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Design and analysis of differential evolution algorithm based automatic generation control for interconnected power system

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Differential Evolution (DE) algorithm

Abstract This paper presents the design and performance analysis of Differential Evolution (DE) algorithm based Proportional-Integral (PI) controller for Automatic Generation Control (AGC) of an interconnected power system. A two area non-reheat thermal system equipped with PI controllers which is widely used in literature is considered for the design and analysis purpose. The design problem is formulated as an optimization problem control and DE is employed to search for optimal controller parameters. Three different objective functions using Integral Time multiply Absolute Error (ITAE), damping ratio of dominant eigenvalues and settling time with appropriate weight coefficients are derived in order to increase the performance of the controller. The superiority of the proposed DE optimized PI controller has been shown by comparing the results with some recently published modern heuristic optimization techniques such as Bacteria Foraging Optimization Algorithm (BFOA) and Genetic Algorithm (GA) based PI controller for the same interconnected power system.

1. Introduction

An interconnected power system is made up of several areas and for the stable operation of power systems; both constant frequency and constant tie-line power exchange should be provided. In each area, an Automatic Generation Controller (AGC) monitors the system frequency and tie-line flows, computes the net change in the generation required (generally referred to as Area Control Error – ACE) and changes the set position of the generators within the area so as to keep the time average of the ACE at a low value [1]. Therefore ACE, which is defined as a linear combination of power net-interchange and frequency deviations, is generally taken as the controlled output of AGC. As the ACE is driven to zero by the AGC, both frequency and tie-line power errors will be forced to zeros [2]. AGC function can be viewed as a supervisory control function which attempts to match the generation trend within an

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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.

The researchers in the world over trying to understand several strategies for AGC of power systems in order to maintain the system frequency and tie line flow at their scheduled values during normal operation and also during small perturbations. A critical literature review on the AGC of power systems has been presented in [3] where various control aspects concerning AGC problem have been studied. Moreover the authors have reported various AGC schemes, AGC strategies and AGC system incorporating BES/SMES, wind turbines, FACTS devices and PV systems. There has been considerable research work attempting to propose better AGC systems based on modern control theory [4,5], artificial neural network [6–9], fuzzy system theory [10–12], reinforcement learning [13] and ANFIS approach has [14,15].

From the literature survey, it may be concluded that there is still scope of work on the optimization of PI controller parameters to further improve the AGC performance. For this, various novel evolutionary optimization techniques can be proposed and tested for comparative optimization performance study. However, ANN, fuzzy, and ES suffer from the requirement of expert user in their design and implementation, a lack of the formal model theory and mathematical rigors and so are vulnerable to the experts' depth of knowledge in problem definition. Modern heuristic optimization techniques, by contrast, access deep knowledge of systems problem by well-established models and have much more potential in power systems. Modern heuristic optimization technique based approaches have been proposed recently to design a controller. These approaches include particle swarm optimization [16–17], differential evolution [18,19], multi-objective evolutionary algorithm [20] and NSGA-II [21,22], etc. Nanda et al. [23] have demonstrated that bacterial foraging, a powerful evolutionary computational technique, based integral controller provides better performance as compared to that with integral controller based on classical and GA techniques in three unequal areas thermal system. E.S. Ali and S.M. Abd-Elazim [24] have reported recently that Bacterial Foraging Optimization Algorithm (BFOA), based proportional integral (PI) controller provides better performance as compared to that with GA based PI controller in two area non-reheat thermal system. Differential Evolution (DE) is a branch of evolutionary algorithms developed by Rainer Stron and Kenneth Price in 1995 for optimization problems [25]. It 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. It has demonstrated its usefulness and robustness in a variety of applications such as, Neural network learning, Filter design and the optimization of aerodynamics shapes. DE differs from other evolutionary algorithms (EA) in the mutation and recombination phases. 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 [18,19]. In view of the above, an attempt has been made in this paper for the optimal design of DE based PI controller for LFC in two area interconnected power system considering small step load perturbation occurring in a single area as well as simultaneously in all the areas.

The aim of the present work is twofold: to demonstrate the advantages of DE over other techniques such as BFOA and GA which are recently presented in the literature for the similar problem and to show advantages of using a modified objective function based on Integral Time multiply Absolute Error (ITAE) criteria, damping ratio of dominant eigenvalues and settling times of frequency and tie line power deviations with appropriate weight coefficients to further increase the performance of the proposed controllers. The design problem of the proposed controller is formulated as an optimization problem and DE is employed to search for optimal controller parameters. By minimizing the proposed objective functions, in which the deviations in the frequency and tie line power, damping ratio and settling times are involved; dynamic performance of the system is improved. 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 loading conditions, disturbance and system parameters. Further, the superiority of the proposed design approach is illustrated by comparing the proposed approach with some recently published approaches such as BFOA and GA.

2. System modeling

2.1. LFC model

The dynamic model of Load Frequency Control (LFC) for a two-area interconnected power system is presented in this section. Each area of the power system consists of speed governing system, turbine and generator. Each area has three inputs and two outputs. The inputs are the controller input ΔP_{ref} (also denoted as u), load disturbance ΔP_D and tie-line power error ΔP_{Tie}. The outputs are the generator frequency Δf and Area Control Error (ACE) given by Eq. (1).

$$ACE = B\Delta f + \Delta P_{Tie} \tag{1}$$

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]:

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

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

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

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

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

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

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

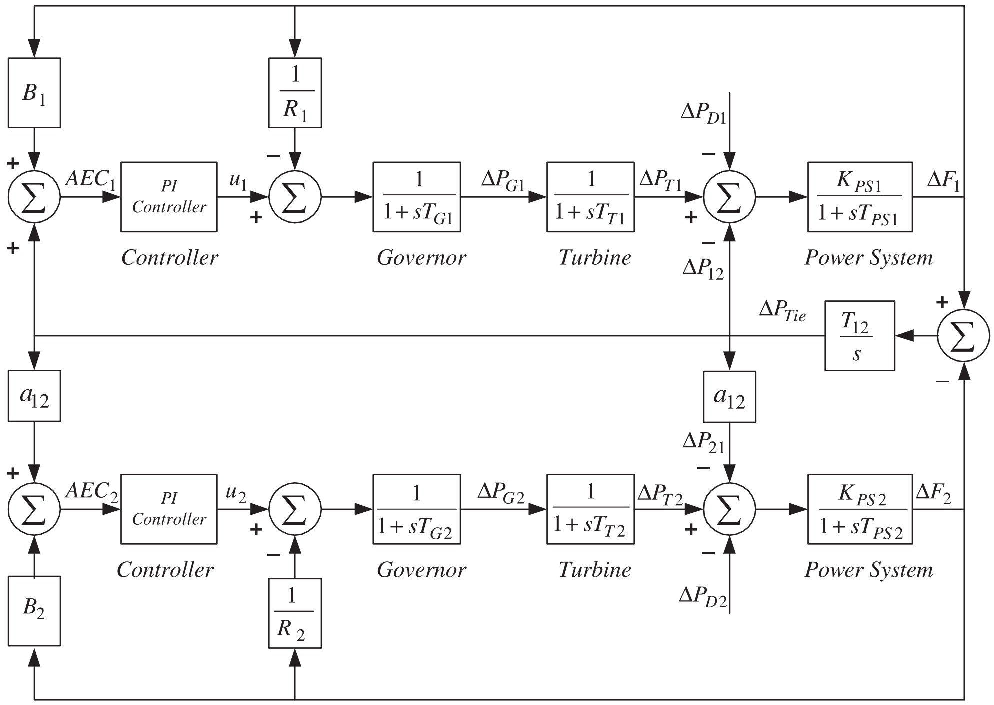

Figure 1 Transfer function model of two-area nonreheat thermal system.

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 out put $\Delta f(s)$ given by [2]:

$$\Delta f(s) = G_P(s)[\Delta P_T(s) - \Delta P_D(s)] \tag{6}$$

2.2. System under study

The system under investigation consists of two area interconnected power system of nonreheat thermal plant as shown in Fig. 1. The system is widely used in literature is for the design and analysis of automatic load frequency control of interconnected areas [24]. In Fig. 2, 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 p.u. 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 (p.u.); ΔP_{G1} and ΔP_{G2} are the governor output command (p.u.); 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.

3. The proposed approach

The proportional integral derivative controller (PID) is the most popular feedback controller used in the process industries. While proportional and integrative modes are often used as single control modes, a derivative mode is rarely used as it amplifies the signal noise. In view of the above, a PI structured controller is considering in the present paper. The design of PI controller requires determination of the two parameters, Proportional gain (K_P) and Integral gain (K_I). The controllers in both the areas are considered to be identical so that $K_{P1} = K_{P2} = K_P$ and $K_{I1} = K_{I2} = K_I$.

The error inputs to the controllers are the respective Area Control Errors (ACEs) given by:

$$e_1(t) = ACE_1 = B_1\Delta f_1 + \Delta P_{Tie} \tag{7}$$

$$e_2(t) = ACE_2 = B_2\Delta f_2 - \Delta P_{Tie} \tag{8}$$

The control inputs of the power system u_1 and u_2 are the outputs of the controllers. The control inputs are obtained as:

$$u_1 = K_{P1}ACE_1 + K_{I1}\int ACE_1 \tag{9}$$

$$u_2 = K_{P2}ACE_2 + K_{21}\int ACE_2 \tag{10}$$

In the design of a PI controller, the objective function is first defined based on the desired specifications and constraints. The design of objective function to tune PI controller is generally based on a performance index that considers the entire closed loop response. Typical output specifications in the time domain are peak overshooting, 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). It has been shown that the ITAE provides better responses as compared to other criteria [26]. Also, the eigenvalues and modal analysis provides an extension of analytical methods to examine the low frequency oscillations that are present in a power system. Eigenvalue analysis uses the standard linear, state space form of system

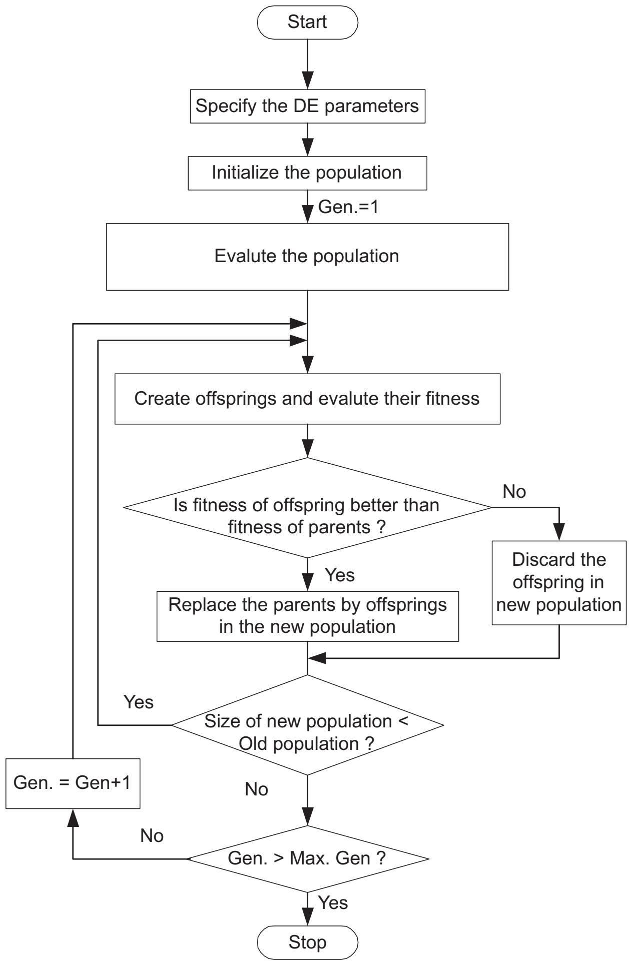

Figure 2 Flow chart of proposed DE optimization approach.

equations and provides an appropriate tool for evaluating system conditions for the study of small signal stability of power system. Eigenvalue analysis investigates the dynamic behavior of the power system under different characteristic frequencies (modes). In a power system, it is required that all modes be stable. Moreover, it is desired that all electromechanical oscillations be damped out as quickly as possible. In other words, the damping ratios of dominant eigenvalues should be maximized as much as possible [1].

Some of the realistic control specifications for Automatic Generation Control (AGC) are [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.

To meet the above design specifications, three different objective functions are employed in the present paper as given by Eqs. (11)–(13). The first objective function (ITAE) given by Eq. (11) is a standard one and employed often in other papers. It tries to achieve the design specifications given by (i and ii). Also, the desired system response should have minimal settling time with a small or no overshoot. To add some degree of stability and damping of oscillating modes, the second objective function given by Eq. (12) is proposed. It aims to minimize the ITAE and maximize minimum damping ratio of dominant eigenvalues. Minimization of this objective function will minimize maximum overshoot also [10,11]. To ensure that the errors are quickly minimized the settling times of Δf_1, Δf_2 and ΔP_{Tie} are also included in the third objective function given by Eq. (13).

$$J_1 = \int_0^{t_{sim}} (|\Delta f_1| + |\Delta f_2| + |\Delta P_{Tie}|) \cdot t \cdot dt \tag{11}$$

$$J_2 = \int_0^{t_{sim}} \omega_1 \cdot \int_0^{t_{sim}} (|\Delta f_1| + |\Delta f_2| + |\Delta P_{Tie}|) \cdot t \cdot dt + \omega_2 \cdot \frac{1}{\min\left(\sum_{i=1}^{n}(1-\zeta_i)\right)} \tag{12}$$

$$J_3 = \int_0^{t_{sim}} \omega_3 \cdot \int_0^{t_{sim}} (|\Delta f_1| + |\Delta f_2| + |\Delta P_{Tie}|) \cdot t \cdot dt + \omega_4 \cdot \frac{1}{\min\left(\sum_{i=1}^{n}(1-\zeta_i)\right)} + \omega_5 \cdot T_S \tag{13}$$

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; T_S is the sum of the settling times of frequency and tie line power deviations; ω_1 to ω_5 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 Eqs. (12) and (13) lie in the same range. Repetitive trial run of the optimizing algorithms reveals that numerical value of ITAE lies in the range 1.25–2.5, minimum damping ratio lies in the range 0.02–0.3 and total settling times of Δf_1, Δf_2 and ΔP_{Tie} lies in the range 15–50. To make each term competitive during the optimization process the weights are chosen as: $\omega_1 = 1.0$, $\omega_2 = 10$, $\omega_3 = 1.0$, $\omega_4 = 1.0$ and $\omega_5 = 0.05$.

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

$$\text{Minimize}\, J \tag{14}$$

Subject to

$$K_{P\min} \leqslant K_P \leqslant K_{P\max}, \quad K_{I_{\min}} \leqslant K_I \leqslant K_{I_{\max}} \tag{15}$$

where J is the objective function (J_1, J_2 and J_3) and $K_{P\min}$, $K_{I_{\min}}$ and $K_{P\max}$, $K_{I_{\max}}$ 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 −1.0 and 1.0 respectively.

4. Differential evolution

Differential Evolution (DE) algorithm is a population-based stochastic optimization algorithm recently introduced [25]. Advantages of DE are: simplicity, efficiency and 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 [18,19].

4.1. 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 $[X_j^L, X_j^U]$.

4.2. 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:

$$V_{i,G+1} = X_{r1,G} + F \cdot (X_{r2,G} - X_{r3,G}) \tag{16}$$

where F is a constant from (0, 2)

4.3. 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:

$$U_{j,i,G+1} = \begin{cases} V_{j,i,G+1} & \text{if} \quad rand_{j,i} \leqslant CR \quad or \quad j = I_{rand} \\ X_{j,i,G+1} & \text{if} \quad rand_{j,i} > CR \quad or \quad j \neq I_{rand} \end{cases} \tag{17}$$

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

Table 1 Tuned controller parameters for different objective function.

Objective function/controller parameters	J_1	J_2	J_3
Proportional gain (K_P)	−0.2146	−0.4741	−0.4233
Integral gain (K_I)	0.4335	0.3047	0.2879

Table 2 System eigenvalues, minimum damping ratio and error criteria.

Parameters	Conventional	DE-J_1	DE-J_2	DE-J_3	GA [24]	BFOA [24]
System modes	−13.7342	−13.1245	−12.9767	−13.0081	−13.1203	−13.01
	−13.6218	−13.1098	−12.916	−12.9575	−13.1043	−12.9601
	−0.086 ± 4.1699i	−0.4813 ± 3.1536i	−0.745 ± 2.8024i	−0.7025 ± 2.8907i	−0.5605 ± 3.1716i	−0.7037 ± 2.8983i
	−0.9568 ± 3.4022i	−1.0009 ± 1.8843i	−0.8499 ± 1.1203i	−1.0391 ± 1.3059i	−1.1751 ± 1.9112i	−1.0637 ± 1.3221i
	−1.8538	−0.8981 ± 0.2791i	−0.7083 ± 0.5092i	−0.7351 ± 0.3756i	−1.1967	−0.733 ± 0.3477i
	−0.2355				−0.4454	
	−0.2359	−0.7717	−1.2675	−0.8476	−0.4288	−0.7958
Minimum damping ratio	0.0206	0.1509	0.2569	0.2361	0.174	0.2359
T_S (s) Δf_1	45	8.96	6.39	5.38	10.59	5.52
Δf_2	45	8.16	6.69	6.95	11.39	7.09
ΔP_{Tie}	28	5.75	4.85	6.21	9.37	6.35
ITAE	3.7568	0.9911	1.5454	1.6766	2.7475	1.7975

4.4. 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:

$$X_{i,G+1} = \begin{cases} U_{i,G+1} & \text{if } f(U_{i,G+1}) < f(X_{i,G}) \\ X_{i,G} & \text{otherwise} \end{cases}. \tag{18}$$

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

5. Results and discussion

5.1. Application 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 10% step load change in area 1. 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. In Appendix B, the method of calculating the system eigenvalues, minimum damping ratio and settling times have been provided.

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 [18,19]. 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. 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 (1, −1). The flow chart of the DE algorithm employed in the present study is given in Fig. 2. 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. The best final solutions obtained in the 20 runs are shown in Table 1.

5.2. Simulation results

Table 2 shows the system eigenvalues, minimum damping ratio, settling time (2%) and various error criteria. To show the effectiveness of the proposed DE method for optimizing controller parameters, results are compared with some recently published modern heuristic optimization methods such as Bacteria Foraging Optimization Algorithm (BFOA) and Genetic Algorithm (GA) for the same interconnected power system [24]. It is clear from Table 2 that the system with conventional controller is provides small damping factor with a minimum damping ratio (ζ = 0.0206) and maximum ITAE value (ITAE = 3.7568). With the proposed DE technique using ITAE as an objective function (DE-J_1), minimum ITAE value (ITAE = 0.9911) is obtained compared to the other objective functions. However, the minimum damping ratios are worse than those obtained with GA and BFOA optimized PI controller, and the settling times are inferior to BFOA even though those are better than GA. With second objective function (DE-J_2), which includes damping ratios in addition to the ITAE, minimum damping ratio has been improved (ζ = 0.2569) and ITAE value (ITAE = 1.5454) compared to those with GA and BFOA techniques. But the settling times are inferior to those with BFOA. However, when third objective function is used (DE-J_3), better performance is obtained in

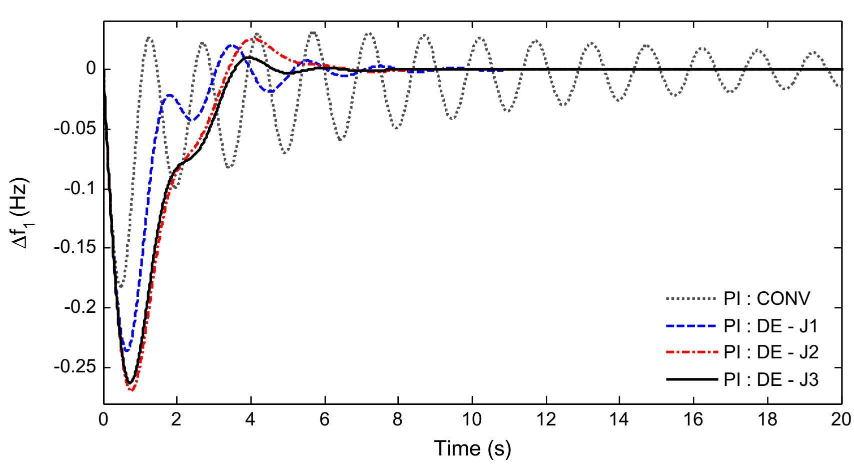

Figure 3 Change in frequency of area-1 for 0.1 p.u. change in area-1.

terms of minimum damping ratio (ζ = 0.2361), ITAE value (ITAE = 1.6766) and settling times compared to those with BFOA technique as presented in the literature. The above analysis shows that the system performance is greatly improved by applying the proposed controller.

Time domain simulations are performed for step load change at different locations and with parameter variations. The response with conventionally optimized PI controller is shown with dotted lines (with legend 'PI: CONV'), the response with PI controller optimized employing DE algorithm

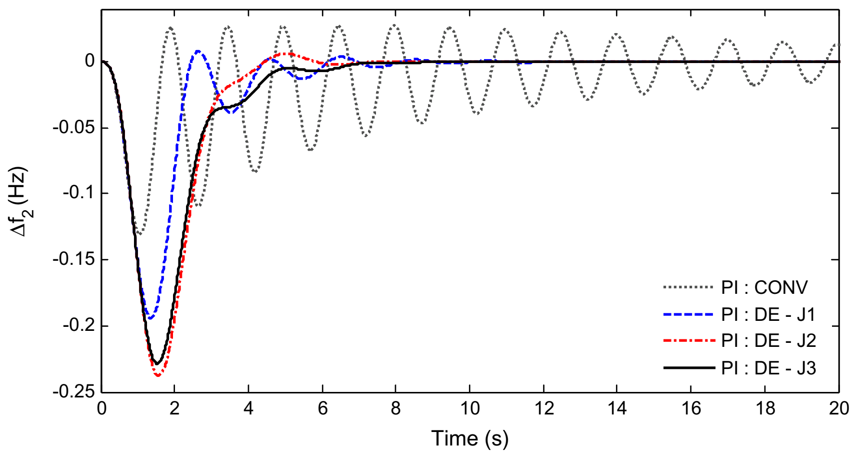

Figure 4 Change in frequency of area-2 for 0.1 p.u. change in area-1.

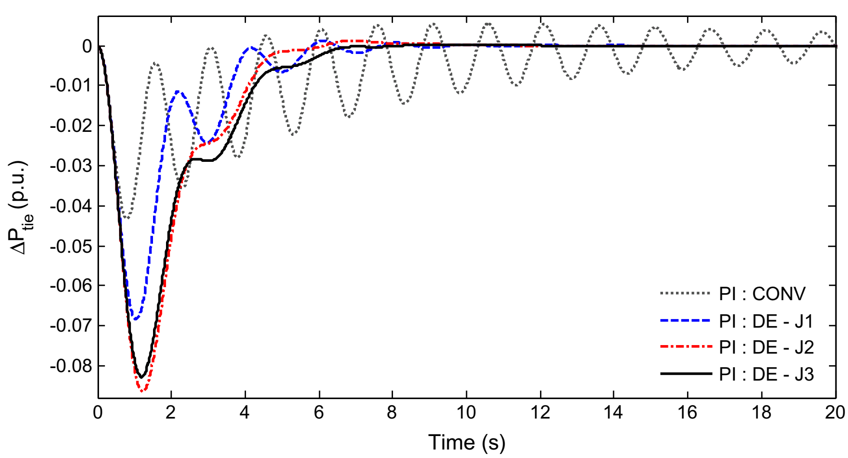

Figure 5 Change in tie line power for 0.1 p.u. change in area-1.

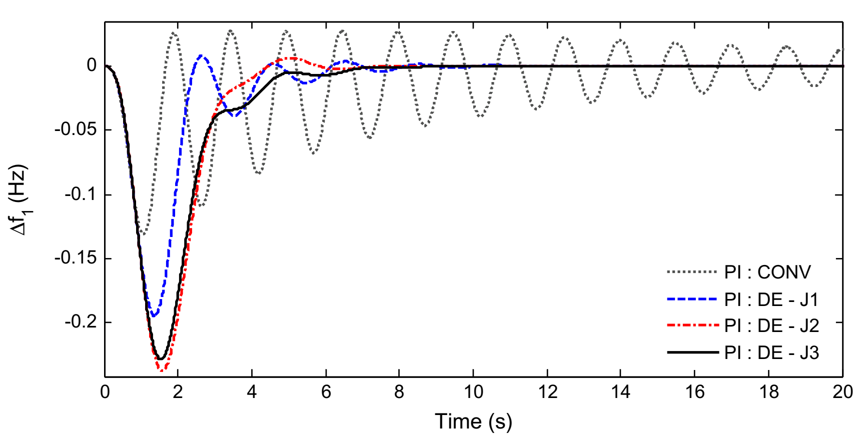

Figure 6 Change in frequency of area-1 for 0.1 p.u. change in area-2.

using objective function J_1, J_2 and J_3 are shown with dash line (with legend PI: DE-J_1), dash-dot line (with legend PI: DE-J_2) and solid line (with legend PI: DE-J_3).The following cases are considered.

5.2.1. Case A: Step load change in area-1

A step increase in demand of 0.1 p.u. is applied at $t = 0$ s in area-1 and the system dynamic responses are shown in Figs. 3–5. Critical analysis of the dynamic responses clearly

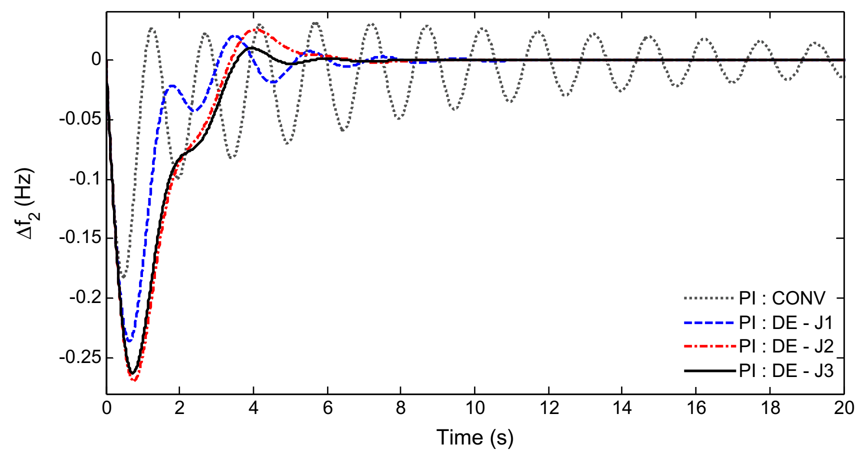

Figure 7 Change in frequency of area-2 for 0.1 p.u. change in area-2.

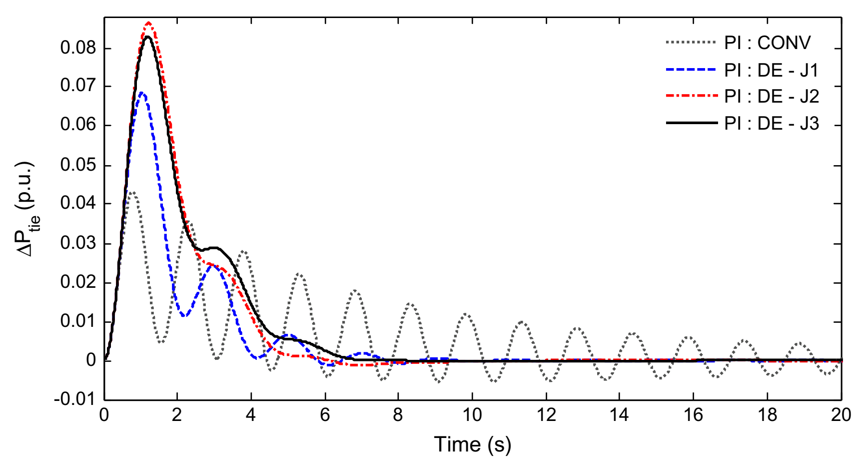

Figure 8 Change in tie line power for 0.1 p.u. change in area-2.

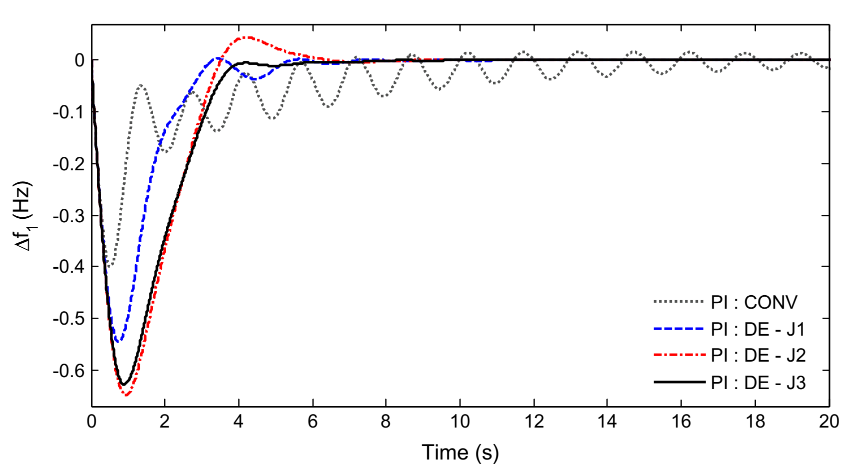

Figure 9 Change in frequency of area-1 for 0.1 p.u. change in area-1 and 0.2 p.u. change in area-2.

reveals better dynamic performance is obtained with minimum settling time and oscillations when objective function J_3 is used.

5.2.2. Case B: Step load change in area-2

Figs. 6–8 show the system dynamic response for a step increase in demand of 0.1 p.u. in area-2. It is clear from Figs. 6–8 that

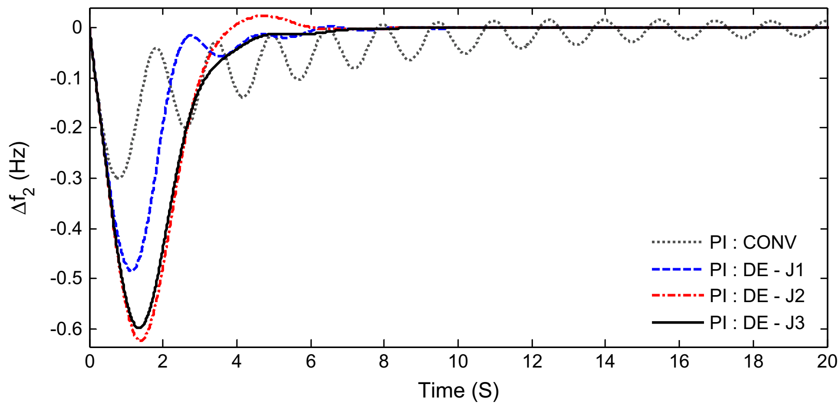

Figure 10 Change in frequency of area-2 for 0.1 p.u. change in area-1 and 0.2 p.u. change in area-2.

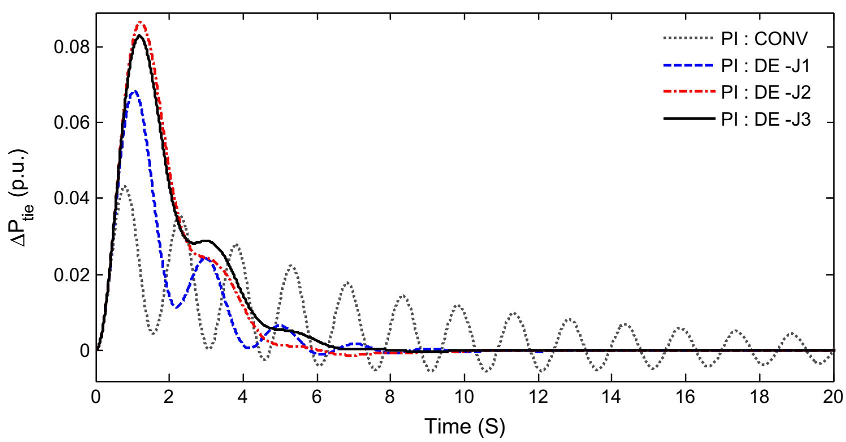

Figure 11 Change in tie line power for 0.1 p.u. change in area-1 and 0.2 p.u. change in area-2.

Table 3 Sensitivity analysis.

Parameter variation	% Change	Performance index	Settling time T_s (s)			Minimum damping ratio
		ITAE	Δf_1	Δf_2	ΔP_{Tie}	
Loading condition Case-A	+25 Case-A1	1.6903	5.42	6.97	6.21	0.2387
	+50 Case-A2	1.7040	5.45	7.00	6.20	0.2412
	-25 Case-A3	1.6630	5.33	6.92	6.21	0.2336
	−50 Case-A4	1.6494	5.27	6.91	6.22	0.2310
T_G Case-B	+25 Case-B1	1.6577	5.39	6.89	6.14	0.2192
	+50 Case-B2	1.6418	7.35	6.86	6.08	0.2024
	−25 Case-B3	1.6961	5.37	7.01	6.31	0.2526
	−50 Case-B4	1.7158	5.33	7.05	6.40	0.2676
T_T Case-C	+25 Case-C1	1.6254	7.63	7.02	6.16	0.1872
	+50 Case-C2	1.7533	8.89	9.86	9.22	0.1543
	−25 Case-C3	1.7505	5.22	6.91	6.50	0.3139
	−50 Case-C4	1.8248	5.25	6.78	7.01	0.4258
T_{12} Case-D	+25 Case-D1	1.6629	6.82	7.53	5.84	0.2095
	+50 Case-D2	1.6538	6.43	7.32	5.52	0.1895
	−25 Case-D3	1.6997	5.22	7.53	6.61	0.2740
	−50 Case-D4	1.7463	6.34	8.18	6.91	0.3333

Table 4 System modes for each case.

Cases A	System modes	Cases-B	System modes	Cases-C	System modes	Cases-D	System modes
Case-A1	−13.0085 −12.9579 −0.7110 ± 2.8927i −1.0523 ± 1.3136i −0.7326 ± 0.3780i −0.8333	Case-B1	−10.6599 −10.589 −0.6576 ± 2.9275i −0.9813 ± 1.3475i −0.7041 ± 0.3979i −0.8317	Case-C1	−12.8884 −12.8487 −0.5526 ± 2.8998i −0.7910 ± 1.3409i −0.6115 ± 0.4300i −0.7858	Case-D1	−13.02 −12.9575 −0.6820 ± 3.1831i −1.0391 ± 1.3059i −0.7497 ± 0.3857i −0.8476
Case-A2	−13.009 −12.9583 −0.7195 ± 2.8947i −1.0653 ± 1.3214i −0.7302 ± 0.3804i −0.8194	Case-B2	−9.1448 −9.0554 −0.6108 ± 2.9549i −0.9220 ± 1.3803i −0.6751 ± 0.4152i −0.8174	Case-C2	−12.8143 −12.7817 −0.4506 ± 2.8863i −0.6231 ± 1.3249i −0.5284 ± 0.4462i −0.7443	Case-D2	−13.0316 −12.9575 −0.6660 ± 3.4507i −1.0391 ± 1.3059i −0.7598 ± 0.3922i −0.8476
Case-A3	−13.0077 −12.9571 −0.6940 ± 2.8888i −1.0257 ± 1.2983i −0.7376 ± 0.3732i −0.8624	Case-B3	−17.028 −16.9971 −0.7426 ± 2.8448i −1.0936 ± 1.2554i −0.7684 ± 0.3467i −0.8656	Case-C3	−13.2326 −13.1632 −0.9269 ± 2.8038i −1.4312 ± 1.0722i −0.8935 −1.0145 −0.9689	Case-D3	−12.9959 −12.9575 −0.7312 ± 2.5659i −1.0391 ± 1.3059i −0.7125 ± 0.3582i −0.8476
Case-A4	−13.0072 −12.9567 −0.6855 ± 2.8868i −1.0121 ± 1.2908i −0.7401 ± 0.3707i −0.8776	Case-B4	−25.2251 −25.2107 −0.7752 ± 2.7908i −1.1433 ± 1.1964i −0.8039 ± 0.3084i −0.8861	Case-C4	−13.7968 −13.6893 −1.1523 ± 2.4484i -3.3517 −2.492 −1.0879 ± 0.3872i −0.6232	Case-D4	−12.9834 −12.9575 −0.7767 ± 2.1969i −1.0391 ± 1.3059i −0.6733 ± 0.3212i −0.8476

the designed controllers perform satisfactorily for the change in location of the disturbance and the dynamic performance with DE-J_3out performs the other two with minimum oscillation and settling times.

5.2.3. Case C: Step load change in both areas

A step increase in demand of 0.1 p.u. in are-1 and a step increase in demand of 0.2 p.u. in area-2 are considered simultaneously. Figs. 9–11 show the system dynamic response from which it is clear that the proposed controller tuned objective function J_3 achieves good dynamic performance for the power system compared to the other alternatives.

5.2.4. Case D: Sensitivity analysis

To study the robustness the system to wide changes in the operating conditions and system parameters, sensitivity analysis is carried out [23,27–29]. The operating load condition and time constants of speed governor, turbine, tie-line power are varied in the range of +50% to −50% from their nominal values in steps of 25% taking one at a time. Due to its superior performance, the controller parameters obtained using the objective function J_2 are considered in all cases. The results obtained are provided in Table 3. The system modes under these cases are shown in Table 4. It is obvious from Table 3 that the system performances hardly change when the operating load condition and system parameters are changed. It is also evident from

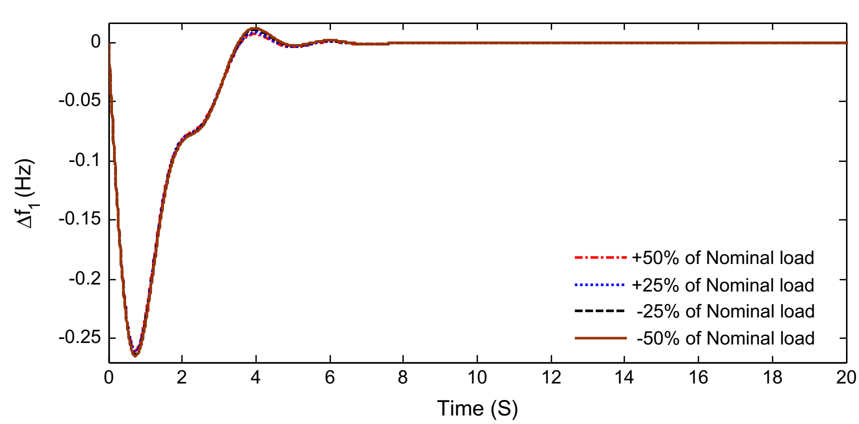

Figure 12 Change in frequency of area-1 for 0.1 p.u. change in area-1with change in loading.

Table 4 that the eigenvalues lie in the left half of s-plane for all the cases thus maintain the stability. The frequency deviation responses for 0.1 p.u. change in area-1 with these varied conditions are shown in Figs. 12–15. It can be observed from Figs. 12–15 that there is negligible effect of the variation of operating loading conditions and system time constants on the frequency deviation responses with the controller parameters obtained at nominal values. So it can be concluded that, the proposed control strategy provides a robust and stable control satisfactorily and the optimum values of controller parameters obtained at the nominal loading with nominal parameters, need not be reset for wide changes in the system loading or system parameters.

6. Conclusion

This study presents the design and performance evaluation of Differential Evolution (DE) optimized Proportional-Integral (PI) controller for Automatic Generation Control (AGC) of

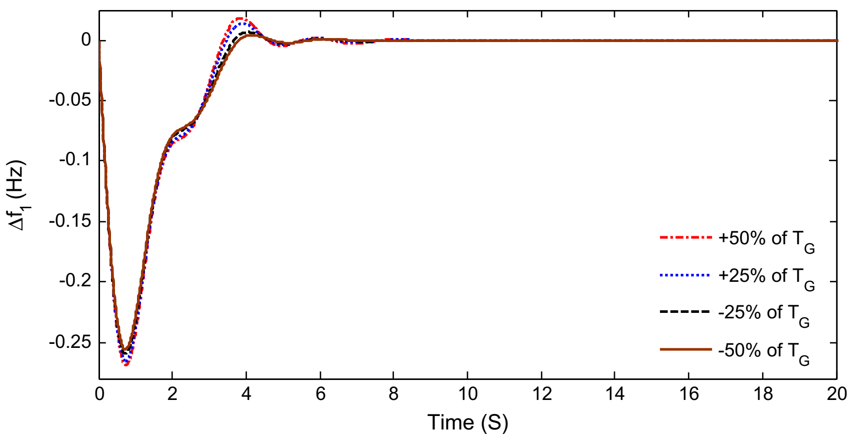

Figure 13 Change in frequency of area-1 for 0.1 p.u. change in area-1with change in T_G.

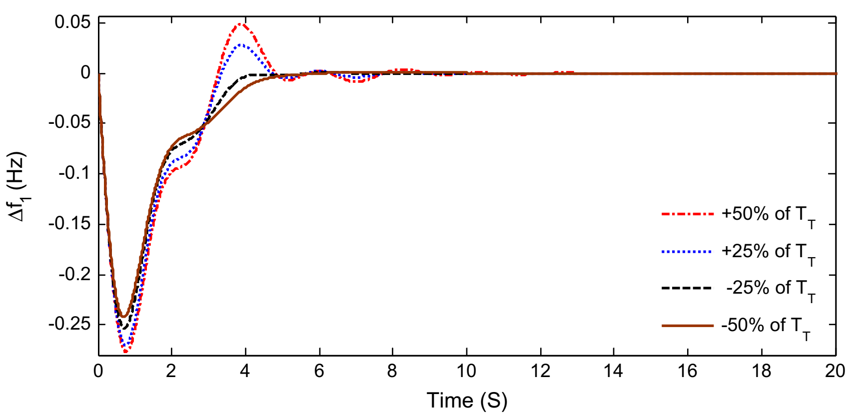

Figure 14 Change in frequency of area-1 for 0.1 p.u. change in area-1with change in T_T.

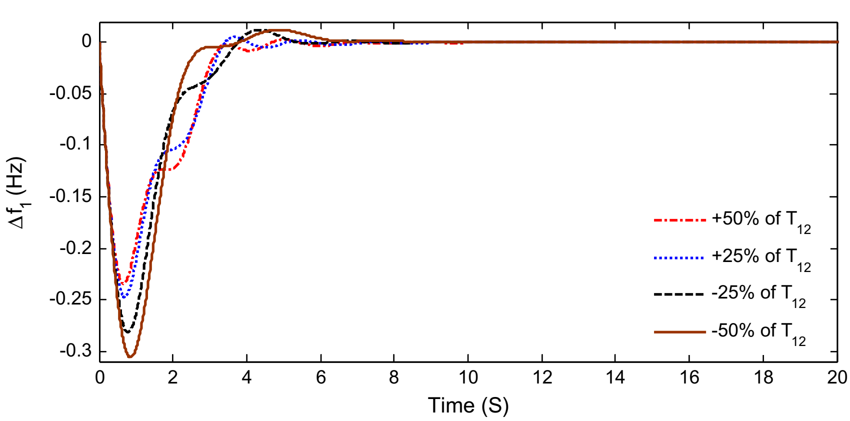

Figure 15 Change in frequency of area-1 for 0.1 p.u. change in area-1with change in T_{12}.

an interconnected power system. For the optimization of controller parameters using modern heuristic optimizations techniques, selection of suitable objective function is very important. In view of the above, different objective functions using Time multiply Absolute Error (ITAE), damping ratio of dominant eigenvalues and settling time with appropriate weight coefficients are employed to increase the performance of the controller. The results obtained from the simulations show that the proposed control strategy optimized with new objective function achieves better dynamic performances than the standard objective functions. The superiority of the proposed design approach has been shown by comparing the results with some recently published modern heuristic optimization techniques such as Bacteria Foraging Optimization Algorithm (BFOA) and Genetic Algorithm (GA) based PI controller for the same interconnected power system. Further, robustness analysis is carried out which demonstrates the robustness of the proposed DE optimized PI controller to wide changes in loading condition and system parameters.

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, $B_2 = 0.045$ p.u. MW/Hz; $R_1 = R_2 = 2.4$ Hz/p.u.; $T_{G1} = T_{G2} = 0.08$ s; $T_{T1} = T_{T2} = 0.3$ s; $K_{PS1} = K_{PS2} = 120$ Hz/p.u. MW; $T_{PS1} = T_{PS2} = 20$ s; $T_{12} = 0.545$ p.u.; $a_{12} = -1$.

Appendix B

It is desirable that the transient response of a system be sufficiently fast with small settling time and be adequately damped. The settling time is the time required for the response curve to reach and stay within a range about the final value of size specified by absolute percentage of the final value (usually 2% or 5%). To make the settling time small, the damping ratio should not be too small. The MATLAB programme to find out system eigenvalues, settling time and minimum damping ratio is given below:

```
[A, B, C, D] = linmod('Model');          % Model is the
                                          SIMULINK model
                                          of system
Eigen_Values = eig(A)                     % Computes the
                                          system eigenvalues
[wn, Z] = damp(A);                        % Computes the
                                          natural frequencies
                                          and damping factors
Minim_Damping_Ratio = min(abs(Z))         % Computes minimum
                                          damping ratio
sim('Model', 50);
time=[0: 0.01: 50];
for t = 1: 5001
  if (Del_f_1(t) ⩾ 0.002||
Del_f_1(t) ⩽ −0.002)
      st = t;
   end
end
Tettling_Time_for_Delf_1 = time(st)%
Computes the settling time
```

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