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Load Frequency Control of Nonlinear Interconnected Hydro-Thermal System Using Differential Evolution Technique

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***Abstract*—**This paper presents a differential evolution algorithm to design a robust PI and PID controllers for Load Frequency Control (LFC) of nonlinear interconnected power systems considering the boiler dynamics, Governor Dead Band (GDB), Generation Rate Constraint (GRC). Differential evolution algorithm is employed to search for the optimal controller parameters. The proposed method easily copes of with nonlinear constraints. Further the proposed controller is simple, effective and can ensure the desirable overall system performance. The superiority of the proposed approach has been shown by comparing the results with published fuzzy logic controller for the same power systems. The comparison is done using various performance measures like overshoot, settling time and standard error criteria of frequency and tie-line power deviation following a 1% step load perturbation in hydro area. It is noticed that, the dynamic performance of proposed controller is better than fuzzy logic controller. Furthermore, it is also seen that the proposed system is robust and is not affected by change in the system parameters.

***Keywords*—**Automatic Generation control (AGC), Generation Rate Constraint (GRC), Governor Dead Band (GDB), Differential Evolution (DE)

I. INTRODUCTION

LOAD frequency control (LFC) is an important issue in power system operation and control. Large power systems are divided into different control areas. All such areas are connected, to be called as an interconnected power system. Interconnected power system is used to increase reliable and uninterrupted power supply. Normally, interconnected thermal-thermal or hydro-thermal type systems are considered. Automatic generation Control (AGC) is used to maintain scheduled system frequency and tie line power deviations in normal operation and small perturbation. AGC function can be viewed as a supervisory control function which attempts to match the generation trend within an area to the trend of the randomly changing load of the area, so as to keep the system frequency and the tie-line power flow close to scheduled value. The growth in size and complexity of electric power systems along with increase in power demand has necessitated the use of intelligent systems that combine knowledge, techniques and methodologies from various sources for the real-time control of power systems. Kothari et al. [1] are possibly the first to consider Generation Rate Constraint (GRC) to investigate the AGC problem of a hydrothermal system with conventional integral controllers. Many a research has been done in AGC in two area thermal - hydro systems with non-linearity as GRC [2], [3]. In [4] Governor Dead Band (GDB) is considered as non-linearity, and the AGC problem is solved by PI controller tuned with Craziness Particle Swarm Optimisation (CPSO).

It is observed that, considerable research work is going on to propose better AGC systems based on modern control theory [5], neural network [6], fuzzy system theory [7], reinforcement learning [8] and ANFIS approach [9]. 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 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 [10], 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. [3] 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. E. S. Ali and S.M. Abd-Elazim [11] have reported that, proportional integral (PI) controllers tuned with the help of Bacterial Foraging Optimization Algorithm (BFOA), provides better performance as compared to that with GA based PI controller in two area non-reheat type thermal systems. In [12], 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. B. Anand et al. [13] have reported conventional PI controller with fuzzy logic controller (FLC) for stabilizing the frequency oscillations of AGC with nonlinearities.

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With increase in size and complexity of power systems has necessitated the use of intelligent systems that combine knowledge, techniques and methodologies from various sources for the real-time control of power systems. Differential Evolution (DE) is a population-based direct search algorithm for global optimization capable of handling non-differentiable, non-linear and multi-modal objective functions, with few, easily chosen, control parameters [14]. DE uses weighted differences between solution vectors to change the population whereas in other stochastic techniques such as Genetic Algorithm (GA) and Expert Systems (ES), perturbation occurs in accordance with a random quantity. DE employs a greedy selection process with inherent elitist features. Also it has a minimum number of control parameters, which can be tuned effectively [15]. In view of the above, an attempt has been made in this paper for the optimal design of DE based classical PI/PID controllers for LFC of multi-area nonlinear interconnected power system. The design problem of the proposed controller is formulated as an optimization problem and DE is employed to search for optimal controller parameters. Simulations results are presented to show the effectiveness of the proposed controller in providing good damping characteristic to system oscillations over a wide range of disturbance. Further, the superiority of the proposed design approach is illustrated by comparing the proposed approach with recently published convention PI controller and FLC [13] for the same AGC system.

II. SYSTEM INVESTIGATED

The block diagram model of two areas interconnected hydro-thermal system with nonlinearities and boiler dynamics are shown in Fig. 1. Thermal area comprised of reheat turbine, GDB, GRC and boiler dynamics. The hydro area incorporated GDB and GRC.

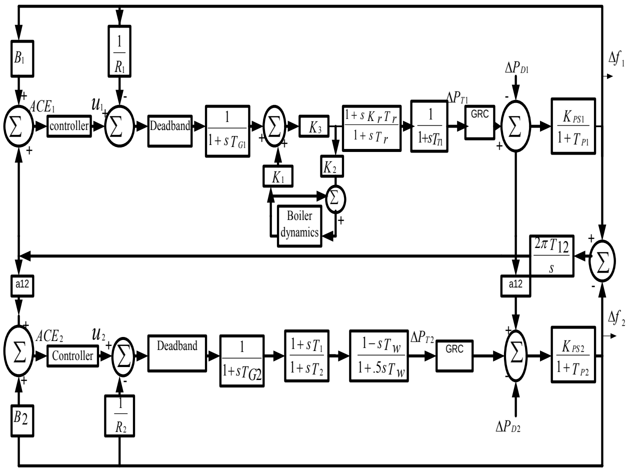

Fig. 1 Transfer function model of two area hydro- thermal system with boiler dynamics, governor dead band and generation rate constraint

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 form 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 sec; T_{T1} is the turbine time constant in sec; k_r and T_r are the gain and time constant of reheat turbine; T_1 and T_2 are the hydro governor time constants in sec; T_w is the water starting time in sec; 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_{P1} and T_{P2} are the power system time constant in sec; 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. Governor dead band is defined as the total magnitude of a sustained speed change within which there is no resulting change in valve position. The backlash non-linearity tends to produce a continuous sinusoidal oscillation with a natural period of about 2s. The speed governor dead band has significant effect on the dynamic performance of load frequency control mechanism. For this analysis, in this study 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 appropriate GRC, for thermal area 0.0017MW per sec and hydro area 4.5% per sec for raising generation and 6% for lowering generation as shown in Fig. 2.

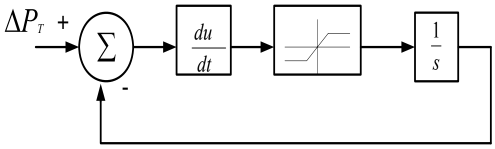

Fig. 2 Generation rate constraint

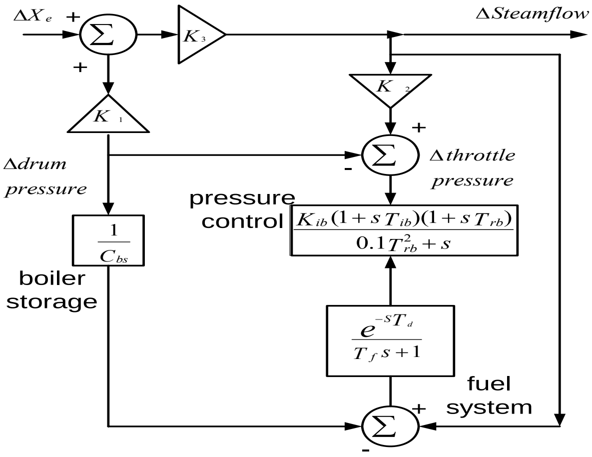

Fig. 3 Boiler dynamics

Boiler is a device for producing steam under pressure. In this study, the effect of the boiler in steam area in the power system is also considered and detailed configuration is shown in Fig. 3 given in [13]. This includes the long term dynamics of fuel and steam flow on boiler drum pressure. Representations for combustion controls are also incorporated. This model is basically a drum type boiler normally in used, fuel used is oil/gas. The model can be used to study the responses of coal fired units with poorly tuned (oscillatory) combustion controls, coal fired units with well tuned controls and well tuned oil or gas fired units.

III. THE PROPOSED APPROACH

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. 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. PID controller is often used when stability and fast response are required. In view of the above, both PI and PID structured controllers are considered in the present paper. Design of PID controller requires determination of the three main parameters, Proportional gain (K_P), Integral time constant (K_I) and Derivative time constant (K_D). For PI controller K_P and K_I are to be determined. The controllers in both the areas are considered to be different so that K_{P1}, K_{P2}, K_{I1}, K_{I2} and K_{D1}, K_{D2}.

The error inputs to the controllers are the respective area control errors (AEC) given by:

$$e_1(t) = ACE_1 = B_1 \Delta f_1 + \Delta P_{Tie} \tag{1}$$

$$e_2(t) = ACE_2 = B_2 \Delta f_2 - \Delta P_{Tie} \tag{2}$$

The control inputs of the power system of each area are u_1 and u_2 . With PI structure ($K_{D1} = K_{D2} = 0$) the control inputs are obtained as:

$$u_1 = K_{P1} ACE_1 + K_{I1} \int ACE_1 \tag{3}$$

$$u_2 = K_{P2} ACE_2 + K_{I2} \int ACE_2 \tag{4}$$

The control inputs of the power system u_1 and u_2 with PID structure are obtained as:

$$u_1 = K_{P1} ACE_1 + K_{I1} \int ACE_1 + K_{D1} \frac{dACE_1}{dt} \tag{5}$$

$$u_2 = K_{P2} ACE_2 + K_{I2} \int ACE_2 + K_{D2} \frac{dACE_2}{dt} \tag{6}$$

In the design of a PI/PID controller, the objective function is first defined based on the desired specifications and constraints. The design of objective function to tune the controller is generally based on a performance index that considers the entire closed loop response. Typical output specifications in the time domain are peak overshoot, rise time, settling time, and steady-state error. Four kinds of performance criteria usually considered in the control design are the Integral of Time multiplied Absolute Error (ITAE), Integral of Squared Error (ISE); Integral of Time multiplied Squared Error (ITSE) and Integral of Absolute Error (IAE).

$$J \ = ISE = \int_0^{t_{sim}} \left(\left|\Delta f_1\right|\right)^2 + \left(\left|\Delta f_2\right|\right)^2 + \left(\left|\Delta P_{Tie}\right|\right)^2 \cdot dt \tag{7}$$

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.

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

$$\text{Minimize } J \tag{8}$$

Subject to

$$K_{P\min} \le K_P \le K_{P\max},\ K_{I\min} \le K_I \le K_{I\max} \text{ and } K_{D\min} \le K_D \le K_{D\max} \tag{9}$$

where J is the objective function and $K_{P\min}$, $K_{I\min}$; $K_{P\max}$,$K_{I\max}$ and $K_{D\max}$, $K_{D\max}$ are the minimum and maximum value of the control parameters. As reported in the literature, the minimum and maximum values of controller parameters are chosen as 0 and 3 respectively.

IV. DIFFERENTIAL EVOLUTION

Differential Evolution (DE) algorithm is a population-based stochastic optimization algorithm recently introduced [13]. Advantages of DE are: simplicity, efficiency & real coding, easy use, local searching property and speediness. DE works with two populations; old generation and new generation of the same population. The size of the population is adjusted by the parameter N_P. The population consists of real valued vectors with dimension D that equals the number of design parameters/control variables. The population is randomly initialized within the initial parameter bounds. The optimization process is conducted by means of three main operations: mutation, crossover and selection. In each generation, individuals of the current population become target vectors. For each target vector, the mutation operation produces a mutant vector, by adding the weighted difference between two randomly chosen vectors to a third vector. The crossover operation generates a new vector, called trial vector, by mixing the parameters of the mutant vector with those of the target vector. If the trial vector obtains a better fitness value than the target vector, then the trial vector replaces the target vector in the next generation. The evolutionary operators are described below [14]-[17];

A. Initialization

For each parameter j with lower bound X_j^L and upper bound X_j^U, initial parameter values are usually randomly selected uniformly in the interval [X_j^L , X_j^U].

B. Mutation

For a given parameter vector $X_{i,G}$, three vectors ($X_{r1,G}$ $X_{r2,G}$ $X_{r3,G}$) are randomly selected such that the indices i, $r1$, $r2$ and $r3$ are distinct. A donor vector $V_{i,G+1}$ is created by adding the weighted difference between the two vectors to the third vector as:

$$V_{i,G+1} = X_{r1,G} + F.(X_{r2,G} - X_{r3,G}) \qquad (10)$$

where F is a constant from (0, 2)

C. Crossover

Three parents are selected for crossover and the child is a perturbation of one of them. The trial vector $U_{i,G+1}$ is developed from the elements of the target vector ($X_{i,G}$) and the elements of the donor vector ($X_{i,G}$). Elements of the donor vector enters the trial vector with probability CR as:

$$U_{j,i,G+1} = \begin{cases} V_{j,i,G+1} & if \;\; rand_{j,i} \le CR \;\; or \;\; j = I_{rand} \\ X_{j,i,G+1} & if \;\; rand_{j,i} > CR \;\; or \;\; j \ne I_{rand} \end{cases} \qquad (11)$$

with $rand_{j,i} \sim U(0,1)$, I_{rand} is a random integer from (1,2,.....D) where D is the solution's dimension i.e. number of control variables. I_{rand} ensures that $V_{i,G+1} \ne X_{i,G}$.

D. Selection

The target vector $X_{i,G}$ is compared with the trial vector $V_{i,G+1}$ and the one with the better fitness value is admitted to the next generation. The selection operation in DE can be represented by the following equation:

$$X_{i,G+1} = \begin{cases} U_{i,G+1} & if \; f(U_{i,G+1}) < f(X_{i,G}) \\ X_{i,G} & otherwise. \end{cases} \qquad (12)$$

where $i \in [1, N_P]$.

V. RESULTS AND DISCUSSIONS

A. Implementation of DE

The model of the system under study has been developed in MATLAB/SIMULINK environment and DE program has been written (in .mfile). The developed model is simulated in a separate program (by .m file using initial population/controller parameters) considering a 1% step load perturbation (SLP) in area-2. The objective function is calculated in the .m file and used in the optimization algorithm. The process is repeated for each individual in the population. Using the objective function values, the population is modified by DE for the next generation.

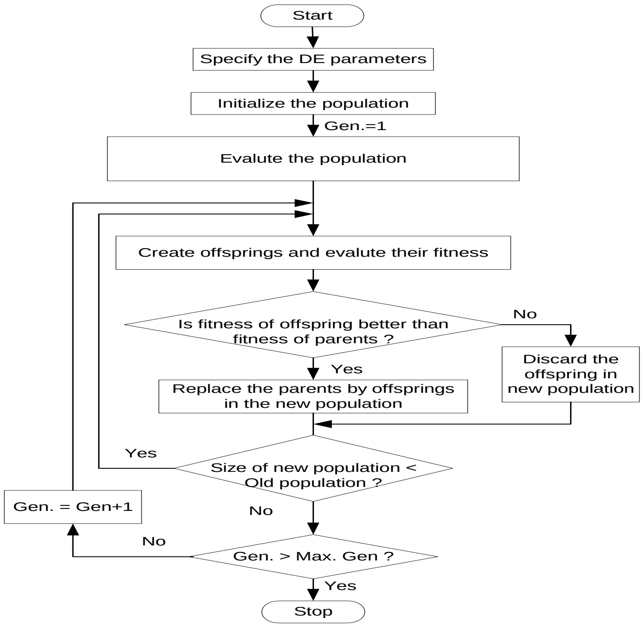

Fig. 4 Flow chart for DE

Implementation of DE requires the determination of six fundamental issues: DE step size function also called scaling factor (*F*), crossover probability (*CR*), the number of population (N_P), initialization, termination and evaluation function. The scaling factor is a value in the range (0, 2) that controls the amount of perturbation in the mutation process. Crossover probability (*CR*) constants are generally chosen from the interval (0.5, 1). If the parameter is co-related, then high value of *CR* work better, the reverse is true for no correlation [15]. DE offers several variants or strategies for optimization denoted by DE/x/y/z, where x=vector used to generate mutant vectors, y= number of difference vectors used in the mutation process and z=crossover scheme used in the crossover operation. In the present study, a population size of N_P=50, generation number *G*=100, step size F=0.8 and crossover probability of *CR* =0.8 have been used. The strategy employed is: DE/best/1/exp. Optimization is terminated by the prespecified number of generations for DE. The flow chart of the DE algorithm employed in the present study is given in Fig. 4. One more important factor that affects the optimal solution more or less is the range for unknowns. For the very first execution of the program, a wider solution space can be given and after getting the solution one can shorten the solution space nearer to the values obtained in the previous iteration. Here the upper and lower bounds of the gains are chosen as (3,0). The flow chart of the DE algorithm employed in the present study is given in Fig. 4. 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 20 times and the best final solution among the 20 runs is chosen as proposed controller parameters given in Table I.

TABLE I
TUNED CONTROLLER PARAMETERS FOR OBJECTIVE FUNCTION

Objective function/ controller parameters			J
PI controller	Proportional gain	K_{P1}	0.0783
		K_{P2}	0.8939
	Integral gain	K_{I1}	0.0295
		K_{I2}	0.0337
PID controller	Proportional gain	K_{P1}	0.3994
		K_{P2}	0.9946
	Integral gain	K_{I1}	0.063
		K_{I2}	0.0335
	Derivative gain	K_{D1}	0.2212
		K_{D2}	2.6994

B. Analysis of Results

A 1% step load perturbation (SLP) in area-2 (hydro-area) is considered at t = 0 sec. The various errors (ISE, ITSE, ITAE and IAE) and settling times of frequency and tie line power deviations with the proposed DE optimized PI and PID controller are given in Table II for the system. To show the superiority of the proposed approach, the results are compared with a published approach (FLC) for the same interconnected power system [13]. It is evident from the Table II that all the error values are improved with the proposed DE optimized PID and PI controllers, especially ITAE is improved by 79.47% and 77.57% respectively for PID and PI controller compared to FLC.

TABLE II
ERROR CRITERIA, SETTLING TIMES, OVERSHOOT AND UNDERSHOOT WITH OBJECTIVE FUNCTION J

parameters		DE optimized PI controller	DE optimized PID controller	FLC controller [13]
ISE		0.1437	0.1403	0.1527
ITSE		1.0323	0.9746	1.4146
ITAE		20.1239	18.4136	89.7002
IAE		1.9858	1.9264	2.7612
T_S (sec)	Δf_1	107.27	64.59	136.95
	Δf_1	105.96	45.61	150
	Δf_{1Te}	57.03	58.48	147
overshoot	Δf_1	0.0061	0.0018	0.0067
	Δf_1	0.0063	0.0019	0.0068
	Δf_{1Te}	4.5706×10^{-4}	2.6078×10^{-4}	0.0019
undershoot	Δf_1	-0.10	-0.1000	-0.1008
	Δf_1	-0.1034	-0.1036	-0.1041
	Δf_{1Te}	-0.0121	-0.0115	-0.0126

The improvements in settling time are:

- For Δf_1 52.84% and 7.07%
- For Δf_2 69.59% and 29.36%
- For ΔP_{tie} 60.22% and 61.2% respectively for PID and PI controller compared to FLC.

Dynamic performance of area control error (Ace), frequency deviation and tie power deviation responses of the system for a 1% step load perturbation (SLP) in area-2 occurring at t = 0 sec are shown in Figs. 5-9. As seen from the Figs. 5 and 6, the performances of ΔAce for both areas are improved compared to FLC and also the overshoot of ΔAce_1 and ΔAce_2 is improved by 48.75% and 93.02% respectively for DE optimized PID controller compared to the FLC [13].

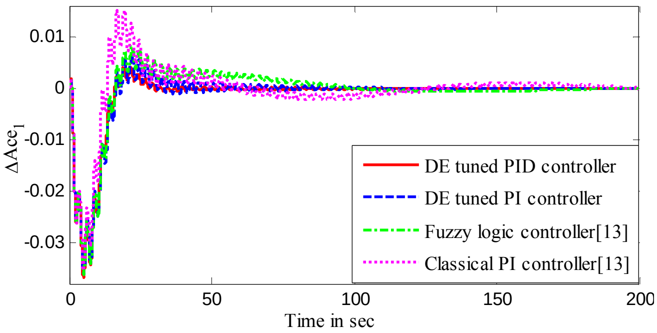

Fig. 5 Area control error of area-1 for load change in area-2

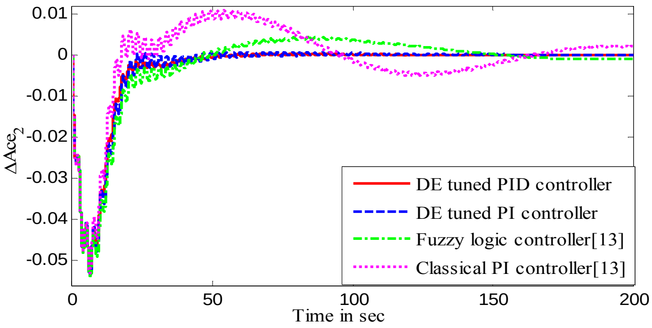

Fig. 6 Area control error of area-2 for load change in area-2

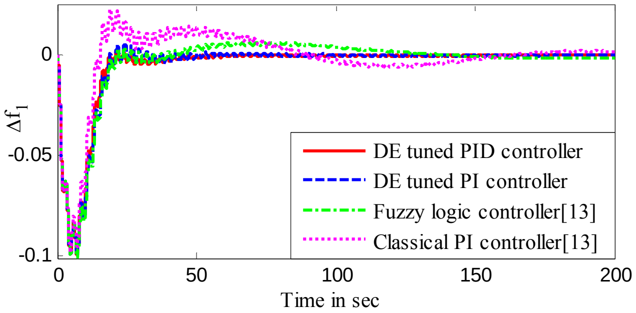

Fig. 7 Frequency deviation of area-1 for load change in area-2

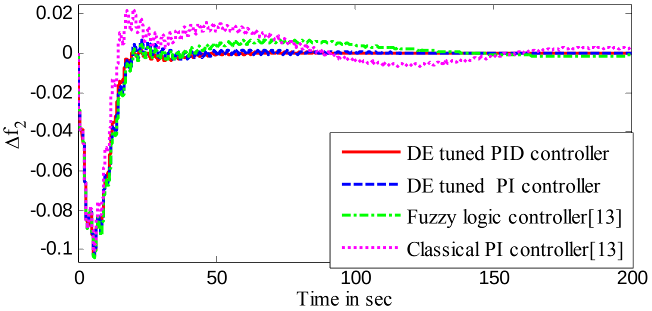

Fig. 8 Frequency deviation of area-2 for load change in area-2

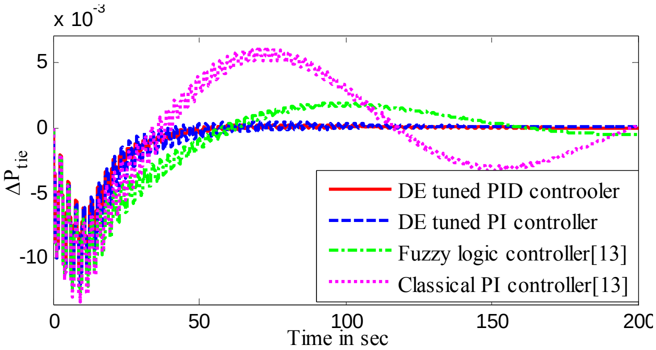

Fig. 9 Change in tie line power for load change in area-2

To study the robustness of the proposed PID controllers obtained by optimizing *J*, variations in the system parameters are deliberately introduced. For testing the controller performance with parameter variations, governor time constants and turbine time constants of both the areas and the synchronizing power coefficient are varied in the range of *-40%* to *+40%* from their respective nominal values in steps of 20% .At each of these changed operating points further 1% perturbation in area-2 are introduced. The results obtained provided in Table III. The frequency deviations are obtained with the variation of turbine, governor and tie line time constants. The dynamics of system remains only marginally affected. These responses are highlighted in Figs. 10 to 13. It can be observed from Figs. 10-13, that there is negligible effect with the variation of system time constants, on the frequency deviation responses with the same controller parameters obtained at nominal values. So it can be concluded that, the proposed control strategy provides a robust and stable control satisfactorily. The optimum values of the proposed controller need not be reset for wide changes in the system parameters for the nominal loading.

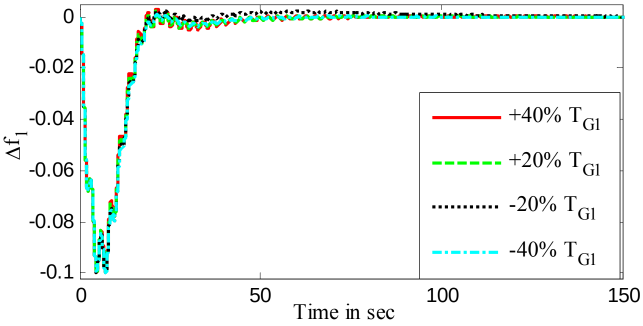

Fig. 10 Frequency deviation of area-1 for load change in area-2 with variation in T_{G1}

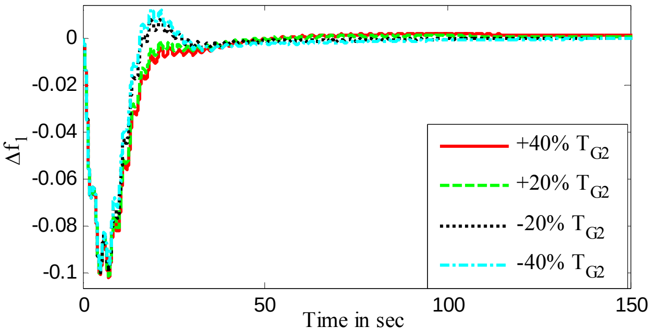

Fig. 11 Frequency deviation of area-1 for load change in area-2 with variation in T_{G2}

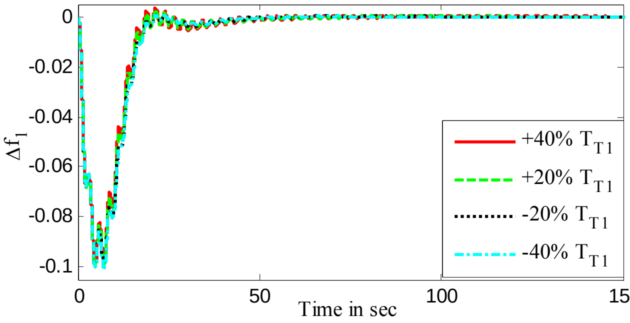

Fig. 12 Frequency deviation of area-1 for load change in area-2 with variation in T_{T1}

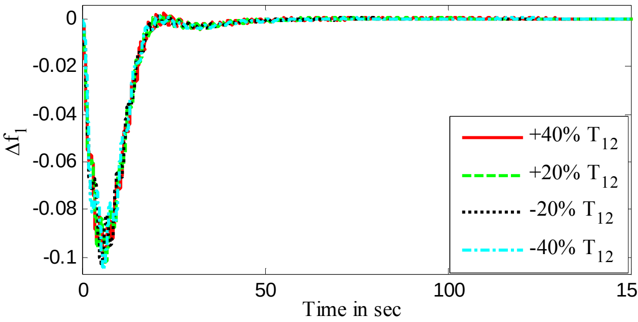

Fig. 13 Frequency deviation in area-1 for load change in area-2 with variation in T_{12}

TABLE III
SENSITIVITY ANALYSIS

Parameter variation	% change	ISE	ITAE	ITSE	IAE	Settling time		
						Δf1	Δf2	ΔPtie
TG1	+40%	0.1368	18.8612	0.9411	1.8978	103.0	98.9	50.71
	+20%	0.1387	18.5976	0.9589	1.9132	69.66	68.2	48.09
	-40%	0.1378	20.2373	0.9465	1.9131	64.95	66.05	50.93
	-20%	0.142	18.4817	0.993	1.9443	59.79	58.52	43.27
TT1	+40%	0.1322	18.7403	0.9084	1.8653	108.52	101.72	53.44
	+20%	0.1367	18.4267	0.9405	1.8951	72.32	68.35	48.27
	-40%	0.146	19.1162	1.0308	1.9819	54.82	55.97	40.76
	-20%	0.1435	18.6963	1.0063	1.957	59.62	58.29	43.07
TG2	+40%	0.1592	36.9598	1.2726	2.5018	102.29	103.45	82.65
	+20%	0.1464	29.3097	1.5097	2.1186	133.3	132.09	50.87
	-40%	0.1225	39.2024	0.8645	2.1311	147.95	147.67	101.49
	-20%	0.1323	27.0531	0.8951	1.9867	117.13	115.87	49.52
T12	+40%	0.1425	19.6926	1.0009	1.9956	96.28	88.25	47.31
	+20%	0.1414	19.055	0.9883	1.9436	66.09	64.81	46.34
	-40%	0.1388	26.1097	0.9543	1.9537	63.3	61.68	45.52
	-20%	0.1396	18.1352	0.966	1.9181	63.5	62	45.14

VI. CONCLUSION

This paper presents the design and performance evaluation of DE optimized PID and PI controller for nonlinear AGC system. The dynamic performances of the proposed controllers are compared with fuzzy logic controller (FLC). The frequency deviations of area and tie line power deviation responses are obtained for 1% step load perturbation in area 2. The proposed DE optimized PI and PID controllers give better responses for frequency deviation and tie line power deviation for having relatively smaller peak overshoot and lesser settling time as compared to FLC. Further, robustness analysis is carried out which demonstrates the robustness of the proposed DE optimized PID controller to wide variations in system parameters.

APPENDIX

Nominal parameters of the system investigated are:

$B_1 = B_2$=0.425p.u.MW/Hz; $R_1 = R_2$=2.4Hz/p.u.;

T_{G1}=0.2s; T_{T1}=0.3s; $T_{G2} = 48.7s$; $T_1 = 0.513s$;

$T_2 = 10s$; $T_w = 1s$; $T_r = 10s$; $K_r = 0.333$;

$K_{PS1} = K_{PS2}$=120Hz/p.u.MW; $T_{P1} = T_{P2}$=20s;

T_{12}=0.0707 pu; a_{12} = -1.

Boiler Data

K_1=0.85, K_2=0.095, K_3=0.92, c_b=200, T_d=0, T_f=10, k_{ib}=0.03, T_{ib}=26, T_{rb}=69

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