_I^{\min} \le K_I \le K_I^{\max}, \; K_D^{\min} \le K_D \le K_D^{\max} \\ & V_s^{\min} \le V_s \le V_s^{\max}, \; -V_s^{\min} \le -V_s \le -V_s^{\max} \\ & K_A^{\min} \le K_A \le K_A^{\max} \end{aligned} \quad (13)$$

The upper and lower limits of the optimized parameters as given in the literature are given in Table 1. The proposed method employs GSA algorithm to solve this optimization problem and search for an optimal or near optimal set of coordinated PID type stabilizer and AVR gain. The optimization of the coordinated stabilizer parameters and AVR gain is carried out by evaluating the objective cost function as given in Equation (12), which considers a multiple of operating conditions are given in Table 2. The operating conditions are considered for wide range of output power at different power factors. To acquire better optimization synthesis, the GSA and PSO parameters is given in Table 3. Results of the PSS parameter set values based on the objective function F, by applying a three phase-to-ground fault for 100 ms at generator terminal at t=1 sec using the proposed GSA, PSO-TVAC [18] and classical PSO algorithms [12] are given in Table 4. Figure 3 shows the minimum fitness functions evaluating process.

Table 1. The upper and lower limits of the optimized parameters

Parameter	T_W	K_P	K_I	K_D	V_s^{max}	V_s^{min}	K_A
Lower limit	1	1	1	1	0.05	-0.5	50
Upper limit	20	50	50	50	0.5	-0.05	200

Table 2. Operation conditions

Case No.	P	Q	x_e	H
Case1 (Base case)	0.8	0.4	0.3	3.25
Case 2	0.5	0.1	0.3	3.25
Case 3	1	0.5	0.3	3.25
Case 4	0.8	0.4	0.6	3.25
Case 5	0.5	0.1	0.6	3.25
Case 6	1	0.5	0.6	3.25
Case 7	0.8	0	0.6	3.25
Case 8	1	-0.2	0.3	3.25
Case 9	0.5	-0.2	0.6	3.25
Case 10	1	0.2	0.3	0.81

Table 3. Control parameters of different algorithm for optimization

GSA		PSO-TVAC		PSO-TVIW		PSO	
Agent dimension	24	C_{1f}	0.2	C_1	2.1	C_1	2.1
Population size	60	C_{1i}	2.5	C_2	2.1	C_2	2.1
G_0	20	C_{2f}	2.5	φ	4.1	ω_{min}	0.4
α	100	C_{2i}	0.2	ω_{min}	0.4	ω_{max}	0.9
Iteration	100	φ	4.1	ω_{max}	0.9	Population	40
-	-	ω_{min}	0.4	Population	40	Iteration	100
-	-	ω_{max}	0.9	Iteration	100	-	-
-	-	Population	40	-	-	-	-
-	-	Iteration	100	-	-	-	-

Table 4. Optimal stabilizer parameters and AVR gain

Method	T_W	K_P	K_I	K_D	V_{Max}	V_{Min}	K_A
PSO	12.65	12.556	4.566	2.673	0.099	0.067	179.276
PSO-TVIW	16.67	14.739	5.877	3.985	0.056	0.066	192.918
PSO-TVAC	13.43	17.654	6.541	1.754	0.088	0.038	187.253
GSA	19.81	26.312	1.231	0.978	0.098	0.078	198.276

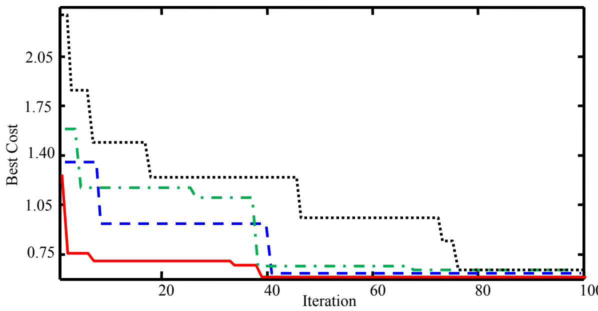

Figure 3. Fitness convergence, solid (GSA), dashed (PSO-TVAC), dashed-dotted (PSO-TVIW) and dotted (PSO)

V. SIMULATION RESULTS

The performance of the proposed GSA based designed coordinated PID type stabilizer and AVR under transient conditions is verified by applying disturbance and fault clearing sequence under different operating conditions in comparison with the PSO-TVAC [19] and classical PSO (CPSO) methods. The disturbances are given at t=1 sec. System responses in the form of slip (S_m) are plotted. The following types of disturbances have been considered.

Scenario 1: A step change of 0.1 pu in the input mechanical torque of the generator.

Scenario 2: A three phase-to-ground fault for 100 msec at the generator terminal.

Scenario 3: Applying a three phase-to-ground fault for 100 msec at the generator terminal at t=1 sec and a step change of 0.1 pu in the input mechanical torque of the generator at t=5 sec.

Figure 4 depicts the system response at the lagging power factor operating conditions with weak transmission system for scenario 1. It is clear that the system with CPSO is highly oscillatory. Both GSA and improved PSO based tuned stabilizers and AVRs are able to damp the oscillations reasonably well and stabilize the system at all operating conditions. Figure 5 shows the responses of same operating conditions but with strong transmission system. System is more stable in this case, following any disturbance. Both PSO-TVAC and PSO-TVIW improve its dynamic stability considerably and GSA based stabilizer shows its superiority over CPSO and PSO-TVAC. System response at the ohmic operating conditions is shown in Figure 6 with the weak and strong transmission system for scenario 1. The proposed GSA based coordinated PSS and AVR are effective and achieve good system damping characteristics.

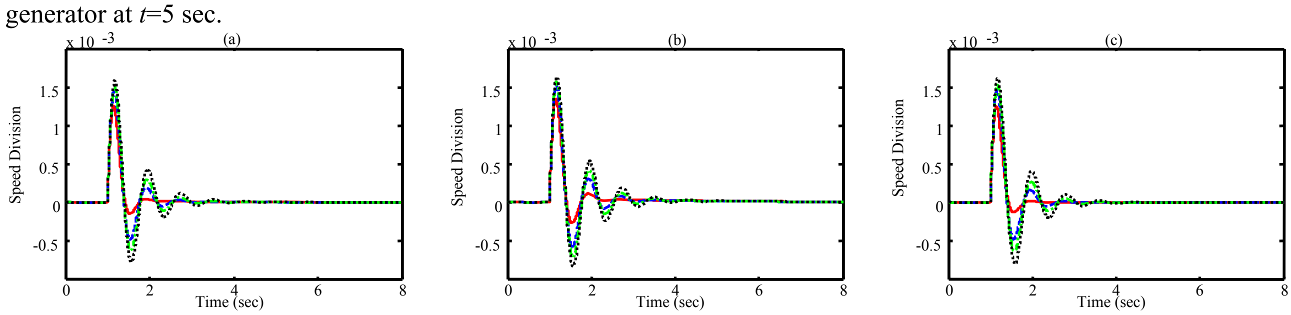

Figure 4. ΔT_m=0.1 (p.u.) under X_e=0.3; CPSO (dotted), PSO-TVIW (dashed-dotted) and PSO-TVACPSS (dashed) and GSA (solid)
(a) P=0.8, Q=0.4 (b) P=0.5, Q=0.1 (c) P=1.0, Q=0.5

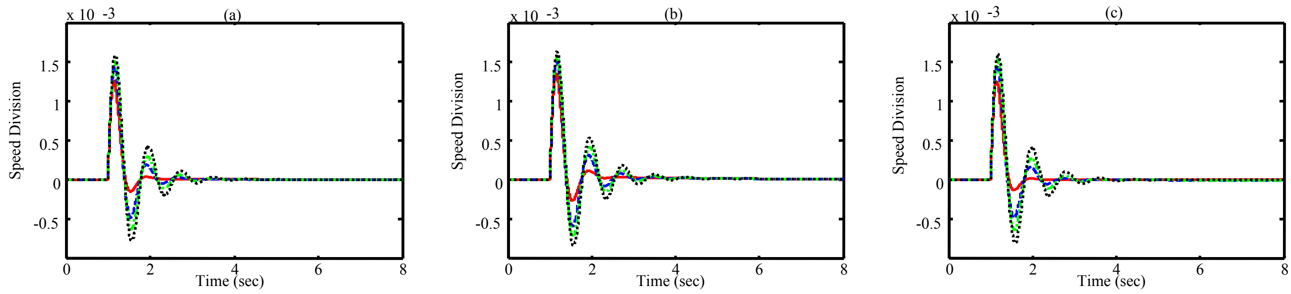

Figure 5. ΔT_m=0.1 (p.u.) under X_e=0.6; CPSO (dotted), PSO-TVIW (dashed-dotted) and PSO-TVACPSS (dashed) and GSA (solid)
(a) P=0.8, Q=0.4 (b) P=0.5, Q=0.1 (c) P=1.0, Q=0.5

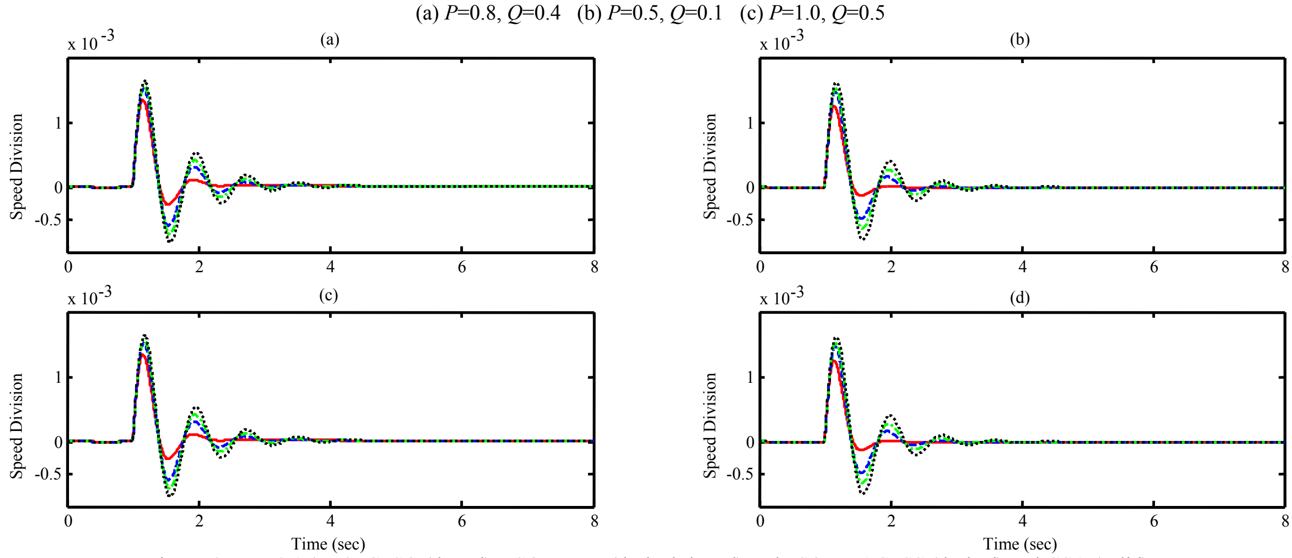

Figure 6. ΔT_m=0.1 (p.u.); CPSO (dotted), PSO-TVIW (dashed-dotted) and PSO-TVACPSS (dashed) and GSA (solid)
(a) P=0.5, Q=0.0, X_e=0.3 (b) P=1.0, Q=0, X_e=0.3 (c) P=0.5, Q=0.0, X_e=0.6 (d) P=1.0, Q=0, X_e=0.6

Also, Figure 7 show the system response at the leading power factor operating conditions with the weak and strong transmission system for scenario 1. Figure 8 refers to a three-phase to ground fault at the generator terminal. Figure 9 depicts the system response in scenario 1 with inertia $H'=H/4$. It can be seen that the proposed GSA based coordinated PID type stabilizer and AVR has good performance in damping low frequency oscillations and stabilizes the system quickly. Moreover, it is superior to the PSO, PSO-TVIW and PSO-TVAC methods tuned stabilizer. The system response using the proposed coordinated PSS and AVR in scenario 3 for operation conditions of cases 1, 7, 8 and 10 is depicted in Figure 10. It is evident that the system low frequency oscillation damping using the proposed GSA tuned coordinated stabilizer and AVR has small overshoot, less settling time and is superior that of the other approaches one.

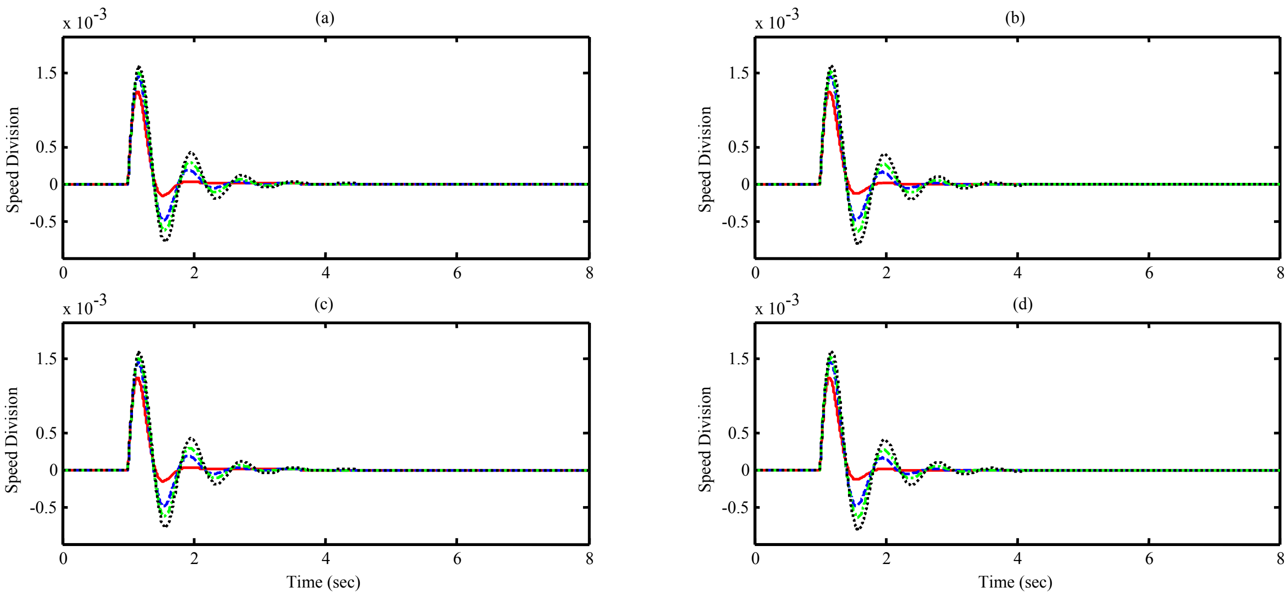

Figure 7. ΔT_m=0.1 (p.u.); CPSO (dotted), PSO-TVIW (dashed-dotted) and PSO-TVACPSS (dashed) and GSA (solid)
(a) P=0.8, Q=-0.2, X_e=0.3 (b) P=1.0, Q=-0.2, X_e=0.3 (c) P=0.8, Q=-0.2, X_e=0.6 (d) P=1.0, Q=-0.2, X_e=0.6

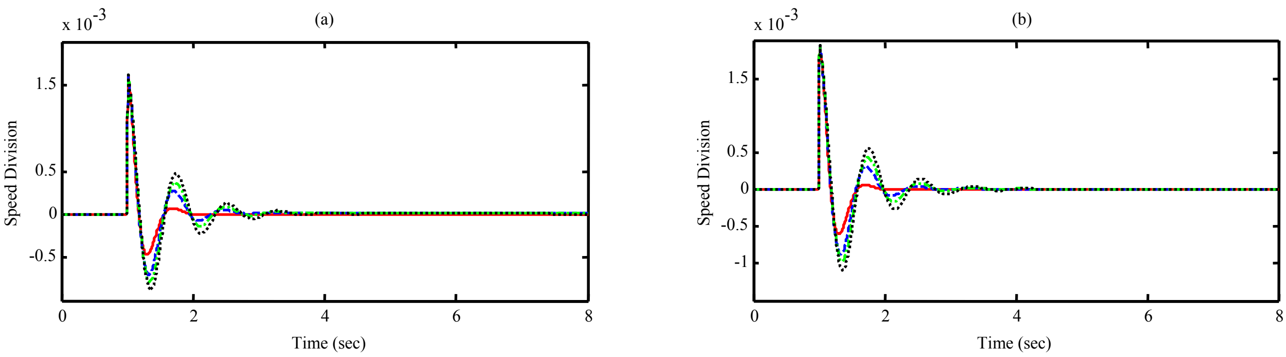

Figure 8. 3-phase to ground fault 100 msec for X_e=0.3, CPSO (dotted), PSO-TVIW (dashed-dotted) and PSO-TVACPSS (dashed) and GSA (solid)
(a) P=0.8, Q=0.4 (b) P=1.0, Q=0.5

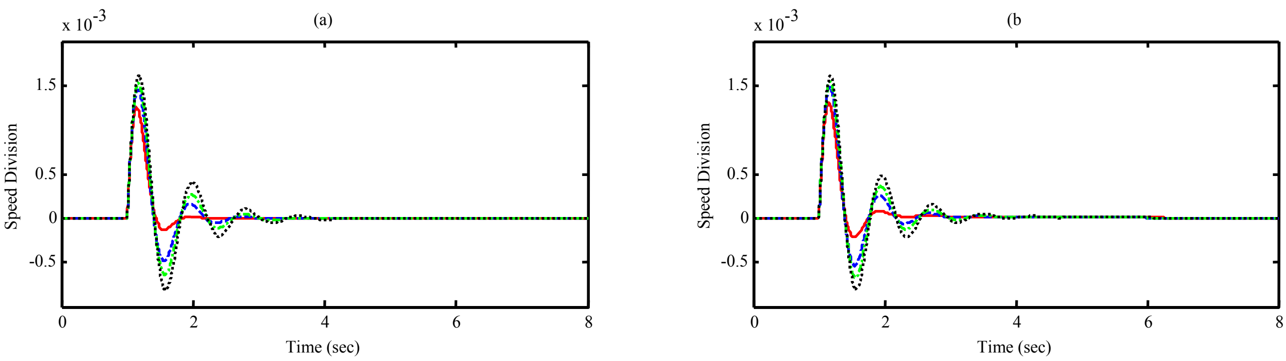

Figure 9. ΔT_m=0.1 (p.u.) under X_e=0.6 and $H'=H/4$, CPSO (dotted), PSO-TVIW (dashed-dotted) and PSO-TVACPSS (dashed) and GSA (solid)
(a) P=1.0, Q=0.5 (b) P=0.6, Q=0.0

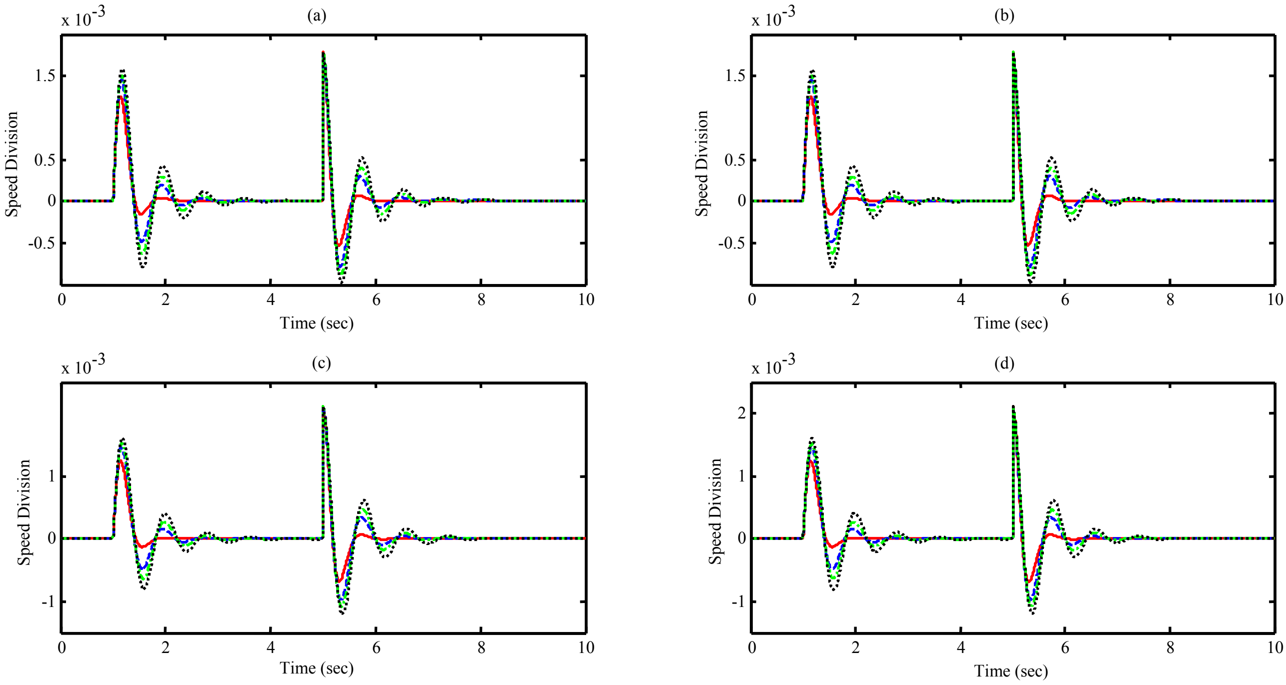

Figure 10. System response in scenario 3; CPSO (dotted), PSO-TVIW (dashed-dotted) and PSO-TVACPSS (dashed) and GSA (solid)
(a) P=0.8, Q=-0.2, X_e=0.3 (b) P=0.8, Q=0.0, X_e=0.6 (c) P=1.0, Q=-0.2, X_e=0.3 (d) P=1.0, Q=0.2, X_e=0.6 and H'=H/4

To demonstrate performance robustness of the proposed method, some performance indices based on the system dynamic characteristics are defined as [16]:

$$ITAE = 1000\int_0^{t_{sim}} t\omega dt \quad (14)$$

$$FD = (1000\times OS)^2 + (2000\times US)^2 + T_s^2 \quad (15)$$

$$IAE = 1000\int_0^{t_{sim}} \omega dt \quad (16)$$

$$ISE = 10000\int_0^{t_{sim}} \omega^2 dt \quad (17)$$

where, Overshoot (OS), Undershoot (US) and settling time of rotor angle deviation of machine is considered for evaluation of the FD. It is worth mentioning that the lower value of these indices is, the better the system response in terms of time domain characteristics. Numerical results of performance robustness for all operating conditions as given in Table 2 for scenario 2 are listed in Table 5. It can be seen that the values of these system performance characteristics with the proposed GSA based tuned coordinated PID type stabilizer and AVR are much smaller compared to that PSO-TVAC and PSO designed stabilizer. This demonstrates that the overshoot, undershoot, settling time and speed deviations of machine is greatly reduced by applying the proposed coordinated stabilizer and AVR.

Table 5. Performance indices value using different methods

No	GSA					PSO-TVAC					PSO				
	ITAE	*FD*	T_s	*IAE*	*ISE*	*ITAE*	*FD*	T_s	*IAE*	*ISE*	*ITAE*	*FD*	T_s	*IAE*	*ISE*
1	0.4993	2.9807	1.3071	0.2932	2.9104	0.8001	4.3901	1.3269	0.2813	4.4396	1.2860	6.6334	1.6800	0.2922	6.5030
2	0.9405	3.4404	1.3235	0.3981	3.5893	1.2279	5.3240	1.6200	0.3900	5.2626	1.7116	7.5164	2.0067	0.3947	7.3467
3	0.5283	2.9542	1.3136	0.2559	2.9359	0.9020	4.4194	1.3386	0.2407	4.5853	1.4141	6.9083	1.7100	0.2562	6.9286
4	0.4993	2.9807	1.3071	0.2932	2.9104	0.8001	4.3901	1.3269	0.2813	4.4396	1.2860	6.6334	1.6800	0.2922	6.5030
5	0.9405	3.4404	1.3235	0.3981	3.5893	1.2279	5.3240	1.6200	0.3900	5.2626	1.7116	7.5164	2.0067	0.3947	7.3467
6	0.5283	2.9542	1.3136	0.2559	2.9359	0.9020	4.4194	1.3386	0.2407	4.5853	1.4141	6.9083	1.7100	0.2562	6.9286
7	0.4993	2.9836	1.3100	0.2932	2.9105	0.8002	4.3934	1.3300	0.2813	4.4398	1.2858	6.6335	1.6800	0.2922	6.5033
8	0.5286	2.9537	1.3129	0.2559	2.9362	0.9024	4.4176	1.3364	0.2407	4.5858	1.4143	6.9092	1.7100	0.2562	6.9295
9	0.9403	3.4405	1.3236	0.3980	3.5894	1.2279	5.3240	1.6200	0.3899	5.2626	1.7116	7.5167	2.0069	0.3946	7.3469
10	0.5285	2.9539	1.3133	0.2559	2.9360	0.9020	4.4184	1.3375	0.2407	4.5856	1.4138	6.9090	1.7100	0.2562	6.9292

VI. CONCLUSIONS

This paper addresses a gravitational search algorithm optimization technique for coordinated design of the PID type stabilizer and AVR in a SMIB power system, simultaneously. To optimal setting stabilizer parameters and AVR gain, a nonlinear simulation-based objective function is developed to improve the system damping and then GSA technique has been successfully applied to search global optimum solution.

It is easy to implement without additional computational complexity and has fewer control parameters to randomly adjustment than the PSO. Thereby, the ability to jump out the local optima, the convergence precision and speed are remarkably improved and thus the high precision and efficiency are achieved. The effectiveness of the proposed GSA based tuned coordinated stabilizer and AVR is demonstrated on a weak connected example power system subjected to severe disturbance in comparison with PSO and PSO-TVAC methods to show its superiority.

The nonlinear simulation results under wide range of operating conditions show the capability the proposed coordinated PID type stabilizer and AVR to provide solution quality and efficient damping of low frequency oscillations and its superiority to the other methods.

APPENDIX

System Data

Generator: R_a=0, x_d= 2.0, x_q = 1.91, x'_d=0.244, x'_q=0.244, f = 50 Hz, T'_{do}=4.18, T'_{qo}=0.75, H=3.25

Transmission Line: R= 0, x_e = 0.3.

Exciter: T_A=0.05, E_{fdmax}=7.0, E_{fdmin}=-7.0

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