

GSA-Based Design of Dual Proportional Integral Load Frequency Controllers for Nonlinear Hydrothermal Power System

M. Elsis, M. Soliman, M. A. S. Aboelela, W. Mansour

Abstract—This paper considers the design of Dual Proportional-Integral (DPI) Load Frequency Control (LFC), using gravitational search algorithm (GSA). The design is carried out for nonlinear hydrothermal power system where generation rate constraint (GRC) and governor dead band are considered. Furthermore, time delays imposed by governor-turbine, thermodynamic process, and communication channels are investigated. GSA is utilized to search for optimal controller parameters by minimizing a time-domain based objective function. GSA-based DPI has been compared to Ziegler-Nichols based PI, and Genetic Algorithm (GA) based PI controllers in order to demonstrate the superior efficiency of the proposed design. Simulation results are carried for a wide range of operating conditions and system parameters variations.

Keywords—Gravitational Search Algorithm (GSA), Load Frequency Control (LFC), Dual Proportional-Integral (DPI) controller.

I. INTRODUCTION

LOAD frequency control represents a very imperative issue in large-scale power systems. It plays an important role in the power system by maintaining the system frequency and tie-line power flow at scheduled values [1]-[3]. There are two different control loops used to accomplish LFC in an interconnected power system, namely primary and supplementary speed control. Primary control is done by governors of the generators, which provide control action to a sudden change of load. The secondary control adjusts the frequency at its nominal value by controlling the output of selected generators.

In last years, many control strategies have been suggested based on the conventional linear control theory. The conventional controller is simple in structure, but its performance deteriorates in the case of most complex systems [4]. For example, the conventional PI controller has some advantages such as small overshoot but settling time is large. Conversely, the conventional I controller has slightly smaller settling time than PI control and larger overshoot [4], [5]. Control system performance can be improved by allowing the controller to switch from one mode to another. For instance,

for certain linear systems switching from a proportional controller to an integral controller in a feedback loop may provide a fast response and small overshoot [6]. Based upon the above-mentioned facts, it is desirable to adopt a dual-mode controller concludes both proportional and integral controller. In [5] the rate of change of the error is used as switching criteria between proportional and integral controller. The proportional controller acts when the rate of change of the error is sufficiently large, whereas the integral controller would be the better one when the rate of change of the error is small. In [7]-[9], the error is used as switching criteria between proportional and integral controller. The proportional controller is used when the error is large, the integral controller acts when the error is small. The main problem which faces dual-mode controller in [5]-[9], it is the switching condition. This paper proposes to solve this problem by make relation between the switching condition and the summation of disturbance on the system. If the summation of disturbance on the system increases the switching condition increase.

In order to get better performance from any controller, its parameters need good optimization. The conventional methods face some difficulties to achieve this purpose, such as complex mathematical equations for large systems. Several approaches such as optimal, Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Bacterial Foraging Optimization (BFO), etc., for the design and optimization of the LFC system, have been reported in the literature [10]-[21]. Modern optimal control concept for AGC designs of interconnected power system was firstly presented by [10], [11]. Genetic algorithms (GAs) have been extensively considered for the design of AGC. Optimal PID and fractional-order PID control parameters have been computed by the GAs technique for interconnected, equal non-reheat and reheat type two generating areas [12], [13]. In [14] the Parameters of PID sliding-mode used in LFC of multi-area power systems with nonlinear elements are optimized by GA. In [15], GA is used to compute the decentralized control parameters to achieve an optimum operating point for a realistic system comprising generation rate constraint (GRC), dead band, and time delays. AGC by an integral controller and PI controller based on PSO is reported in [16]. In [17] the parameters of PI controller are designed by PSO with the new objective function and compared their results with [16]. In [18], a robust PID controller based ICA is used for LFC application. The authors of [19], [20] have proposed bacterial foraging optimization algorithm (BFOA) for designing PI and PID-based load

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frequency control for a two-area power system with and without GRC. Application of BFOA to optimize several important parameters in AGC of an interconnected three unequal area thermal systems such as the integral controller gains, governor speed regulation, and the frequency bias parameters, has been reported in [21]. In [22] a new optimization algorithm based on the law of gravity and mass interactions is introduced. In the algorithm, the searcher agents are a collection of masses which work with each other based on the Newtonian gravity and the laws of motion.

This paper proposes the GSA for optimal tuning of dual PI controller in two area interconnected power system to damp out power system oscillations. The dual PI controller design is formulated as an optimization problem and GSA is employed to search for optimal controller parameters by minimizing a candidate time-domain based objective function. The performance of the proposed dual PI controller-based GSA is evaluated by comparison with a conventional PI controller and PI-based GA. Simulations results on a two-area test system are presented to assure the superiority of the proposed method compared with PI-based GA and conventional one.

II. GRAVITATIONAL SEARCH ALGORITHM

Gravitational Search Algorithm (GSA) is a novel heuristic algorithm inspired by the Newtonian laws of gravity and motion [22]. In GSA, agents are considered as objects and their performance is evaluated by their masses. All these objects attract each other by the force of gravity and moves toward the objects with a heavier mass. The heavy masses correspond to the good solution, and this guarantees the exploitation step of the algorithm. In GSA, each mass (agent) has four representations: position, inertial mass, active gravitational mass and passive gravitational mass. The position of the mass represent a solution of the problem and it's gravitational and inertia masses are determined using a fitness function. In other words, each mass presents a solution and the algorithm is run by properly adjusting the gravitational and inertia masses. By lapse of time, it is predictable that masses be attracted by the heavier mass. This mass will represent an optimum solution in the search space. GSA is representing a small artificial world of masses obeying the Newtonian laws of gravitation and motion. Masses obey the following laws [22]-[24].

A. Law of Gravity

Each agent attracts every other agent and the gravitational force between the two agents is directly proportional to the product of their masses and inversely proportional to the distance between them R . It has been concluded in the literature that R provides better results than R^{λ^2} in all experiment cases [22].

B. Law of Motion

The current velocity of any agent 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 agent is equal to the force acted on the system divided by the mass

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

$$X_i = (x_i^1, \dots, x_i^d, \dots, x_i^n), i = 1, 2, \dots, n \quad (1)$$

where n is the space dimension of the problem and, 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:

$$F_{ij}^d = G(t) \frac{M_{pi}(t) \times M_{pj}(t)}{R_{ij}(t) + \varepsilon} (x_j^d(t) - x_i^d(t)) \quad (2)$$

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

$$R_{ij}(t) = \|x_i(t), x_j(t)\|_2 \quad (3)$$

To give a stochastic characteristic to algorithm, it is supposed that the total force that acts on mass i in a dimension d be a randomly weighted sum of d^{th} components of the forces exerted from other agents:

$$F_i^d(t) = \sum_{j=1, j \neq i}^n rand_j(F_{ij}^d) \quad (4)$$

where $rand_j$ is a random number in the interval $[0,1]$. Hence, by the law of motion, the acceleration of the mass i at time t , and in d^{th} direction, $a_i^d(t)$ is given as:

$$a_i^d(t) = F_i^d(t) / M_{ii}(t) \quad (5)$$

where $M_{ii}(t)$ is the inertial mass of i^{th} agent. Furthermore, the next velocity of a mass is considered as a fraction of its current velocity added to its acceleration. Therefore, its position and its velocity could be calculated as:

$$v_i^d(t+1) = rand_i \times v_i^d(t) + a_i^d(t) \quad (6)$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \quad (7)$$

where $rand_i$ is a uniform random variable in the interval $[0,1]$. The gravitational constant G is initialized at the beginning and will be reduced with time to control the search update. In other words, G is a function of the initial value (G_0) and time (t) as:

$$G(t) = G_0 e^{(-\alpha t/T)} \quad (8)$$

where α is a constant and T is the number of iteration. Gravitational and inertia masses are calculated by the fitness evaluation. A heavier mass means a more efficient object. This means that better objects have higher attractions and walk

more slowly. The gravitational and inertial masses of agents are updated by:

$$M_{ai} = M_{pi} = M_{ii} = M_i, \quad i = 1, 2, \dots, N \quad (9)$$

$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \quad (10)$$

$$M_i(t) = m_i(t) / \sum_{j=1}^N m_j(t) \quad (11)$$

where $fit_i(t)$ present the fitness value of the agent i at time t , and, $worst(t)$ and $best(t)$ are defined as (for a minimization problem):

$$best(t) = \min_{j \in \{1, 2, \dots, N\}} fit_j(t) \quad (12)$$

$$worst(t) = \max_{j \in \{1, 2, \dots, N\}} fit_j(t) \quad (13)$$

It is to be noted that for a maximization problem, (12) and (13) are changed to (14) and (15), respectively:

$$best(t) = \max_{j \in \{1, 2, \dots, N\}} fit_j(t) \quad (14)$$

$$worst(t) = \min_{j \in \{1, 2, \dots, N\}} fit_j(t) \quad (15)$$

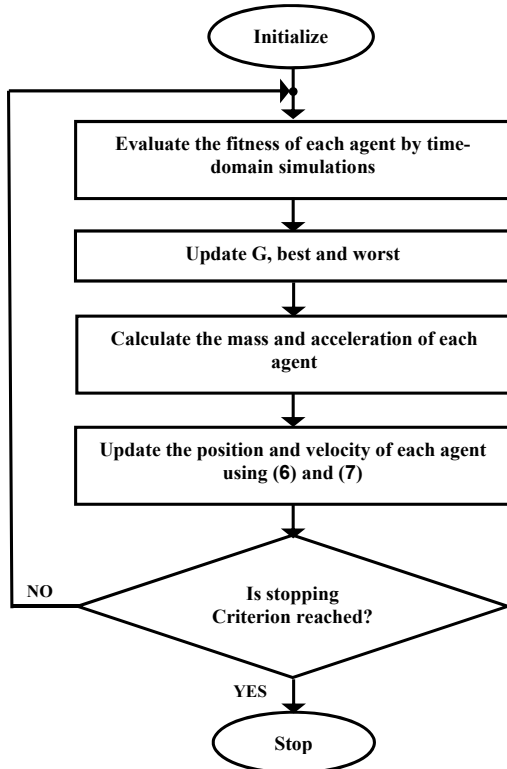


Fig. 1 Flow chart of GSA optimization approach

To achieve a good compromise between exploration and exploitation, the number of objects is reduced with lapse of (4) and therefore a set of objects with bigger mass are used for applying their force to the other.

The steps of the proposed algorithm are summarized as:

- 1) Search space identification.
- 2) Random initialization.
- 3) Fitness evaluation of objects.
- 4) Update $G(t)$, $best(t)$, $worst(t)$ and $M_i(t)$ for $i = 1, 2, \dots, N$.
- 5) Calculation of the total force.
- 6) Calculation of acceleration and velocity.
- 7) Update the position of the objects.
- 8) Repeat steps c to g until the stop criteria is achieved.

The flow chart of proposed optimization is shown in Fig. 1.

III. DUAL PI CONTROLLER

The control law employed depending upon the magnitude of the rate of change of the error signal.

$$\text{For } \left| \frac{d(ACE(t))}{dt} \right| > \varepsilon$$

$$U_i = -K_{pr} ACE(t) \quad (16)$$

where, $ACE(t)$ is an error signal at a particular instant, ε is a small positive constant indicating the specified limit of rate of change of the error signal, U_i the control signal to i^{th} area and K_{pr} is the proportional gain.

$$\varepsilon = K_c \sum_{i=1}^N \Delta P_{Di} \quad (17)$$

where K_c is a scaling factor, ΔP_{Di} is the disturbance in i^{th} area and N the total number of area.

$$\text{For } \left| \frac{d(ACE(t))}{dt} \right| \leq \varepsilon$$

$$U_i = -K_i \int ACE(t) dt \quad (18)$$

where K_i is the integral gain. Then if the parameters K_{pr} , K_i and K_c are suitably selected, one can ensure a high-quality transient response. By choosing a suitable value of K_{pr} , one makes sure that speed of the system is high. Whenever the rate of change of error falls within the specified error bound $|d(ACE(t))/dt| \leq \varepsilon$, the integrator starts accumulating the error. But if the error exceeds the bound the integrator resets to zero. The GSA is proposed in this paper to get the best value of K_{pr} , K_i and K_c . The proposed control scheme is shown in Fig. 2.

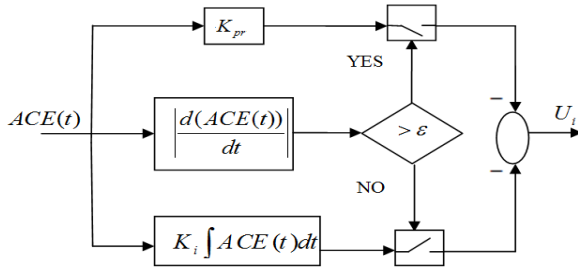


Fig. 2 Block diagram for the proposed dual PI controller

IV. TWO AREA HYDRO-THERMAL POWER SYSTEM

A model of controlled hydro-thermal plants in a two-area interconnected power system with nonlinearities and boiler dynamics is shown in Fig. 3 where the system abbreviations and symbols are defined in Table I.

The speed governor dead band has a significant effect on the dynamic performance of the system. For this analysis, in this paper backlash non-linearity of about 0.05% for thermal system and the dead band non-linearity of about 0.02% for hydro system are considered. The system is provided with single reheat turbine with suitable GRC, for thermal area 0.0017MW per sec and hydro area 4.5% per sec for rising generation and 6% for lowering generation. The boiler is used to producing steam under pressure. In this study, the effect of the boiler in a steam area in the power system is also considered and detailed scheme is shown in Fig. 4 given in [25]. The objective function which selected in this paper can be defined by (19).

$$J = \int (|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|) dt \quad (19)$$

This study focuses on the optimal tuning of controllers for LFC using GSA. The aim of the optimization is to search for the optimum dual PI controller parameters that improve the damping characteristics of the system under all operating conditions and various loads and finally designing a low order controller for easy implementation.

TABLE I
SYSTEM ABBREVIATIONS AND SYMBOLS

| | |
|------------------|---------------------------------------|
| B_i | : Frequency bias parameter |
| ACE_i | : Area control error |
| U_i | : Controller output |
| R_i | : Speed regulation in pu Hz |
| T_{gi} | : Governor time constants in sec |
| T_{ti} | : Turbine time constant in sec |
| T_{ri} | : Time constant of reheater in sec |
| k_{ri} | : Gain of reheater |
| T_i | : Hydro governor time constant in sec |
| T_w | : Water starting time in sec |
| ΔP_{Di} | : Load demand change |
| ΔP_{tie} | : Change in tie line power in p.u Mw |
| T_{pi} | : Power system time constant in sec |
| K_{pi} | : Power system gain |
| T_{12} | : Synchronizing coefficient |
| Δf_i | : System frequency deviation in Hz |

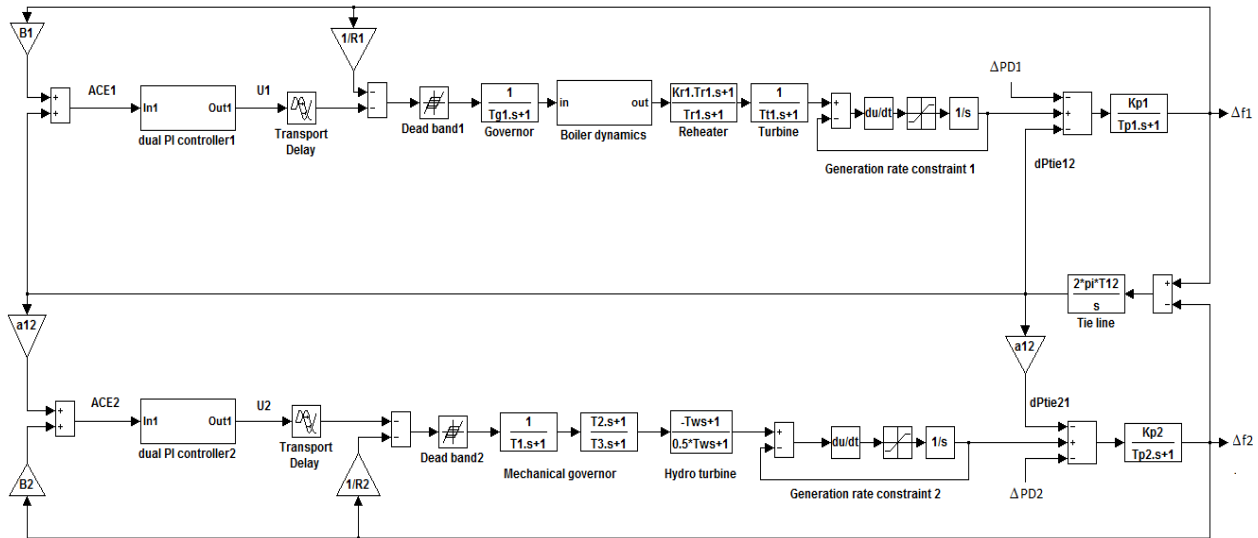


Fig. 3 Two-area interconnected power system

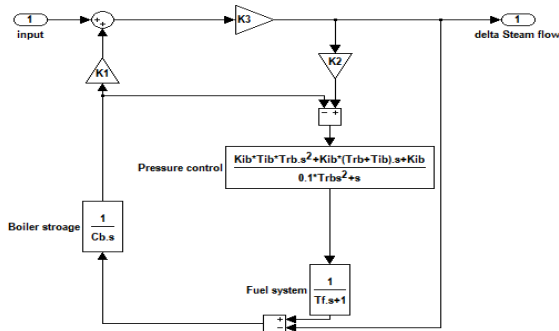


Fig. 4 Boiler dynamics

V. SIMULATION RESULTS

In this section, different comparative cases are examined to show the effectiveness of the proposed GSA method for optimizing controller parameters of dual PI controller. Table II gives the optimum values of controller parameters for different methods. The PI controller parameters of the conventional controller due to [26].

TABLE II
CONTROLLER PARAMETERS, AND OBJECTIVE FUNCTION (J)

| Controller Parameters | Conventional PI | GA-PI | dual PI |
|-----------------------|---|--|---|
| | $K_{pr1}=K_{pr2}=0.3, K_{il}=K_{i2}=0.12$ | $K_{pr1}=0.9795, K_{il}=0.0399, K_{pr2}=1.0719, K_{i2}=0.0440$ | $K_{pr1}=0.1845, K_{il}=0.0496, K_{cl}=0.7672, K_{pr2}=0.2512, K_{i2}=0.0288, K_{c2}=0.4189,$ |
| J | 14.1752 | 8.0265 | 7.1108 |

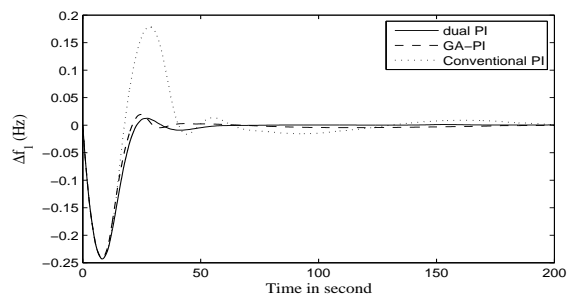
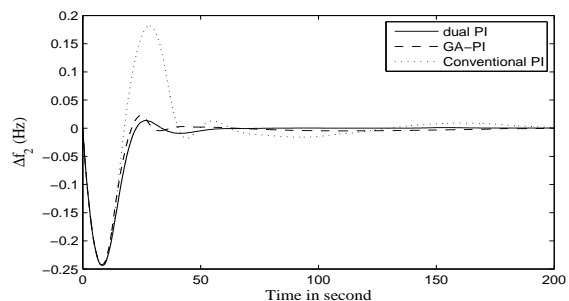
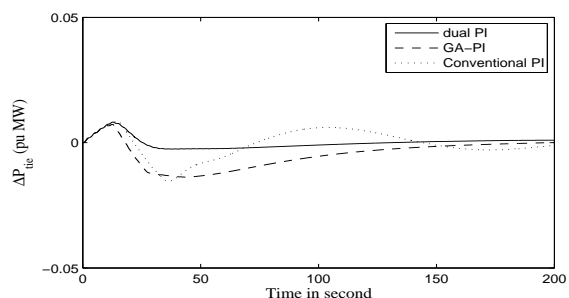
Case 1. A 1% step increase in demand of the first area (ΔP_{D1}), the second area (ΔP_{D2}) simultaneously and time delay equal 2 seconds are applied (nominal test case). The change in frequency of the first area Δf_1 , the change in frequency of the second area Δf_2 , and change in tie-line power of the closed loop system are shown in Figs. 5–7. Remarkably, the response with conventional PI controller has high settling time and undesirable oscillations. Also compared with PI-based GA the proposed method is indeed more efficient in improving the damping characteristic of the power system.

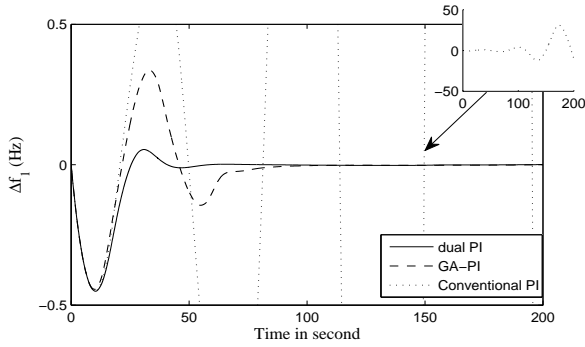
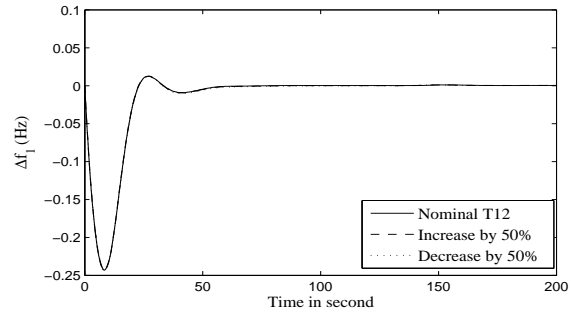
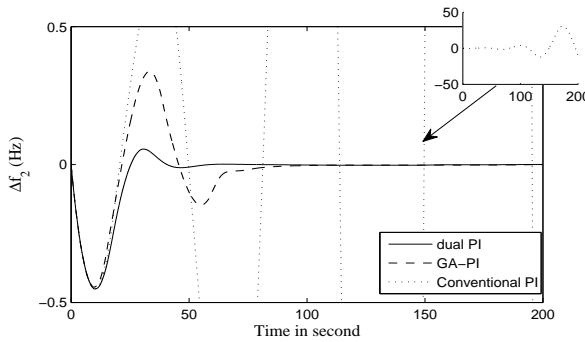
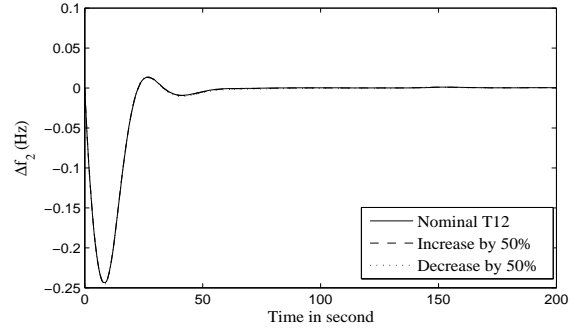
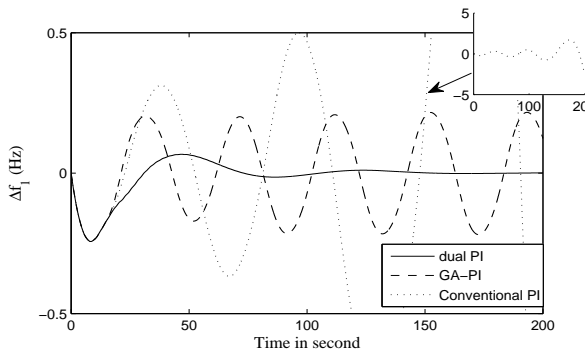
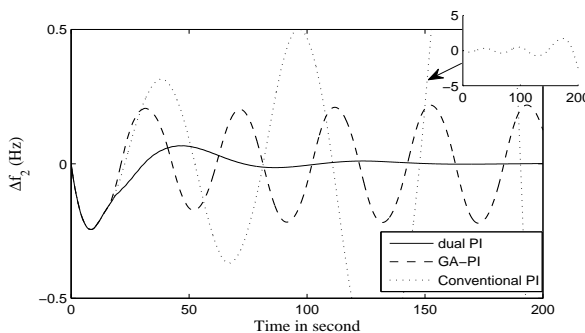
Case 2. A 1.5% step increase is applied as a change of demand in first area (ΔP_{D1}), the second area (ΔP_{D2}) simultaneously and time delay equal 2 seconds. The change in frequency of the first area Δf_1 , the change in frequency of the second area Δf_2 and change in tie-line power of the closed loop system are shown in Figs. 8, 9. From these figures, the response with the conventional controller is unstable. Moreover, the proposed method outperforms and outlasts PI-based GA in damping oscillations effectively and reducing settling time. Hence compared to the conventional controller, and PI-based GA, dual PI controller based GSA greatly enhances the system stability and improves the damping characteristics of the power system. Because of the large values of conventional PI

controller response, a sub figure of this part is shown beside the main response.

Case 3. A 1% step increase in demand of the first area (ΔP_{D1}), the second area (ΔP_{D2}) simultaneously and time delay equal 15 seconds are applied. The change in frequency of the first area Δf_1 , the change in frequency of the second area Δf_2 , and change in tie-line power of the closed loop system are shown in Figs. 10, 11. It is clear from these figures that the response with PI-based GA and conventional controller are unstable. The potential and superiority of the proposed method over the conventional and PI-based GA is demonstrated.

Case 4. A parameter variation test is also applied to validate the robustness of the proposed controller. Figs. 12, 13 show the change in frequency of the first area Δf_1 , the change in frequency of the second area Δf_2 , and change in tie-line power of the closed loop system with variation in T_{12} . It is clear that the system stable with the proposed controller.

Fig. 5 Change in f_1 for case 1Fig. 6 Change in f_2 for case 1Fig. 7 Change in P_{tie} for case 1

Fig. 8 Change in f_1 for case 2Fig. 12 Change in f_1 for case 4Fig. 9 Change in f_2 for case 2Fig. 13 Change in f_2 for case 4Fig. 10 Change in f_1 for case 3Fig. 11 Change in f_2 for case 3

VI. CONCLUSION

This paper presents the application of the GSA algorithm as a new artificial intelligence technique in order to optimize the AGC in a two-area interconnected power system. GSA algorithm is proposed to tune the parameters of dual PI controller. A two-area power system is considered to demonstrate the proposed method. The simulation results emphasize that the designed dual PI controller -based GSA is robust in its operation and gives a superb damping performance for frequency and tie line power deviation compared to conventional PI controller, and PI-based GA. Besides the simple architecture of the proposed controller, it has the potentiality of implementation in real-time environment.

APPENDIX

The typical values of parameters of system under study are: $T_{il}=0.3$ s; $T_{gl}=0.2$ s; $T_{rl}=10$ s; $K_{rl}=0.333$; $T_1=48.7$ s; $T_2=0.513$ s; $T_3=10$ s; $T_w=1$ s; $T_{p1}=20$ s; $T_{p2}=13$ s; $K_{p1}=120$ Hz/p.u MW; $K_{p2}=80$ Hz/p.u MW; $T_{12}=0.0707$ MW rad⁻¹; $a_{12}=-1$; $R_1=R_2=2.4$ Hz/p.u MW; $B_1=B_2=0.425$ p.u MW/Hz.

Boiler (oil fired) data: $K_1=0.85$; $K_2=0.095$; $K_3=0.92$; $C_b=200$; $T_f=10$; $K_{ib}=0.03$; $T_{ib}=26$; $T_{rb}=69$.

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