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Controller parameters tuning of differential evolution algorithm and its application to load frequency control of multi-source power system

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ABSTRACT

This paper presents controller parameters tuning of Differential Evolution (DE) algorithm and its application to Load Frequency Control (LFC) of a multi-source power system having different sources of power generation like thermal, hydro and gas power plants. Initially, a single area multi-source power system with integral controllers for each unit is considered and DE technique is applied to obtain the controller parameters. Various mutation strategies of DE are compared and the control parameters of DE for best obtained strategy are tunned by executing multiple runs of algorithm for each parameter variation. The study is further extended to a multi-area multi-source power system and a HVDC link is also considered in parallel with existing AC tie line for the interconnection of two areas. The parameters of Integral (I), Proportional Integral (PI) and Proportional Integral Derivative (PID) are optimized employing tunned DE algorithm. The superiority of the proposed approach has been shown by comparing the results with recently published optimal output feedback 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 step load perturbation (SLP). It is noticed that, the dynamic performance of proposed controller is better than optimal output feedback controller. Furthermore, it is also seen that the proposed system is robust and is not affected by change in the loading condition, system parameters and size of SLP.

1. Introduction

The problem of controlling the real power output of generating units in response to changes in system frequency and tie-line power interchange within specified limits is known as Load Frequency Control (LFC). It is generally regarded as a part of automatic generation control (AGC) and is very important in the operation and control of power systems [1,2]. Large scale power systems are normally composed of control areas or regions representing coherent groups of generators. The control area may have the combination of thermal, hydro, gas, nuclear, renewable energy sources, etc. [3]. In a practically interconnected power system, the generation normally comprises of a mix of thermal, hydro nuclear and gas power generation. However, owing to their high efficiency, nuclear plants are usually kept at base load. Gas power generation is ideal for meeting the varying load demand and are normally used to meet peak demands. Keeping in view the present power scenario, combination of multi-source generators in a control area with their corresponding participation factors is more realistic for the study of LFC.

The researchers in the world over are trying to propose several strategies for LFC 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. In [4], a critical literature review on the AGC of power systems has been presented. It is noticed from literature survey, that most of the LFC works have been carried out on two area hydro-thermal or thermal–thermal systems. 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 favourable ratio between performances and cost. Additionally, it also offers simplified dynamic modelling, 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

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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. [11] 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 [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. Literature survey also shows that mostly AC tie lines are used for the interconnection of multi-area power systems and lesser attention is given to AC–DC parallel tie lines. Parmar et al. have reported in [13] a multi-sources generation including thermal-hydro-gas systems, considering HVDC link connected in parallel with existing AC link for stabilizing frequency oscillation and used an optimal output feedback controller for frequency stabilization.

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. 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 I/PI/PID controllers for LFC of multi-area multi-unit 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. As the success of DE in solving a specific problem significantly depends on appropriately choosing trial vector generation strategies and their associated control parameter values namely the step size F, cross over probability CR, number of population NP and generations G. Hence, selection of mutation strategy and DE control parameters is an important issue and often depends on the given problem. Therefore, it is desirable to determine an appropriate strategy and its associated control parameter values for an AGC problem. 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 optimal controller [5,13] for the same AGC system.

2. Control design of system under study

A single area system comprising hydro, thermal with reheat turbine and gas units is considered at the first instance for designing controller for the system. The linearized models of governors, reheat turbines, Hydro turbines, Gas turbines are used for simulation and LFC study of the power system as shown in Fig. 1. Each unit has its regulation parameter and participation factor which decide the contribution to the nominal loading. Summation of participation factor of each control should be equal to 1. In Fig. 1, R_1, R_2, R_3 are the regulation parameters of thermal, hydro and gas units respectively, U_T, U_H and U_G are the control outputs for of thermal, hydro and gas units respectively, K_T, K_H and K_G are the participation factors of thermal, hydro and gas generating units, respectively, T_{SG} is speed governor time constant of thermal unit in sec, T_T is steam turbine time constant in sec, K_r is the steam turbine reheat constant, T_r is the steam turbine reheat time constant in sec, T_W is nominal starting time of water in penstock in sec, T_{RS} is the hydro turbine speed governor reset time in sec, T_{RH} is hydro turbine speed governor transient droop time constant in sec, T_{GH} is hydro turbine speed governor main servo time constant in sec, X_C is the lead time constant of gas turbine speed governor in sec, Y_C is the lag time constant of gas turbine speed governor in sec, c_g is the gas turbine valve positioner, b_g is the gas turbine constant of valve positioner, T_F is the gas turbine fuel time constant in sec, T_{CR} is the gas turbine combustion reaction time delay in sec, T_{CD} is the gas turbine compressor discharge volume-time constant in sec, K_{PS} power system gain in Hz/puMW, T_{PS} is the power system time constant in sec, ΔF is the incremental change in frequency and ΔP_D incremental load change. The nominal parameters of the system are given in reference [5].

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, I, PI and PID structured controllers are considered in the present paper.

In the design of a modern heuristic optimization technique based 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 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). ISE and ITAE criterions are often used in literature for their better performance compared to IAE and ITSE criterion. ISE criterion integrates the square of the error over time. ISE will penalize large errors more than smaller ones (since the square of a large error will be much bigger). Control systems specified to minimize ISE will tend to eliminate large errors quickly, but will have to tolerate small errors persisting for a long period of time. Often this leads to fast responses, but with considerable, low amplitude, oscillation. ITAE integrates the absolute error multiplied by the time over time. What this does is to weight errors which exist after a long time much more heavily than those at the start of the response. ITAE tuning produces systems which settle much more quickly than the ISE tuning methods.

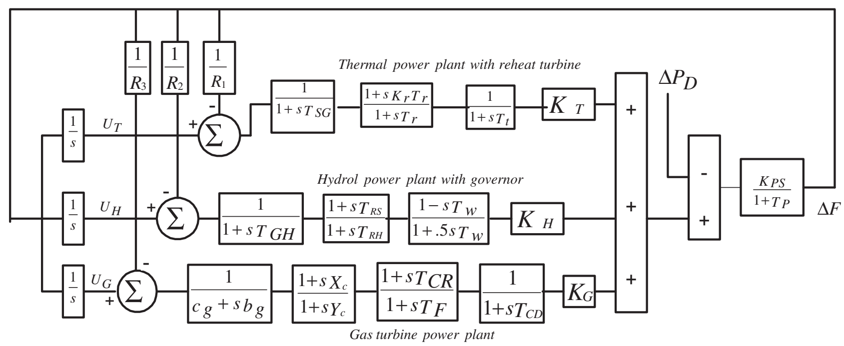

Fig. 1. Transfer function model of multi-source single area system with integral controllers.

As, the power change between control areas will be minimized quickly, ITAE is a better objective function in AGC studies and hence employed in the present paper. The objective function is expressed as:

$$J = ITAE = \int_0^{t_{sim}} |\Delta F| \cdot t \cdot dt \quad (1)$$

where ΔF is the system frequency deviation and 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.

$$\text{Minimize } J \quad (2)$$

Subject to

$$K_{I\min} \leqslant K_I \leqslant K_{I\max} \quad (3)$$

where J is the objective function and $K_{I\min}$ and $K_{I\max}$ 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 and 1 respectively.

3. Differential evolution

Differential Evolution (DE) algorithm is a population-based stochastic optimization algorithm recently introduced [14]. 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 [14–17].

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

3.2. 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:

$$V_{i,G+1} = X_{r1,G} + F \cdot (X_{r2,G} - X_{r3,G}) \quad (4)$$

where F is a constant from $(0,2)$

3.3. 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:

$$U_{j,i,G+1} = \begin{cases} V_{j,i,G+1} & \text{if } rand_{j,i} \leqslant CR \quad \text{or} \quad j = I_{rand} \\ X_{j\ \ i\ \ G+1} & \text{if } rand_{j,i} > CR \quad \text{or} \quad j \neq I_{rand} \end{cases} \quad (5)$$

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 $V_{i\ ,\ G+1} \neq X_{i,G}$.

3.4. 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:

$$X_{i,G+1} = \begin{cases} U_{i,G+1} & \text{if } f(U_{i,G+1}) < f(X_{i,G}) \\ X_{i,G} & \text{otherwise.} \end{cases} \quad (6)$$

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

4. Results and discussions

4.1. Implementation of DE

Implementation of DE requires the determination of some fundamental issues like: mutation strategy, 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 [15–17]. 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. The success of DE is also heavily dependent on setting of control parameters namely; population size N_P, DE step size F and crossover probability of CR. While applying DE, the strategy and control parameters should be carefully chosen for the successful implementation of the algorithm. A series of experiments were conducted to select the strategy control parameters.

4.2. Multi-source single area power system

At the first instance, a single area power system with integral controllers as shown in Fig. 2 is considered for selecting the DE strategy and control parameters. In all the cases (with variation in strategy and control parameters), the parameters of integral controller are optimized employing ITAE objective function pertaining to a 1% step load perturbation (SLP). The upper and lower bounds of the gains are chosen as $(1, -1)$. 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 flow chart of the DE algorithm employed in the present study is given in Fig. 2. To quantify the results, 20 independent runs were executed for each parameter variation. The mutation strategy is varied and the minimum, average, maximum values of the ITAE value along with the standard deviation obtained in 20 runs are presented in Table 1. In this case, the control parameters are chosen as: step size F = 0.9 and crossover probability of CR = 0.9 [17]. It is clear from Table 1 that DE/best/2/bin strategy (strategy 9) gives the minimum objective function value of 0.5634. After selecting

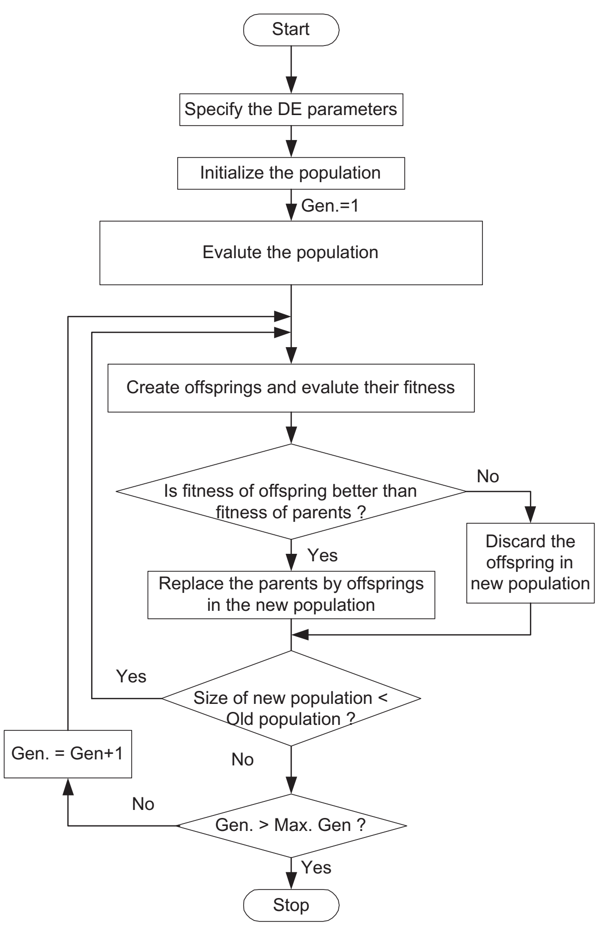

Fig. 2. Flow chart of DE algorithm.

Table 1
Comparison of strategy (F = 0.8, CR = 0.8, N_P = 20, Gen. = 30).

Sl. no	Strategy	Min.	Ave.	Max.	Std. Dev.
1	DE/best/1/exp	0.6579	0.9495	1.3307	0.2189
2	DE/rand/1/exp	0.7725	1.1762	1.6759	0.2954
3	DE/rand-to-best/1/exp	0.7461	0.9384	1.1809	0.1898
4	DE/best/2/exp	0.5984	0.8940	1.2333	0.2041
5	DE/rand/2/exp	0.6678	0.9484	1.3084	0.1981
6	DE/best/1/bin	0.6480	0.9312	1.2512	0.2011
7	DE/rand/1/bin	0.6825	0.8863	1.1195	0.1668
8	DE/rand-to-best/1/bin	0.7190	0.9060	1.2326	0.1604
9	**DE/best/2/bin**	**0.5634**	1.0304	1.2883	0.2217
10	DE/rand/2/bin	0.7047	0.9689	1.4791	0.2191

Bold fonts indicates minimum objective function value.

the strategy, the control parameters are varied from 0.2 to 1.0 in steps of 0.2 taking one a time and the results are summarized in Table 2. It is evident from Table 2 that the control parameters F and CR significantly affect the performance of the DE algorithm but N_P values ($\geqslant 20$) did not have a greater impact on the performance of DE algorithm. It appears from the results shown in Table 2 that the best settings of control parameters are: step size F = 0.2 and crossover probability of CR = 0.6, Population size N_P = 40 and Generation G = 30. Note that increasing the population size N_P beyond 40 and generations G beyond 30 will improve the solution accuracy slightly at the expense of increasing the computation time significantly.

To study the dynamic behavior of the system with DE optimized controllers, a 1% step load perturbation (SLP) is applied at t = 0 s and the frequency deviation response is shown in Fig. 3. To show the superiority of the proposed approach, the results are compared with a recently published approach (optimal control) for the same power system [5]. It can be seen from Fig. 3 that that proposed DE optimized integral controller gives better dynamic response having relatively smaller peak overshoot and lesser settling time as compared to the optimal controller.

To study the effect of variation in the loading conditions and system parameters on the system dynamic performances, the operating load condition and system parameters and are varied by ±25% from their nominal values, taking one at a time [18,19]. Table 3 gives the DE optimized integral controller parameters and performance of the system for a 1% SLP under varied operating load condition and system parameters. For comparison the system

Table 2
Tuning of DE controller parameters for single area power system (Strategy 9).

Parameters	Min.	Ave.	Max.	Std. Dev.		Other parameters
F	0.2	**0.5572**	0.9397	1.2425	0.2212	Gen. = 30,
	0.4	0.7001	0.9043	1.1962	0.1724	N_P = 20; CR = 0.8
	0.6	0.7461	0.9201	1.1809	0.1781	
	0.8	0.5634	1.0304	1.2883	0.2217	
	1.0	0.6678	0.9358	1.3084	0.2081	
CR	0.2	0.6480	0.9691	1.2512	0.1955	Gen. = 30, F = 0.2;
	0.4	0.6825	0.8811	1.1195	0.1597	N_P = 20;
	0.6	**0.5443**	0.8561	1.2326	0.1826	
	0.8	0.7725	1.1762	1.6759	0.2954	
	1.0	0.7047	1.0006	1.4791	0.2123	
N_P	10	0.9050	1.2212	2.1807	0.3634	Gen. = 30, F = 0.2;
	20	0.5443	0.8561	1.2326	0.1826	CR = 0.6
	30	0.5293	1.0574	1.7023	0.3430	
	40	**0.5165**	0.7108	0.8429	0.0942	
	50	0.5165	1.0124	1.5050	0.2405	
Gen.	10	0.8182	1.2324	2.2871	0.6645	N_P = 40, F = 0.2;
	20	0.6421	0.9864	2.2326	0.1976	CR = 0.6
	30	**0.5165**	0.7108	0.8429	0.0942	
	40	0.5165	0.8236	0.9512	0.1572	
	50	0.5165	0.7383	0.9711	0.1494	

Bold fonts indicates minimum objective function value.

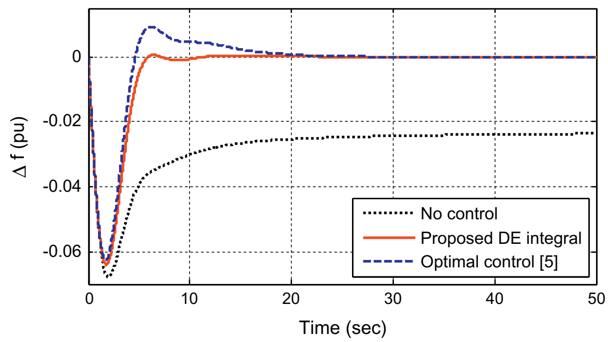

Fig. 3. Frequency deviation response for 1% step load perturbation.

performance with optimal output feedback controller [5] is also provided in Table 3. Various performance indexes like ITAE value, settling time and maximum overshoot in frequency deviation following a step load perturbation are used for comparison. It is evident that there is negligible effect of the variation of load condition and system parameters on the frequency deviation responses obtained at nominal values. It is also clear from Table 3 that the dynamic performance with proposed DE optimized integral controller is better than the recently reported optimal controller [5] for all the cases.

2.3. Extension to multi-area multi-source power system

The study is further extended to a multi-area power system interconnected by AC–DC tie lines as shown in Fig. 4. Each area comprises reheat thermal, hydro and gas generating units. The transfer function model of system under study is shown in Fig. 5. The nominal parameters of the system are given in Appendix B. For the power system with AC tie line only, a PID controller is considered for each unit and for the power system with AC-DC parallel tie line, I, PI and PID controllers are considered for each unit. In AGC, the power change between control areas should be minimized quickly. Also, AGC provides the control only during normal changes in load which are small and slow but not under large disturbances. Further, with the present dedicated communication links neglecting transport delays is a valid assumption. For the above reasons, PID controller [4,7,10,17–19], and even double

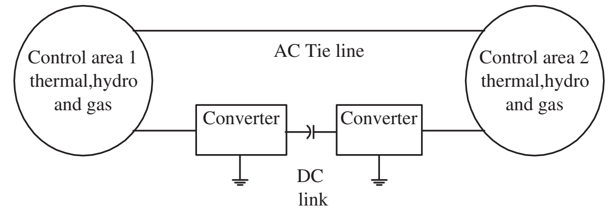

Fig. 4. System under study: two area power systems interconnected through AC–DC parallel tie lines.

derivative controllers [10] are used in AGC schemes. In view of the above, PID controller is adopted in the present paper.

The objective function for multi-area power system is defined as:

$$J = ITAE = \int_0^{t_{sim}} (\Delta F_1) + (\Delta F_2) + (\Delta P_{Tie}) \cdot t.dt \qquad (7)$$

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 control inputs of each unit of the power system U_T, U_H and U_G with PID structure are obtained as:

$$U_T = K_{P1}AEC_1 + K_{I1}\int AEC_1 + K_{D1}\frac{dAEC_1}{dt} \qquad (8)$$

$$U_H = K_{P2}AEC_1 + K_{I2}\int AEC_1 + K_{D2}\frac{dAEC_1}{dt} \qquad (9)$$

$$U_G = K_{P3}AEC_1 + K_{I3}\int AEC_1 + K_{D3}\frac{dAEC_1}{dt} \qquad (10)$$

When only integral controller is considered the proportional and derivative terms will be zero. The optimization was repeated 20 times using tuned DE algorithm and the best final solution among the 20 runs is chosen as proposed controller parameters. The best final solutions obtained in the 20 runs for the power system with AC line only and with AC-DC parallel tie line are shown in Table 4.

A 1% step load perturbation (SLP) in area 1 is considered at $t = 0$ s. The various errors (ISE, ITSE, ITAE and IAE) and settling times of frequency and tie line power deviations along with the settling times of ACEs with the proposed DE optimized PID

Table 3
Sensitivity analysis of single area system.

Parameter variation	% Change	DE optimized controller Parameter			Performance index with proposed approach			Performance index with optimal control [5]		
		K_{I1}	K_{I2}	K_{I3}	ITAE	Settling time	Max. overshoot	ITAE	Settling time	Max. overshoot
Nominal	0	0.0516	0.0071	0.1701	0.5165	5.4	0.0006	0.9934	15.76	0.0093
Loading	−25	0.0511	0.0178	0.1677	0.6241	6.7	0.0021	1.0116	15.69	0.0102
	+25	0.0624	0.0112	0.1508	0.6344	5.5	0.0011	0.9762	15.82	0.0084
T_{SG}	−25	0.0644	0.0115	0.1513	0.6647	5.31	0.0015	0.9955	15.89	0.0086
	+25	0.0307	0.0406	0.191	0.7386	5.34	0.0009	0.9986	15.79	0.0093
T_{GH}	−25	0.0432	0.0158	0.1866	0.4873	5.38	0.0007	0.9896	15.75	0.009
	+25	0.0429	0.0009	0.1761	0.7525	9.57	0	0.9971	15.75	0.0096
T_R	−25	0.0835	0.0103	0.1806	0.5580	7.7	0.0083	0.7902	13.76	0.0108
	+25	0.0525	0.009	0.151	0.7783	6.41	0.0009	1.1791	17.56	0.0081
T_T	−25	0.0512	0.0042	0.1847	0.5066	5.42	0.0008	0.9716	15.63	0.009
	+25	0.0511	0.0178	0.1677	0.6207	5.15	0.0018	1.0165	15.87	0.0098
T_{RH}	−25	0.0816	0.0074	0.1493	0.6504	6.56	0.0031	0.9277	15.71	0.0084
	+25	0.0624	0.0112	0.1508	0.7343	5.48	0.0020	1.0362	15.79	0.0100
T_W	−25	0.0302	0.0406	0.191	0.7305	5.82	0.0003	1.0129	15.79	0.0086
	+25	0.0432	0.0158	0.1866	0.5235	9.39	0.0027	0.9947	15.64	0.0105
T_{CD}	−25	0.0525	0.009	0.151	0.5690	5.91	0.0004	1.0117	15.64	0.0099
	+25	0.0512	0.0042	0.1847	0.5205	5.14	0.0019	1.0218	15.74	0.0103

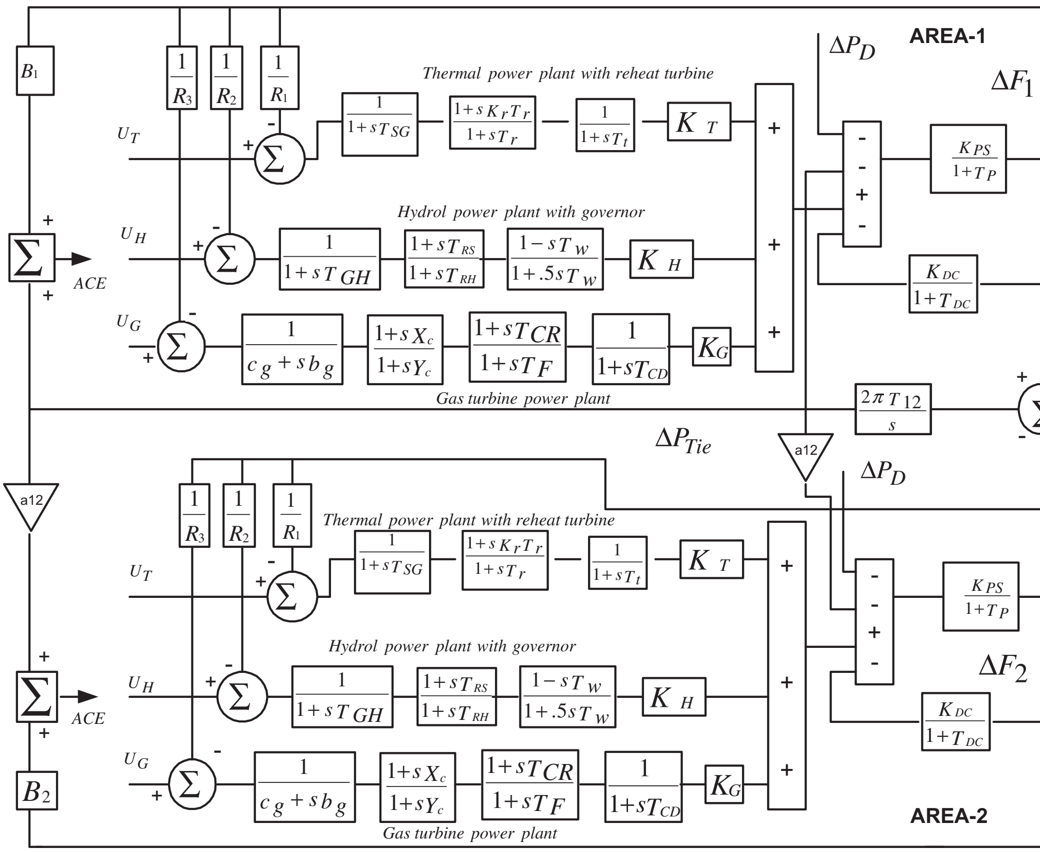

Fig. 5. Transfer function model of multi-source multi area with HVDC link.

Table 4
Controller parameters for system with AC tie line only.

System/parameters		Thermal	Hydro	Gas
System with AC line only		$K_P = 0.779$	$K_P = 0.5805$	$K_P = 0.5023$
		$K_I = 0.2762$	$K_I = 0.2291$	$K_I = 0.9529$
		$K_D = 0.6894$	$K_D = 0.7079$	$K_D = 0.6569$
System with AC–DC parallel line	I controller	$K_I = 1.781$	$K_I = 1.5979$	$K_I = 1.4687$
	PI controller	$K_P = 1.0103$	$K_P = 0.5428$	$K_P = 0.2015$
		$K_I = 1.6974$	$K_I = 1.8336$	$K_I = 1.9739$
	PID controller	$K_P = 1.6929$	$K_P = 1.77731$	$K_P = 0.9094$
		$K_I = 1.9923$	$K_I = 0.7091$	$K_I = 1.9425$
		$K_D = 0.8269$	$K_D = 0.4355$	$K_D = 0.2513$

Table 5
Performance criteria for system with AC tie line only.

Parameters		DE optimised PID controller		Optimal controller [13]
		Value	% Improvement	Value
ITAE		44.7442×10^{-4}	71.03	15.445×10^{-3}
ISE		52.551×10^{-2}	69.75	1.7372
ITSE		28.23×10^{-4}	49.36	$55.742\text{x } 10^{-4}$
IAE		11.7244×10^{-2}	52.1	$24.475\text{x } 10^{-2}$
Settling times (sec)	Δf_1	3.77	68.55	11.86
	Δf_2	4.58	68.35	14.47
	ΔP_{Tie}	4.29	36.07	6.71
	ACE_1	5.61	79.2	26.97
	ACE_2	8.06	68.92	25.93

controller are given in Table 5 for the system with AC line only. To show the superiority of the proposed approach, the results are compared with a recently published approach (optimal control) for the same interconnected power system [13]. As shown in Table 5, the ITAE value is improved by 71.03% compared to optimal output feedback controller. Settling time of Δf_1, Δf_2, ΔP_{tie}, ACE_1 and ACE_2 are improved by 68.55%, 68%, 35%, 36.07%, 79.2% and 68.92% respectively with DE tuned PID controller compared to

Table 6
Performance criteria for system with AC–DC parallel tie lines.

Parameters		DE optimised PID controller		DE optimised PI controller		DE optimised I controller		Optimal controller [13]
		Value	% Imp.	Value	% Imp.	Value	% Imp.	Value
ITAE		0.1987	89.56	0.241	87.34	0.2821	85.18	1.9037
ISE		19.22×10^{-5}	79.75	24.14×10^{-5}	74.56	3×10^{-4}	68.39	9.49×10^{-4}
ITSE		34.79×10^{-5}	93.4	44.96×10^{-5}	91.48	65.12×10^{-5}	87.65	$52.74\text{x}10^{-4}$
IAE		0.0384	72.19	0.0439	68.21	0.0512	62.93	0.1381
Settling times (sec)	Δf_1	1.93	57.68	2.07	54.61	2.29	49.78	4.56
	Δf_2	4.13	28.68	4.67	18.22	5.31	9.3	5.61
	ΔP_{Tie}	3.81	66.46	3.95	65.23	9.94	12.5	11.36

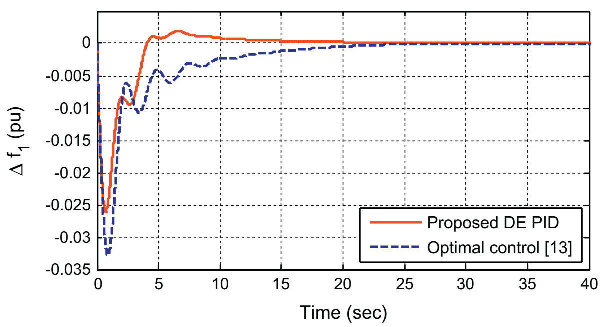

Fig. 6. Change in frequency of area-1 for 1% change in area-1 with AC tie line only.

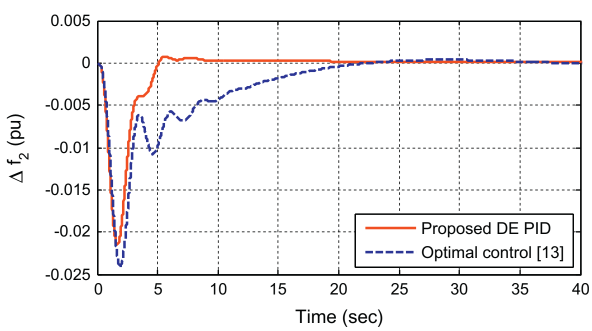

Fig. 7. Change in frequency of area-2 for 1% change in area-1 with AC tie line only.

optimal output feedback controller for the power system with AC line only. For the system with AC–DC parallel line, Table 6 shows the various errors (ISE, ITSE, ITAE and IAE) and settling times of frequency and tie line power deviations with the proposed DE optimized PID/PI/I controller and the results are compared with optimal output feedback controller for the similar system. It is evident from Table 6 that all error values are improved with the proposed DE optimized PID/PI/I controllers, especially ITSE is improved by 93.4%, 91.48% and 87.65% respectively with proposed PID, PI and I controller compared to optimal output feedback

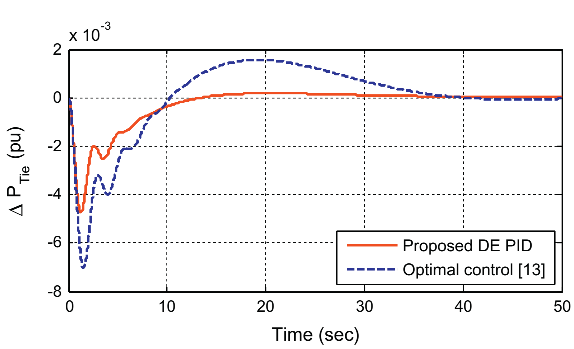

Fig. 8. Change in tie line power for 1% change in area-1 with AC tie line only.

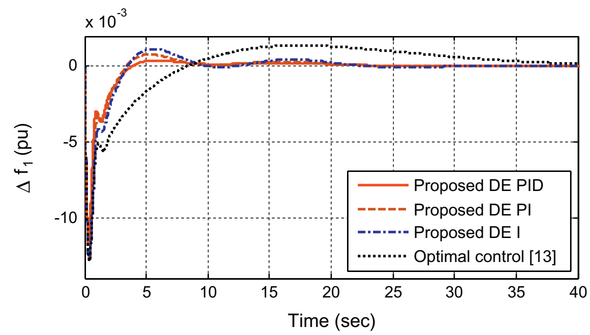

Fig. 9. Change in frequency of area-1 for 1% change in area-1 with AC–DC parallel tie lines.

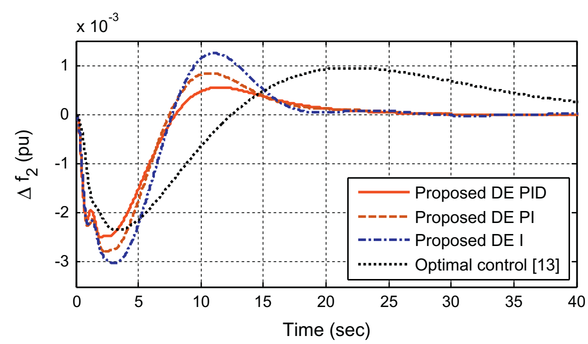

Fig. 10. Change in frequency of area-2 for 1% change in area-1 with AC–DC parallel tie lines.

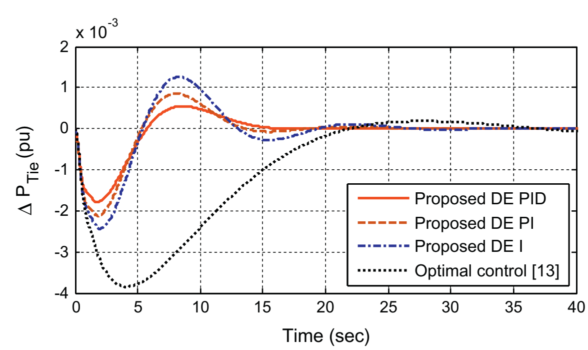

Fig. 11. Change in tie line power for 1% change in area-1 with AC–DC parallel tie lines.

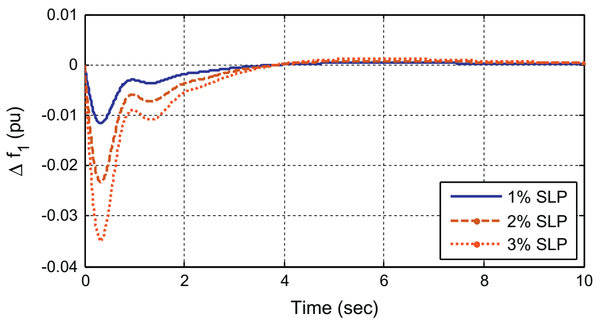

Fig. 12. Change in frequency of area-1 for 1-3% change in area-1 with AC-DC parallel tie lines.

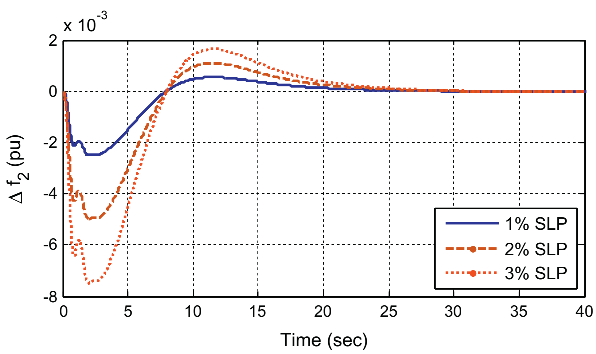

Fig. 13. Change in frequency of area-2 for 1-3% change in area-1 with AC-DC parallel tie lines.

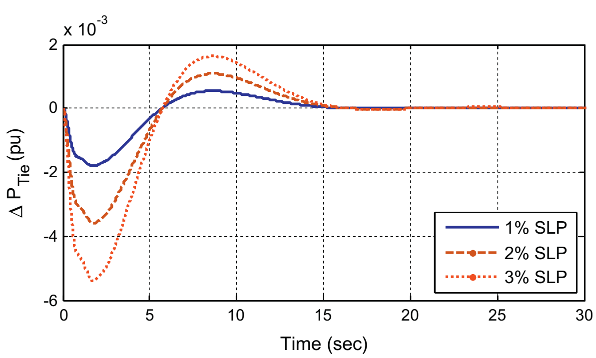

Fig. 14. Change in tie line power of area-1 for 1-3% change in area-1 with AC–DC parallel tie lines.

controller. The improvements in settling times are: for Δf_1: 49.78%, 54.61%, 57.68%, for Δf_2: 9.3%, 18.22% and 28.68% and for ΔP_{tie}: 66.46%, 65.23% and 12.5% respectively for PID, PI and I controllers compared to the optimal output feedback controller.

Dynamic frequency deviation responses of the system with AC line only for a 1% step load perturbation (SLP) in area 1 occurring at $t = 0$ s are shown in Figs. 6–8. It is clear from Figs. 6–8 that undershoot of Δf_1 and Δf_2 are improved by 20.36% and 10.79% respectively compared to optimal output feedback controller. Fig. 6 shows the tie line power deviation with time under the same SLP from which it can be seen that both the overshoot and undershoot with proposed DE optimized PID controller is improved by 88.32% and 32.86% respectively from the published result in Ref. [13].

Figs. 9–11 show the frequency deviation response of the power system with AC–DC parallel line for a 1% SLP in area-1. It is noticed from Figs. 9–11 that better performance is obtained with proposed DE optimized PID controller compared to optimal output feedback controller. To show the robustness of proposed controllers, SLP is increase from 1% to 3% in steps of 1% and the dynamic responses are shown in Figs. 12–14 from which it is clear that the designed controllers are robust and perform satisfactorily for different SLP.

For a single area system, less effective integral controllers are considered for better illustration of influence of DE parameters on the performance of the DE algorithm. It is observed that even with proposed integral controllers, better performance is obtained compared to optimal control [5] for the same power system. As integral controllers are considered in single area system, the sensitivity analysis is done with integral controllers. However, the sensitivity analysis can be easily done with PI and PID controller if desired. For a multi-area multi-source power system, PI and PID controllers are considered in addition to the integral controllers and the sensitivity analysis is shown with the best controller i.e. PID controller.

3. Conclusion

Load Frequency Control (LFC) of multi-unit source power system having different sources of power generation like thermal, hydro and gas power plants is presented in this paper. The controller parameters are optimized using Differential Evolution (DE) optimization technique. Initially a single area power system with multiple source of energy is considered and the control parameters of DE algorithm are tuned by carrying out multiple runs of algorithm for each control parameter variation. The best DE parameters are found to be: step size $F = 0.2$ and crossover probability of $CR = 0.6$, Population size $N_P = 40$ and Generation $G = 30$. The study is further extended to a multi-area multi-source power system and a HVDC link is also considered in parallel with existing AC tie line for the interconnection of two areas. The parameters of Integral (I), Proportional Integral (PI) and Proportional Integral Derivative (PID) are optimized employing tunned DE algorithm. The superiority of the proposed approach has been shown by comparing the results with recently published optimal output feedback controller for the same power systems by using various performance measures like overshoot, settling time and standard error criteria of frequency and tie-line power deviation following a step load perturbation (SLP). It is noticed that, the dynamic performance of proposed controller is better than optimal output feedback controller. Furthermore, it is also seen that the proposed system is robust and is not affected by change in the loading condition, system parameters and size of SLP.

Appendix A: modeling of gas turbine power plant

A gas turbine power plant usually consists of valve positioner, speed governor, fuel system & combuster and gas turbine. The load-frequency model of gas turbine power plant is shown in Fig. A, where ΔP_{CGref} is reference power setting of the gas plant and ΔP_{GT} is the gas turbine output power. The system frequency deviation and governor speed regulation parameters are

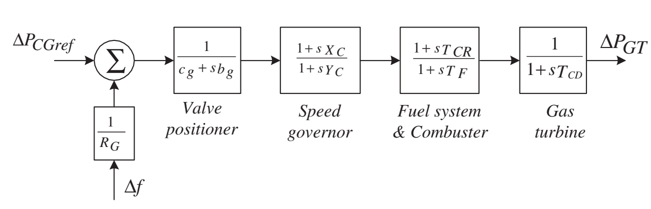

Fig. A. Load frequency model of gas turbine power plant.

represented by Δf in pu and R_G in Hz/puMW respectively. The transfer function representation of valve positioner is shown in Fig. A, where, c_g is the gas turbine valve positioner, b_g is the gas turbine constant of valve positioner. The speed governing system is represented by a lead-lag compensator as shown in Fig. A, where, X_C is the lead time constant of gas turbine speed governor in sec, Y_C is the lag time constant of gas turbine speed governor in sec. the fuel system and combuster is represented by a transfer function with appropriate time constants as shown in Fig. A, where, T_F is the gas turbine fuel time constant in sec and T_{CR} is the gas turbine combustion reaction time delay in sec. The gas turbine is represented by a transfer function, consisting of a single time constant i.e. the gas turbine compressor discharge volume–time constant (T_{CD}) in sec.

Appendix B: system parameters

$B_1 = B_2 = 0.4312$ p.u. MW/Hz; $P_{rt} = 2000$ MW; $P_L = 1840$ MW; $R_1 = R_2 = R_3 = 2.4$ Hz/p.u.; $T_{SG} = 0.08$ s; $T_T = 0.3$ s; $K_R = 0.3$; $T_R = 10$ s; $K_{PS1} = K_{PS2} = 68.9566$ Hz/p.u. MW; $T_{PS1} = T_{PS2} = 11.49$ s; $T_{12} = 0.0433$; $a_{12} = -1$; $T_W = 1$ s; $T_{RS} = 5$ s; $T_{RH} = 28.75$ s; $T_{GH} = 0.2$ s; $X_C = 0.6$ s; $Y_C = 1$ s; $c_g = 1$; $b_g = 0.05$ s; $T_F = 0.23$ s; $T_{CR} = 0.01$ s; $T_{CD} = 0.2$ s; $K_T = 0.543478$; $K_H = 0.326084$; $K_G = 0.130438$; $K_{DC} = 1$; $T_{DC} = 0.2$ s.

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