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Optimal gravitational search algorithm for automatic generation control of interconnected power systems



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Sensitivity

Abstract An attempt is made for the effective application of Gravitational Search Algorithm (GSA) to optimize PI/PIDF controller parameters in Automatic Generation Control (AGC) of interconnected power systems. Initially, comparison of several conventional objective functions reveals that ITAE yields better system performance. Then, the parameters of GSA technique are properly tuned and the GSA control parameters are proposed. The superiority of the proposed approach is demonstrated by comparing the results of some recently published techniques such as Differential Evolution (DE), Bacteria Foraging Optimization Algorithm (BFOA) and Genetic Algorithm (GA). Additionally, sensitivity analysis is carried out that demonstrates the robustness of the optimized controller parameters to wide variations in operating loading condition and time constants of speed governor, turbine, tie-line power. Finally, the proposed approach is extended to a more realistic power system model by considering the physical constraints such as reheat turbine, Generation Rate Constraint (GRC) and Governor Dead Band nonlinearity.

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1. Introduction

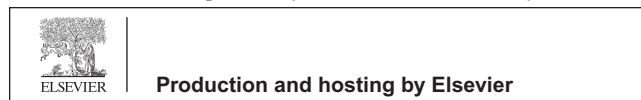
The main objective of a power system utility is to maintain continuous supply of power with an acceptable quality to all the consumers in the system. The system will be in equilibrium, when there is a balance between the power demand and the

power generated. There are two basic control mechanisms used to achieve power balance; reactive power balance (acceptable voltage profile) and real power balance (acceptable frequency values). The former is called the Automatic Voltage Regulator (AVR) and the latter is called the Automatic Load Frequency Control (ALFC) or Automatic Generation Control (AGC). For multiarea power systems, which normally consist of interconnected control area, AGC is an important aspect to keep the system frequency and the interconnected area tie-line power as close as possible to the intended values [1]. The mechanical input power to the generators is used to control the system as it is affected by the output electrical power demand and to maintain the power exchange between the areas as planned. AGC monitors the system frequency and tie-line flows, calculates the net change in the generation

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required according to the change in demand and changes the set position of the generators within the area so as to keep the time average of the ACE (Area Control Error) at a low value. ACE is generally treated as controlled output of AGC. As the ACE is adjusted to zero by the AGC, both frequency and tie-line power errors will become zero [2].

Several control strategies for AGC of power systems have been proposed in order to maintain the system frequency and tie line power flow at their scheduled values during normal and disturbed conditions. In [3], a critical literature review on the AGC of power systems has been presented. It is observed that, considerable research work is going on to propose better AGC systems based on modern control theory [4], neural network [5], fuzzy system theory [6], reinforcement learning [7] and ANFIS approach [8]. But, these advanced approaches are complicated and need familiarity of users to these techniques thus reducing their applicability. Alternatively, a classical Proportional Integral Derivative (PID) controller and its variant remain an engineer's preferred choice due to its structural simplicity, reliability, and the favorable ratio between performances and cost. Additionally, it also offers simplified dynamic modeling, lower user-skill requirements, and minimal development effort, which are major issues of in engineering practice. In recent times, new artificial intelligence-based approaches have been proposed to optimize the PI/PID controller parameters for AGC system. In [9], several classical controllers structures such as Integral (I), Proportional Integral (PI), Integral Derivative (ID), PID and Integral Double Derivative (IDD) have been applied and their performance has been compared for an AGC system. Nanda et al. [10] have demonstrated that Bacterial Foraging Optimization Algorithm (BFOA) optimized controller provides better performance than GA based controllers and conventional controllers for an interconnected power system. In [11], Ali and Abd-Elazim have employed a BFOA to optimize the PI controller parameters and shown its superiority over GA in a two area non-reheat thermal system. A gain scheduling PI controller for an AGC system has been proposed by Gozde and Taplamacioglu [12] for a two area thermal power system with governor dead-band nonlinearity where the authors have employed a Craziness based Particle Swarm Optimization (CPSO) with different objective functions to minimize the settling times and standard error criteria. Shabani et. al [13] employed an Imperialist Competitive Algorithm (ICA) to optimize the PID controller parameters in a multiarea multiunit power system. In [14], a modified objective function using Integral of Time multiplied by Absolute value of Error (ITAE), damping ratio of dominant eigenvalues and settling time is proposed where the PI controller parameters are optimized employed Differential Evolution (DE) algorithm and the results are compared with BFOA and GA optimized ITAE based PI controller to show its superiority.

It obvious from literature survey that, the performance of the power system not only depends on the artificial techniques employed but also depends on the controller structure and chosen objective function. Hence, proposing and implementing new high performance heuristic optimization algorithms to real world problems are always welcome. Gravitational Search Algorithm (GSA) is a newly developed heuristic optimization method based on the law of gravity and mass interactions [15]. It has been reported in the literature that GSA is more

efficient in terms of CPU time and offers higher precision with more consistent results [16]. However, studied on choosing the controller parameters of GSA has not been reported in the literature. In a PID controller, the derivative mode improves stability of the system and increases speed of the controller response but it produces unreasonable size control inputs to the plant. Also, any noise in the control input signal will result in large plant input signals which often lead to complications in practical applications. The practical solution to these problems is to put a first filter on the derivative term and tune its pole so that the chattering due to the noise does not occur since it attenuates high frequency noise. Surprisingly, in spite of these advantages, Proportional Integral Derivative with derivative Filter (PIDF) controller structures are not attempted for the AGC problems. Having known all this, an attempt has been made in the present paper for the optimal design of GSA based PI/PIDF controller for AGC in a multiarea interconnected power system.

The aim of the present work is as follows:

- (i) to study the effect of objective function of the system performance
- (ii) to tune the control parameters of GSA
- (iii) to demonstrate the advantages of GSA over other techniques such as DE, BFOA and GA which are recently reported in the literature for the similar problem
- (iv) to show advantages of using a modified controller structure and objective function to further increase the performance of the power system
- (v) to study the effect of the physical constraints such as Generation Rate Constraints and governor dead band on the system performance.

2. System modeling

The system under investigation consists of two area interconnected power system of non-reheat thermal plant as shown in Fig. 1. Each area has a rating of 2000 MW with a nominal load of 1000 MW. The system that is widely used in the literature is for the design and analysis of automatic load frequency control of interconnected areas. In Fig. 1, B_1 and B_2 are the frequency bias parameters; ACE_1 and ACE_2 are area control errors; u_1 and u_2 are the control outputs from the controller; R_1 and R_2 are the governor speed regulation parameters in pu Hz; T_{G1} and T_{G2} are the speed governor time constants in s; ΔP_{V1} and ΔP_{V2} are the change in governor valve positions (pu); ΔP_{G1} and ΔP_{G2} are the governor output command (pu); T_{T1} and T_{T2} are the turbine time constant in s; ΔP_{T1} and ΔP_{T2} are the change in turbine output powers; ΔP_{D1} and ΔP_{D2} are the load demand changes; ΔP_{Tie} is the incremental change in tie line power (p.u); K_{PS1} and K_{PS2} are the power system gains; T_{PS1} and T_{PS2} are the power system time constant in s; T_{12} is the synchronizing coefficient and Δf_1 and Δf_2 are the system frequency deviations in Hz. The relevant parameters are given in Appendix A.

Each area of the power system consists of speed governing system, turbine and generator as shown in Fig. 1. Each area has three inputs and two outputs. The inputs are the controller input ΔP_{ref} (denoted as u_1 and u_2), load disturbances (denoted as ΔP_{D1} and ΔP_{D2}), and tie-line power error ΔP_{Tie} . The

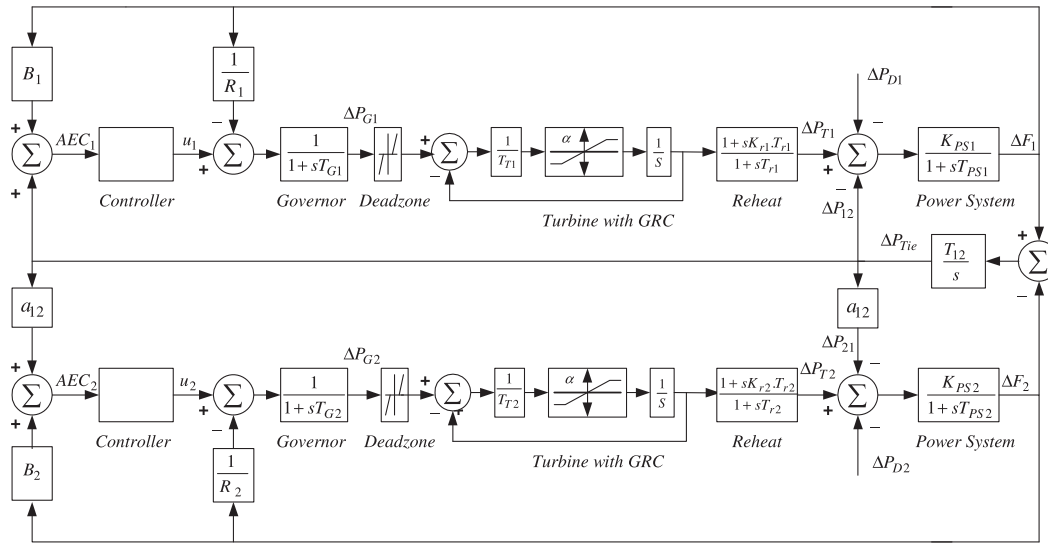


Figure 1 Transfer function model of two-area non-reheat thermal system.

outputs are the generator frequency deviations (denoted as ΔF_1 and ΔF_2) and Area Control Error (ACE) given by [2].

$$ACE = B\Delta F + \Delta P_{Tie} \quad (1)$$

where B is the frequency bias parameter.

To simplicity the frequency-domain analyses, transfer functions are used to model each component of the area. Turbine is represented by the transfer function [2]:

$$G_T(s) = \frac{\Delta P_T(s)}{\Delta P_V(s)} = \frac{1}{1 + sT_T} \quad (2)$$

From [2], the transfer function of a governor is as follows:

$$G_G(s) = \frac{\Delta P_V(s)}{\Delta P_G(s)} = \frac{1}{1 + sT_G} \quad (3)$$

The speed governing system has two inputs ΔP_{ref} and ΔF with one output $\Delta P_G(s)$ given by [2]:

$$\Delta P_G(s) = \Delta P_{ref}(s) - \frac{1}{R} \Delta F(s) \quad (4)$$

The generator and load is represented by the transfer function [2]:

$$G_P(s) = \frac{K_P}{1 + sT_P} \quad (5)$$

where $K_P = 1/D$ and $T_P = 2H/fD$.

The generator load system has two inputs $\Delta P_T(s)$ and $\Delta P_D(s)$ with one output $\Delta F(s)$ given by [2]:

$$\Delta F(s) = G_P(s)[\Delta P_T(s) - \Delta P_D(s)] \quad (6)$$

3. Overview of Gravitational Search Algorithm

Gravitational Search Algorithm (GSA) is one of the newest heuristic algorithms inspired by the Newtonian laws of gravity and motion [15]. In GSA, agents are considered as objects and their performance is measured by their masses. All these objects attract each other by the force of gravity and this force causes a global movement of all objects toward the objects with a heavier mass. Hence masses co-operate using a direct

form of communication through gravitational force. The heavy masses that correspond to good solution move more slowly than lighter ones, and this guarantees the exploitation step of the algorithm.

In GSA, each mass (agent) has four specifications: position, inertial mass, active gravitational mass and passive gravitational mass. The position of the mass corresponds to a solution of the problem and its gravitational and inertia masses are determined using a fitness function. In other words each mass presents a solution and the algorithm is navigated by properly adjusting the gravitational and inertia masses. By lapse of time it is expected that masses be attracted by the heavier mass. This mass will present an optimum solution in the search space. The GSA could be considered as an isolated system of masses. It is like a small artificial world of masses obeying the Newtonian laws of gravitation and motion. Masses obey the following laws [15,16].

3.1. Law of gravity

Each particle attracts every other particle and the gravitational force between the two particle is directly proportional to the product of their masses and inversely proportional to the distance between them R . It has been reported in the literature that R provides better results than R^2 in all experiment cases [15].

3.2. Law of motion

The current velocity of any mass is equal the sum of the fraction of its previous velocity and the variation in the velocity. Variation in the velocity or acceleration of any mass is equal to the force acted on the system divided by mass of inertia.

For a system with 'n' agent (masses), the i th position of an agent X_i is defined by:

$$X_i = (x_i^1, \dots, x_i^d, \dots, x_i^n) \quad \text{for } i = 1, 2, \dots, n \quad (7)$$

where, x_i^d is the represents the position of i th agent in the d th dimension.

At a specific time ' t ', the force acting on mass ' i ' from mass ' j ' is defined as follows:

$$F_{ij}^d(t) = G(t) \frac{M_{pi}(t) * M_{aj}(t)}{R_{ij}(t) + \epsilon} (x_j^d(t) - x_i^d(t)) \quad (8)$$

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

$$R_{ij}(t) = \|X_i(t), X_j(t)\|_2 \quad (9)$$

The stochastic characteristic in GSA algorithm is incorporated by assuming that the total forces that act on agent ' i ' in a dimension ' d ' be a randomly weight sum of d th components of the forces exerted from other agents as follows:

$$F_i^d(t) = \sum_{j=1, j \neq i}^n rand_j F_{ij}^d(t) \quad (10)$$

where $rand_j$ is a random number in the interval $[0, 1]$

The acceleration of the agent ' i ' at the time t and in the direction d th, is given by the law of the motion as:

$$a_i^d(t) = \frac{F_i^d(t)}{M_{ii}(t)} \quad (11)$$

where $M_{ii}(t)$ is the inertia mass of i th agent.

The velocity of an agent is updated depending on the current velocity and acceleration. The velocity and position are updated as follows:

$$v_i^d(t+1) = rand_i * v_i^d(t) + a_i^d(t) \quad (12)$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \quad (13)$$

where $rand_i$ is a uniform random variable in the interval $(0, 1)$. The random number is used to give a randomized characteristic to the search process.

The gravitational constant G is initialized at the beginning. To control the search accuracy it is reduced with time and expressed as function of the initial value (G_0) and time t as:

$$G(t) = G_0 e^{(-\alpha t/T)} \quad (14)$$

where α is a constant and T is the number of iteration.

The masses (gravitational and inertia) are evaluated by the fitness function. Efficient agents are characterized by heavier masses. Assuming the equal gravitational and inertia mass, the values of masse are calculated using the map of fitness. The gravitational and inertial masses are updated as follows:

$$M_{ai} = M_{pi} = M_{ii} = M_i, \quad i = 1, 2, \dots, n. \quad (15)$$

$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \quad (16)$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^N m_j(t)} \quad (17)$$

where $fit_i(t)$ represents the fitness value of the agent ' i ' at time t and $best(t)$ is defined for a minimization problem as:

$$Best(t) = \min_{j \in \{1..n\}} fit_j(t) \quad (18)$$

$$Worst(t) = \max_{j \in \{1..n\}} fit_j(t) \quad (19)$$

To achieve a good compromise between exploration and exploitation, the number of agents is reduced with lapse of Eq. (10) and therefore a set of agents with bigger mass are used for applying their force to the other.

The performance of GSA is improved by controlling exploration and exploitation. To avoid trapping in a local optimum GSA must use the exploration at beginning. By lapse of iterations, exploration must fade out and exploitation must fade in. In GSA only the $Kbest$ (which is a function of time, with the initial value K_0 at the beginning and decreasing with time) agents attract the others. At the beginning, all agents apply the force, and as time passes $Kbest$ is decreased linearly and at the end there is just one agent applying force to the others. Therefore, Eq. (10) is modified as follows:

$$F_i^d(t) = \sum_{j \in Kbest, j \neq i} rand_j F_{ij}^d(t) \quad (20)$$

where $Kbest$ is the set of first K agents with the best fitness value and biggest mass k .

The different steps of the GSA are the followings:

- i. Identify the search space of parameters to be searched.
- ii. Initialize the variables.
- iii. Evaluate the fitness of each agent.
- iv. Update $G(t)$, $best(t)$, $worst(t)$ and $M_i(t)$ for $i = 1, 2, \dots, n$.
- v. Calculate the total force in various directions.
- vi. Calculate the acceleration and velocity.
- vii. Update the position of the agents.
- viii. Repeat steps (iii) to (vii) until the stop criteria is reached.
- ix. End.

GSA is characterized as a simple concept which is easy to implement and computationally efficient. In order to improve exploration and exploitation capabilities, GSA has a flexible and balanced mechanism. More precise search is achieved by assuming a higher inertia mass which causes a slower motion of agents in the search space. Faster convergence is obtained by considering a higher gravitational mass which causes a higher attraction of agents. GSA is a memory-less algorithm but works powerfully like the other memory based algorithms. The nature inspired population based techniques have proved themselves to be effective solutions to optimization problems control parameters and objective function is involved in these optimization techniques, and appropriate selection of these is a key point for success. It has been reported that, GSA tends to find the global optimum faster than other algorithms and has a higher convergence rate for uni-modal high-dimensional functions. The performance of GSA for multi-modal functions is comparable with other algorithms [15].

4. The proposed approach

4.1. Controller structure

The Proportional Integral Derivative Controller (PID) is the most popular feedback controller used in the process industries. It is a robust, easily understood controller that can provide excellent control performance despite the varied dynamic characteristics of process plant. As the name suggests, the PID algorithm consists of three basic modes, the proportional mode, the integral and the derivative modes. A proportional

controller has the effect of reducing the rise time, but never eliminates the steady-state error. An integral control has the effect of eliminating the steady-state error, but it may make the transient response worse. A derivative control has the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response. Proportional integral (PI) controllers are the most often type used today in industry. A control without derivative (D) mode is used when: fast response of the system is not required, large disturbances and noises are present during operation of the process and there are large transport delays in the system. PID controllers are used when stability and fast response are required. Derivative mode improves stability of the system and enables increase in proportional gain and decrease in integral gain which in turn increases speed of the controller response. However, when the input signal has sharp corners, the derivative term will produce unreasonable size control inputs to the plant. Also, any noise in the control input signal will result in large plant input signals. These reasons often lead to complications in practical applications. The practical solution to these problems is to put a first filter on the derivative term and tune its pole so that the chattering due to the noise does not occur since it attenuates high frequency noise. In view of the above a filter is used for the derivative term in the present paper.

In the present paper, identical controllers have been considered for the two areas as the two areas are identical. The structure of PID controller with derivative filter is shown in Fig. 2 where K_P , K_I and K_D are the proportional, integral and derivative gains respectively, and N is the derivative filter coefficient. When used as PI controller, the derivative path along with the filter is removed from Fig. 2. The error inputs to the controllers are the respective area control errors (ACE) given by:

$$e_1(t) = ACE_1 = B_1 \Delta F_1 + \Delta P_{Tie} \quad (21)$$

$$e_2(t) = ACE_2 = B_2 \Delta F_2 - \Delta P_{Tie} \quad (22)$$

The control inputs of the power system u_1 and u_2 are the outputs of the controllers. The transfer function of the controller is given by:

$$TF_{PID} = \left[K_P + K_I \left(\frac{1}{s} \right) + K_D \left(\frac{Ns}{s+N} \right) \right] \quad (23)$$

4.2. Objective function

While designing a controller, the objective function is first defined based on the desired specifications and constraints. The design of objective function to tune controller parameters is

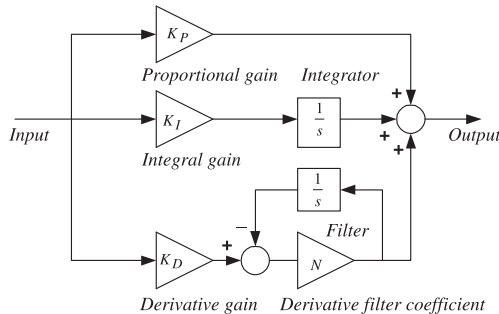


Figure 2 Structure of PID controller with derivative filter.

generally based on a performance index that considers the entire closed loop response. Some of the realistic control specifications for Automatic Generation Control (AGC) are as follows [2]:

- (i) The frequency error should return to zero following a load change.
- (ii) The integral of frequency error should be minimum.
- (iii) The control loop must be characterized by a sufficient degree of stability.
- (iv) Under normal operating conditions, each area should carry its own load and the power exchange between control areas following a load perturbation should maintained at its prescheduled value as quickly as possible.

To determining the optimum values of controller parameters conventional objective functions are considered at the first instance. Time-domain techniques based on objective functions can be classified into two groups: (a) Criteria based on a few points in the response (b) Criteria based on the entire response, or integral criteria. The integral criteria are generally accepted as a good measure for system performance. An advantage of using the integral gain is that it can be easily extended to a multi-loop system. The commonly used integral based error criteria are as follows: Integral of Squared Error (ISE), Integral of Absolute Error (IAE), Integral of Time multiplied Squared Error (ITSE) and Integral of Time multiply by Absolute Error (ITAE). These integral based objective functions for the present problem are expressed as given below:

$$J_1 = ISE = \int_0^{t_{sim}} (|\Delta F_1| + |\Delta F_2| + |\Delta P_{Tie}|)^2 \cdot dt \quad (24)$$

$$J_2 = IAE = \int_0^{t_{sim}} (|\Delta F_1| + |\Delta F_2| + |\Delta P_{Tie}|) \cdot dt \quad (25)$$

$$J_3 = ITSE = \int_0^{t_{sim}} (|\Delta F_1| + |\Delta F_2| + |\Delta P_{Tie}|)^2 \cdot t \cdot dt \quad (26)$$

$$J_4 = ITAE = \int_0^{t_{sim}} (|\Delta F_1| + |\Delta F_2| + |\Delta P_{Tie}|) \cdot t \cdot dt \quad (27)$$

In the above equations, ΔF_1 and ΔF_2 are the system frequency deviations; ΔP_{Tie} is the incremental change in tie line power; t_{sim} is the time range of simulation.

The problem constraints are the PI/PIDF controller parameter bounds. Therefore, the design problem can be formulated as the following optimization problem.

$$\text{Minimize } J \quad (28)$$

Subject to

$$\text{For PI controller : } K_{P_{min}} \leq K_P \leq K_{P_{max}}, \quad K_{I_{min}} \leq K_I \leq K_{I_{max}} \quad (29)$$

$$\text{For PIDF controller : } K_{P_{min}} \leq K_P \leq K_{P_{max}}, \\ K_{I_{min}} \leq K_I \leq K_{I_{max}}, \quad K_{D_{min}} \leq K_D \leq K_{D_{max}} \quad (30)$$

where J is the objective function (J_1 , J_2 , J_3 and J_4) and $K_{PID_{min}}$ and $K_{PID_{max}}$, are the minimum and maximum value of the PI/PID control parameters. As reported in the literature [10–14,17], the minimum and maximum values of PID controller parameters are chosen as -2.0 and 2.0 respectively. The range for filter coefficient N is selected as 1 and 100 [17].

5. Results and discussions

5.1. Application of GSA

At the first instance physical constraints such as reheat turbine, Generation Rate Constraint and governor dead band are neglected. In the absence of above physical constraints, the studied power system becomes similar to that used in references [11,14]. The model of the system under study is developed in MATLAB/SIMULINK environment and GSA program is written (in .mfile). The developed model is simulated in a separate program (by .mfile using initial population/controller parameters) considering a 10% step load change in area 1. The objective function is calculated in the .mfile and used in the optimization algorithm. At the first instance, the following parameters are chosen for the application of GSA: population size $NP = 30$; maximum iteration = 500; gravitational constants $G_0 = 30$ and $\alpha = 10$; $K_0 =$ total number of agents and decreases linearly to 1 with time [18]. Optimization is terminated by the prespecified number of generations. The flow-chart of proposed optimization is shown in Fig. 3. Simulations were conducted on an Intel, core 2 Duo CPU of 2.4 GHz and 2 GB MB RAM computer in the MATLAB 7.10.0.499 (R2010a) environment. The optimization was repeated 50

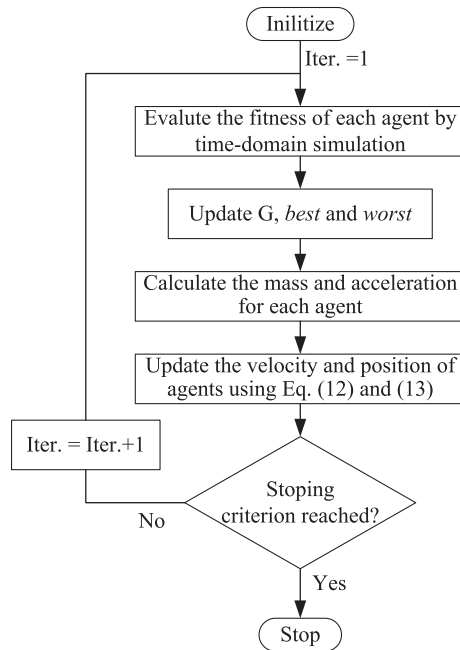


Figure 3 Flow chart of proposed GSA optimization approach.

times and the best final solution among the 50 runs is chosen as final controller parameters. The best final solutions obtained in the 50 runs for each objective functions are shown in Table 1. To investigate the effect of objective function on the dynamic performance of the system, settling times (2% of final value) and peak overshoots in frequency and tie-line power deviations along with minimum damping ratios are also provided in Table 1. It can be seen from Table 1 that best system performance is obtained with maximum value of damping ratio and minimum values of settling times and peak overshoots in frequency and tie-line power deviations when ITAE is used as objective function.

5.2. GSA parameters tuning

The success of GSA is heavily dependent on setting of control parameters namely; constant α , initial gravitational constant G_0 , population size NP and number of iteration T . While applying GSA these control parameters should be carefully chosen for the successful implementation of the algorithm. A series of experiments were conducted to properly tune the GSA control parameters in order to optimize the PI parameters employing ITAE objective function. Table 2 shows the GSA outcomes as a result of varying its control parameters. To quantify the results, 50 independent runs were executed for each parameter variation. It is clear from results shown in Table 2 that the best settings for constant α , gravitational constant G_0 , population size NP and number of iteration T are $\alpha = 20$, $G_0 = 100$, $NP = 20$ and $T = 100$ respectively. Note that increasing the population size NP beyond 20 and iterations T beyond 100 will improve the average, maximum and standard deviation values slightly (with same minimum value) at the expense of increasing the computation time significantly.

5.3. Modified objective function

Once the GSA control parameters are set, modifications in the objective function and controller structure are considered to further improve the performance of the power system. The modified objective function J_5 tries to minimize the ITAE error, maximizes the minimum damping ratios of dominant eigenvalues and minimizes the settling times of Δf_1 , Δf_2 and ΔP_{Tie} as given by Eq. (31) below:

$$J_5 = \int_0^{t_{sim}} \omega_1 \cdot \int_0^{t_{sim}} (|\Delta F_1| + |\Delta F_2| + |\Delta P_{Tie}|) \cdot t \cdot dt + \omega_2 \cdot \frac{1}{\min(\sum_{i=1}^n (1 - \zeta_i))} + \omega_3(ST) \quad (31)$$

Table 1 Tuned controller parameters, settling time, peak overshoot and minimum damping ratio for each objective function.

Objective function	Controller parameters		T_s (s)			Peak overshoot			ζ
	Proportional gain (K_p)	Integral gain (K_I)	ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}	
J_1 :ISE	-0.0120	0.8641	21.30	21.30	15.10	0.0594	0.0877	0.0152	0.0626
J_2 :IAE	-0.0117	0.7668	18.00	18.00	12.90	0.0450	0.0710	0.0119	0.0733
J_3 :ITSE	-0.1228	0.7849	16.20	16.20	11.10	0.0499	0.0838	0.0127	0.0882
J_4 :ITAE	-0.1701	0.6492	12.00	11.90	8.90	0.0390	0.0590	0.0083	0.1144

Bold signifies the best results.

Table 2 Study of tuning GSA parameters.

Parameter	Min	Ave	Max	St. Dev	Other parameters
$\alpha = 10$	0.6659897	0.8980626	1.0123918	0.1265678	NP = 20, $T = 50$, $G_0 = 100$
$\alpha = 15$	0.6659897	0.7841139	1.0001651	0.1267459	
$\alpha = 20$	0.6659897	0.7291873	0.9182768	0.0802699	
$\alpha = 25$	0.6749712	0.9000713	0.9754091	0.1228549	
$\alpha = 30$	0.6870195	0.9164638	1.0123918	0.1375834	
$G_0 = 30$	0.6659945	0.8046012	1.0123918	0.1184529	NP = 20, $T = 50$, $\alpha = 20$
$G_0 = 70$	0.6659988	0.8512434	1.0225763	0.1282661	
$G_0 = 100$	0.6659897	0.7291873	0.9182768	0.0802699	
$G_0 = 130$	0.6680531	0.7790509	1.0225763	0.1055190	
$G_0 = 150$	0.6678854	0.7991217	1.0035452	0.1988937	
NP = 10	0.6881325	0.8231840	1.0315944	0.1988937	$T = 50$, $\alpha = 20$, $G_0 = 100$
NP = 15	0.6706229	0.8019416	0.9426240	0.1250767	
NP = 20	0.6659897	0.7291873	0.9182768	0.0802699	
NP = 25	0.6659897	0.7280129	0.9146560	0.0702121	
NP = 30	0.6659897	0.7279858	0.9135081	0.0679424	
$T = 30$	0.6650960	0.8781403	0.9742163	0.1040270	NP = 20, $G_0 = 100$, $\alpha = 20$
$T = 50$	0.6659897	0.7291873	0.9182768	0.0802699	
$T = 100$	0.6659897	0.6774539	0.8739539	0.0571679	
$T = 200$	0.6659897	0.6764037	0.8739539	0.0570019	

Bold signifies the best results.

Table 3 Tuned controller parameter and error with ITAE objective function.

Technique	Tuned controller parameter				ITAE
	K_P	K_I	K_D	N	
GA:PI [11]	-0.2346	0.2662	-	-	2.7474
BFOA:PI [11]	-0.4207	0.2795	-	-	1.8270
DE:PI [14]	-0.2146	0.4335	-	-	0.9911
GSA:PI	-0.1880	0.6179	-	-	0.6659
GSA:PIDF	1.1884	1.9589	0.3456	54.3260	0.1174

Bold signifies the best results.

where, ΔF_1 and ΔF_2 are the system frequency deviations; ΔP_{Tie} is the incremental change in tie line power; t_{sim} is the time range of simulation; ζ_i is the damping ratio and n is the total number of the dominant eigenvalues; ST is the sum of the settling times of frequency and tie line power deviations respectively; ω_1 to ω_3 are weighting factors. Inclusion of appropriate weighting factors to the right hand individual terms helps to make each term competitive during the optimization process. Wrong choice of the weighting factors leads to incompatible numerical values of each term involved in the definition of fitness function which gives misleading result. The weights are so chosen that numerical value of all the terms in the right hand side of Eq. (31) lie in the same range. Repetitive trial runs of the optimizing algorithms are executed with both PI and PIDF

controller to select the weights. To make each term competitive during the optimization process the following weights are chosen: PI controller: $\omega_1 = 1.0$, $\omega_2 = 0.3$ and $\omega_3 = 0.08$ and PIDF controller: $\omega_1 = 1.0$, $\omega_2 = 0.05$ and $\omega_3 = 0.02$. A 10% step load change in area 1 is considered at $t = 0$ s and the optimum PI and PIDF controller parameters with ITAE and modified objective function are obtained employing tuned GSA parameters as given in Tables 3 and 4. The ITAE values, minimum damping ratios and settling times (2% of final value) for above controllers are also provided in Table 4. For comparison, the results of some recently published technique/controller/objective function for the same power system are also given in the Tables 3 and 4.

5.4. Analysis of results

It is clear from Table 3 that with PI structured controller and ITAE objective function (J_d), minimum ITAE value is obtained with GSA (ITAE = 0.6659) compared to ITAE values with GA (ITAE = 2.74), BFOA (ITAE = 1.827) and DE (ITAE = 0.9911) techniques. So it can be concluded that for the similar controller structure (PI) and same objective function (ITAE) GSA outperforms GA, BFOA and DE techniques. It is also evident from Table 3 that minimum ITAE value (ITAE = 0.1174) is obtained with a PIDF controller and therefore the performance of PIDF controller is superior to that of PI controller. When ITAE is used as objective

Table 4 Settling time, minimum damping ratio and error with modified objective function.

Technique	Tuned controller parameter				Settling time T_s (s)			ζ	ITAE
	K_P	K_I	K_D	N	ΔF_1	ΔF_2	ΔP_{tie}		
DE:PI [14]	-0.4233	0.2879	-	-	5.38	6.95	6.21	0.2361	1.6766
GSA:PI	-0.4383	0.3349	-	-	5.17	6.81	4.59	0.2374	1.3096
GSA:PIDF	1.4011	1.9981	0.7102	93.2760	1.92	3.19	2.86	0.4470	0.1362

Bold signifies the best results.

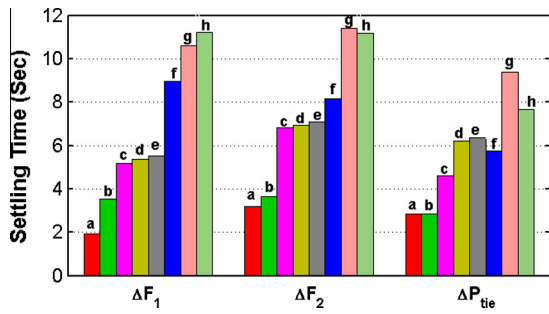


Figure 4 Comparison of settling time (a) GSA PIDF:J₅; (b) GSA PIDF:J₄; (c) GSA PI:J₅; (d) DE PI:J₅; (e) BFOA PI:J₄; (f) DE PI:J₄; (g) GA PI:J₄; (h) GSA PI:J₄.

function, the system performance in terms of minimum damping ratio and settling times of ΔF_1 , ΔF_2 and ΔP_{Tie} with GSA are inferior to GA, BFOA and DE. However, when the modified objective function (J_5) given by Eq. (31) is used better performance is obtained in all respects. The minimum damping ratio ($\zeta = 0.2374$), ITAE value (ITAE = 1.3096) and settling times (5.17, 6.81 and 4.59 s for ΔF_1 , ΔF_2 and ΔP_{Tie} respectively) are better compared to those with DE, BFOA and GA technique as shown in Table 4. The best system performance is obtained with GSA optimized PIDF controller optimized using the modified objective function as evident from Table 4. For better visualization of the improvements with the proposed approach, the above results are presented graphically in Fig. 4.

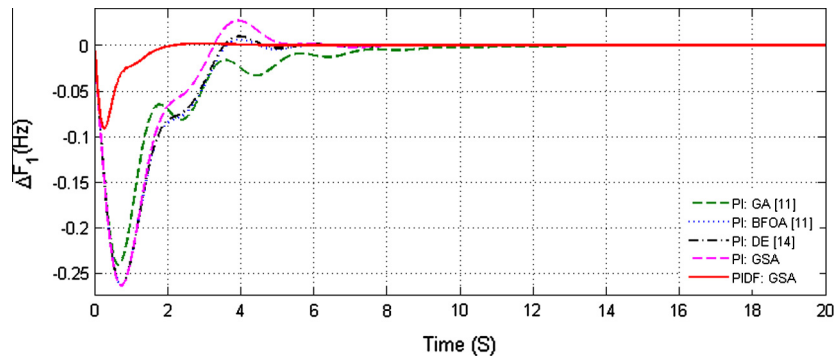


Figure 5 Change in frequency of area-1 for 10% change in area-1.

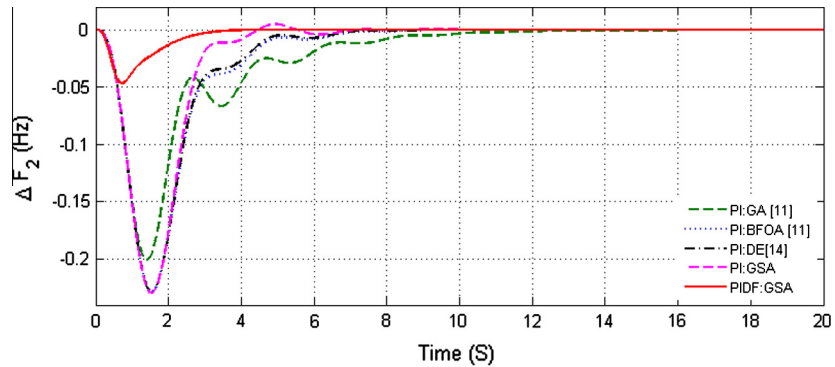


Figure 6 Change in frequency of area-2 for 10% change in area-1.

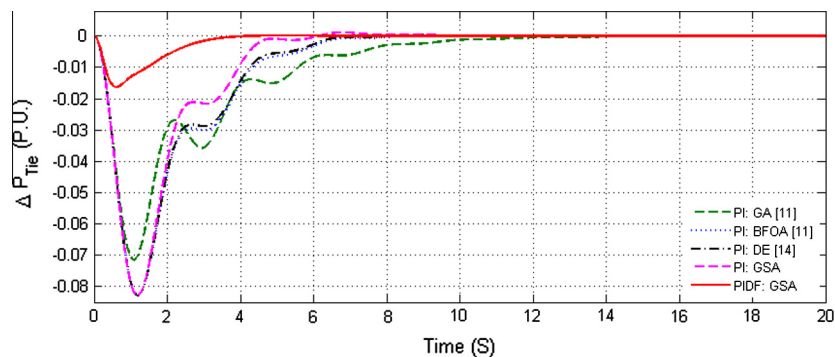


Figure 7 Change in the tie line power for 10% change in area-1.

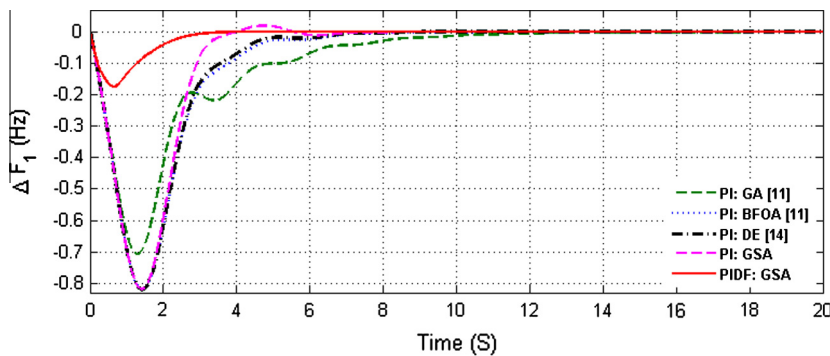


Figure 8 Change in frequency of area-1 for 10% change in area-1 and 30% change in area-2.

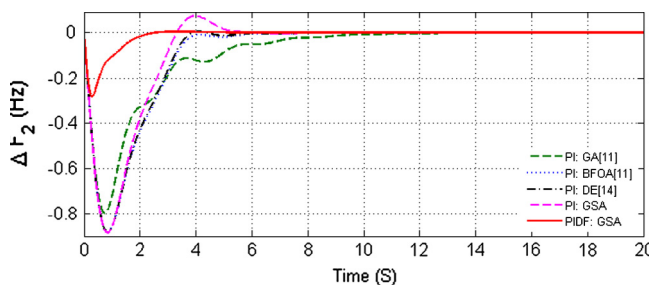


Figure 9 Change in frequency of area-2 for 10% change in area-1 and 30% change in area-2.

To study the dynamic performance of the proposed controllers optimized employing tuned GSA using modified objective function (J_5), a step increase in demand of 10% is applied at $t = 0$ s in area-1 and the system dynamic responses are shown in Figs. 5–7. For comparison, the simulation results with GA and BFOA optimized PI controller using ITAE objective function [11] and DE optimized PI controller using modified objective function [14] for the same power system are also shown in Figs. 5–7. Critical analysis of the dynamic responses clearly reveals that significant improvement is observed with PIDF controller optimized employing GSA using modified objective function (J_5) compared to GA, BFOA and DE PI.

The performance of the proposed controllers is further investigated for simultaneous load disturbance at both areas. A simultaneous step increase in demand of 10% in area-1

and 30% in area-2 is considered at $t = 0$ s and the system responses are shown in Figs. 8–10 from which it is evident that the designed controllers are robust and perform satisfactorily when the location of the disturbance changes.

5.5. Sensitivity analysis

Sensitivity analysis is carried out to study the robustness the system to wide changes in the operating conditions and system parameters [9,10]. Taking one at a time, the operating load condition and time constants of speed governor, turbine, tie-line power are changed from their nominal values (given in Appendix A) in the range of +50% to –50% in steps of 25%. PIDF controller optimized employing GSA using modified objective function J_5 is considered due to its superior performance.

The optimum values of controller parameters, at changed loading conditions and changed system parameters (for a step increase in demand of 10% at $t = 0$ s in area-1) are provided in Table 5. The corresponding performance indexes (ITAE values, settling times and minimum damping ratios) with the above varied system conditions are given in Table 5. Critical examination of Table 5 clearly reveals that the performance indexes are more or less same. The frequency deviation response of area 1 with above varied conditions is shown in Figs. 11–14. It can be observed from Figs. 11–14 that the effect of the variation in operating loading conditions and system time constants on the system responses is negligible. So it can be concluded that, the proposed control strategy provides a robust control and the controller parameters obtained at the nominal

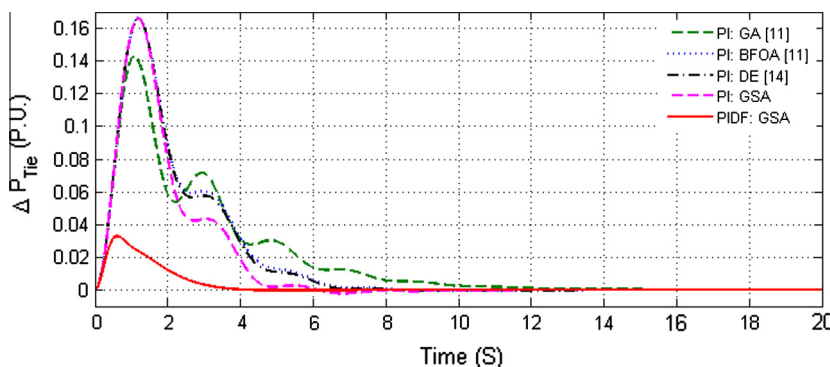


Figure 10 Change in tie line power for 10% change in area-1 and 30% change in area-2.

Table 5 Sensitivity analysis of system without physical constraints.

Parameter variation	% Change	Tuned controller parameter				Settling time, T_s (s)			ζ	ITAE
		K_P	K_I	K_D	N	ΔF_1	ΔF_2	ΔP_{tie}		
Nominal	0	1.4011	1.9981	0.7102	93.2760	1.92	3.19	2.86	0.4470	0.1362
Loading condition	+50	1.4103	1.9945	0.7257	89.0014	1.96	3.21	2.88	0.4501	0.1386
	+25	1.4081	1.9983	0.7255	92.7390	1.95	3.20	2.87	0.4515	0.1379
	-25	1.4067	1.9909	0.7137	86.4434	1.94	3.20	2.87	0.4424	0.1372
	-50	1.4178	1.9901	0.7052	93.9838	1.93	3.22	2.88	0.4409	0.1362
T_G	+50	1.5001	1.9923	0.7746	95.0011	1.99	3.29	2.92	0.2906	0.1373
	+25	1.4386	1.9942	0.7212	93.7709	1.89	3.23	2.88	0.3518	0.1348
	-25	1.3293	1.9991	0.6013	94.9823	1.83	3.14	2.79	0.5067	0.1315
	-50	1.3112	1.9986	0.6021	90.4946	1.87	3.11	2.79	0.5949	0.1313
T_T	+50	1.5792	1.9338	0.8224	91.9358	1.82	3.37	2.99	0.3368	0.1349
	+25	1.4975	1.9972	0.7406	94.9587	1.80	3.24	2.88	0.3728	0.1322
	-25	1.3002	1.9992	0.6004	95.0012	1.93	3.16	2.81	0.5032	0.1360
	-50	1.3009	1.9911	0.6009	94.8310	2.09	3.25	2.86	0.5112	0.1483
T_{12}	+50	1.4165	1.9980	0.7496	94.9982	2.19	2.98	2.71	0.3107	0.1386
	+25	1.4127	1.9870	0.7006	95.0012	2.10	3.09	2.78	0.3608	0.1354
	-25	1.4145	1.9920	0.7002	94.9467	3.57	3.48	3.05	0.5417	0.1375
	-50	1.2517	1.9989	0.6025	94.0867	4.10	3.83	3.24	0.6683	0.1264

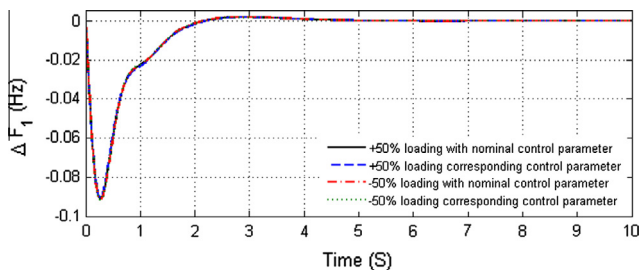


Figure 11 Frequency deviation of area-1 for change in nominal load.

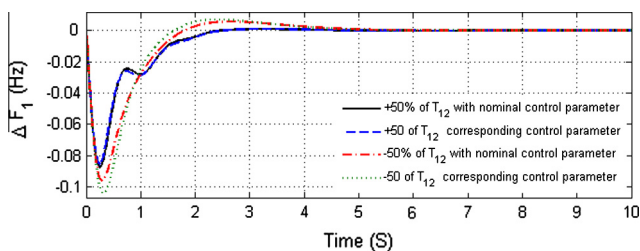


Figure 12 Frequency deviation of area-1 for change in T_{12} .

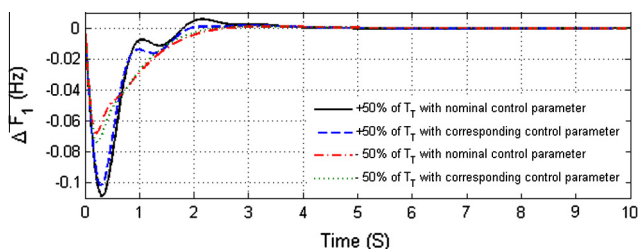


Figure 13 Frequency deviation of area-1 for change in T_T .

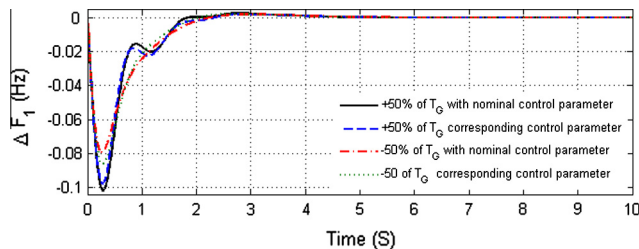


Figure 14 Frequency deviation of area-1 for change in T_G .

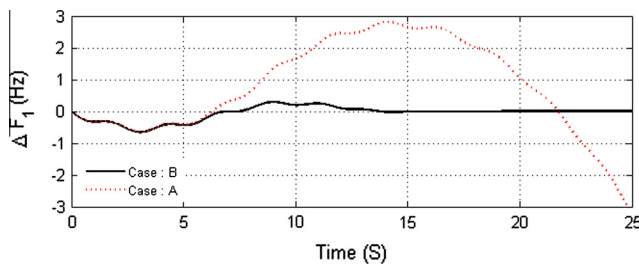


Figure 15 Change in frequency of area-1 for 10% change in area-1.

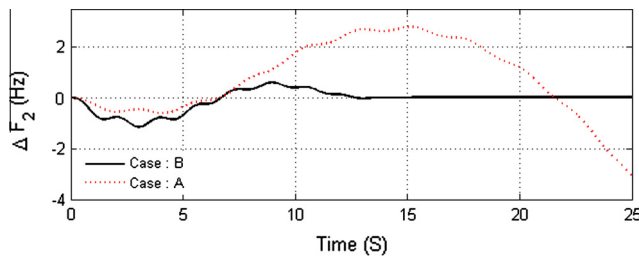


Figure 16 Change in frequency of area-2 for 10% change in area-1.

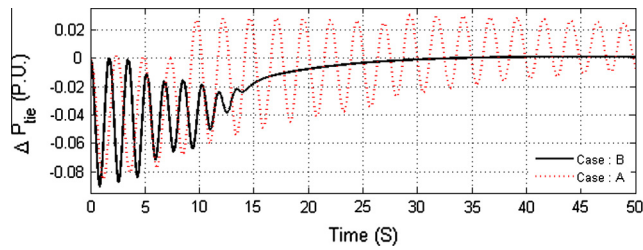


Figure 17 Change in tie line power for 10% change in area-1.

loading with nominal parameters, need not be reset for wide changes in the system loading or system parameters.

5.6. Inclusion of physical constraints

To get an accurate insight into the AGC problem, it is necessary to include the important inherent requirement and the basic physical constraints and include them model. The major constraints that affect the power system performance are reheat turbine, Generation Rate Constraint (GRC), and governor dead band (GBD) nonlinearity [19]. In view of the above, the study is further extended to a more realistic power system by considering the effect of reheat turbine, GRC, and GBD. As most of the thermal plants are of reheat type, a reheat turbine is also considered in the proposed realistic power system model. In a power system having steam plants, power generation can change only at a specified maximum rate. The generation rate for non-reheat thermal units is usually higher than the generation rate for reheat units. The reheat units have a generation rate about of 3–10% pu MW/min [20]. The speed governor dead band has a great effect on the dynamic performance of electric energy system. GBD is defined as the total amount of a continued speed change within which there is no change in valve position. The effect of the GBD is to increase the apparent steady-state speed regulation.

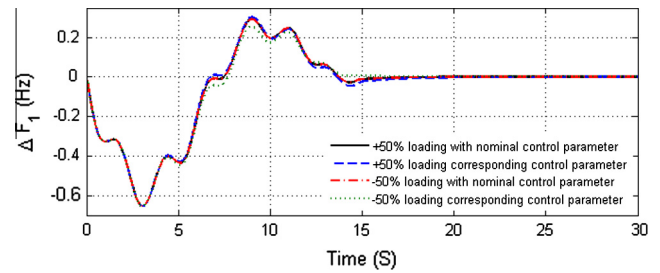


Figure 18 Frequency deviation of area-1 for 10% change in area-1 with physical constraints.

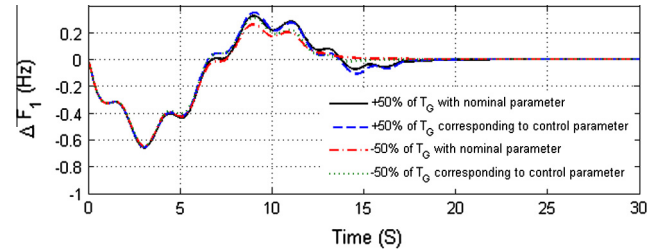


Figure 19 Frequency deviation of area-1 for 10% change in area-1 with physical constraints.

The speed-governor dead band has makes the system oscillatory. A describing function approach is used to include the GBD nonlinearity. The maximum value of dead band for governors of large steam turbines is typically specified as 0.06% (0.036 Hz) [19]. In view of the above, a GRC of 3%/ min and GBD of 0.036 Hz are considered in the present work.

To investigate the importance of considering the physical constraints, two cases (Case A and Case B) are considered. In Case A, no constraint is considered in the model and in

Table 6 Sensitivity analysis of system with physical constraints.

Parameter variation	% Change	Tuned controller parameter				Settling time, T_s (s)			ζ	ITAE
		K_P	K_I	K_D	N	ΔF_1	ΔF_2	ΔP_{tie}		
Nominal	0	0.8589	0.0791	1.9920	44.5678	18.21	19.50	37.44	0.4400	40.4612
Loading condition	+50	0.8630	0.0753	1.9057	43.3623	14.34	13.96	42.37	0.4492	31.4246
	+25	0.8397	0.0758	1.8949	49.1008	16.83	18.98	41.29	0.4670	35.6197
	-25	0.7508	0.0831	1.7503	43.2105	20.56	21.60	34.95	0.4743	49.8424
	-50	0.7500	0.0765	1.9995	48.4272	20.62	21.64	37.78	0.4511	50.4765
T_G	+50	0.8000	0.0800	1.6614	48.8137	19.73	20.51	36.12	0.3802	49.2855
	+25	0.8000	0.0800	1.9168	44.4899	19.57	20.52	36.57	0.3926	43.8609
	-25	0.8811	0.0841	1.8552	44.2036	18.51	19.79	35.09	0.5445	40.4841
	-50	0.9560	0.0855	1.8971	44.4794	17.13	18.43	34.84	0.6684	38.1144
T_T	+50	0.7757	0.0787	1.8821	42.9658	18.03	19.42	37.09	0.4944	40.1139
	+25	0.7908	0.0720	1.9924	47.5757	15.17	19.06	43.01	0.4840	38.3354
	-25	0.7036	0.0749	1.8137	46.2931	16.25	19.15	39.76	0.4297	38.3024
	-50	0.7003	0.0761	1.7980	49.4480	15.85	18.85	38.84	0.3897	38.2674
T_{12}	+50	0.7000	0.0770	1.9987	48.9204	21.54	22.22	38.97	0.3620	47.2833
	+25	0.7000	0.0737	1.9575	49.9986	19.19	20.51	40.96	0.4186	41.6126
	-25	0.7000	0.0684	1.8434	48.6640	17.04	15.48	43.34	0.5116	33.0340
	-50	0.6026	0.0806	1.5000	42.7331	16.29	22.51	30.90	0.5901	35.3342

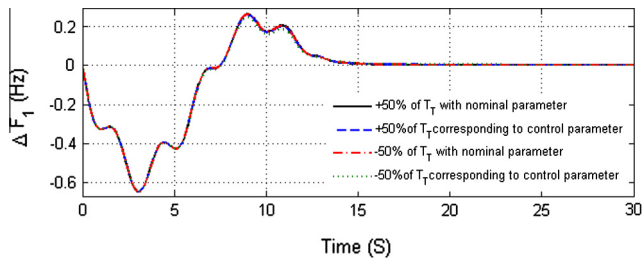


Figure 20 Frequency deviation of area-1 for 10% change in area-1 with physical constraints.

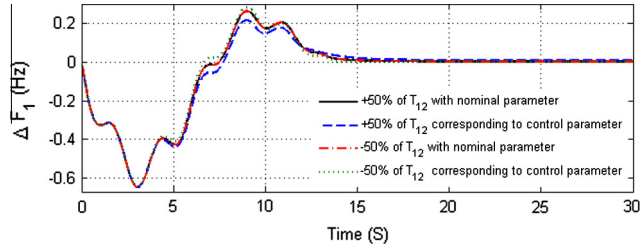


Figure 21 Frequency deviation of area-1 for 10% change in area-1 with physical constraints.

Case B, GBD, GRC and reheat turbine are considered. It is observed that the system becomes unstable when the optimum parameters which were obtained for Case A are applied to the Case B. Hence, the PIDF controller parameters are retuned for Case B employing GSA using modified objective function (J_5) for a 10% step load increase in area-1 at $t = 0$ s. The optimum values of controller parameters are as follows:

$$K_P = 0.8589, \quad K_I = 0.0791, \quad K_D = 1.992, \quad N = 44.5678.$$

A step increase in demand of 10% is applied at $t = 0$ s in area-1 and the system dynamic responses is shown in Figs. 15–17. It is evident from Figs. 15–17 that the system is stable with retuned controller parameters but the dynamics of the power system is affected with increased overshoot, performance errors and settling times. Finally, sensitivity analysis is done to study the robustness the system to wide changes in the operating conditions and system parameters as before. The various performance indexes (ITAE values, settling times and minimum damping ratios) under normal and parameter variation cases are given in Table 6. It can be noticed from Table 6 that when physical constraints are introduced, the variations in performance index are more prominent. So it can be concluded that in the presence of GBD, GRC and reheat turbine, the system becomes highly non-linear (even for small load perturbation) and hence the performance of the designed controller is degraded. To complete the analysis, a 10% step load increase in area-1 at $t = 0$ s is considered and the frequency deviation response of area-1 for the above varied conditions are shown in Figs. 18–21. From Table 6 and Figs. 18–21 it can be concluded that once the controller parameters are tuned under varied conditions, the performance of the proposed controllers that are satisfactory is more or less the same under varied conditions.

6. Conclusion

An attempt has been made for the first time to apply a powerful computational intelligence technique like GSA to optimize PI and PIDF controller parameters for AGC of a multiarea interconnected power system. Firstly, the system without any physical constraint is optimized using conventional objective functions. It is observed the performance of the power system is better in terms of minimum damping ratio, settling times and peak overshoots in frequency and tie-line power deviations when ITAE objective function is used compared to IAE, ISTE and ISE objective functions. Then, the parameters of GSA technique are properly tuned and the recommended GSA parameters are found to be: $\alpha = 20$, $G_0 = 100$, $NP = 20$ and $T = 100$ respectively. Further, a modified objective function is employed and the parameters of PI and PIDF controller are optimized by tuned GSA. The superiority of the proposed approach is demonstrated by comparing the results with Differential Evolution (DE), Bacteria Foraging Optimization Algorithm (BFOA) and Genetic Algorithm (GA) techniques. Sensitivity analysis reveals that the optimum PIDF controller tuned at the nominal and varied conditions are quite robust and performs satisfactorily under wide changes in system loading conditions or in system parameters. Finally, the proposed approach is extended to a more realistic power system model by considering the physical constraints such as reheat turbine, GRC and governor dead band nonlinearity. It is observed that the when physical constraints are introduced, the variations in performance index are more prominent as evident from the sensitivity analysis.

Appendix A

Nominal parameters of the system investigated are: $P_R = 2000$ MW (rating), $P_L = 1000$ MW (nominal loading); $f = 60$ Hz, $B_1, B_2 = 0.045$ pu MW/Hz; $R_1 = R_2 = 2.4$ Hz/pu; $T_{G1} = T_{G2} = 0.08$ s; $T_{T1} = T_{T2} = 0.3$ s; $K_{PS1} = K_{PS2} = 120$ Hz/pu MW; $T_{PS1} = T_{PS2} = 20$ s; $T_{12} = 0.545$ pu; $a_{12} = -1$, $K_{r1} = K_{r2} = 0.5$, $T_{r1} = T_{r2} = 10$.

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