Engineering Science and Technology, an International Journal 18 (2015) 555–578

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: http://www.elsevier.com/locate/jestch

Full length article

AGC of a multi-area power system under deregulated environment using redox flow batteries and interline power flow controller

Tulasichandra Sekhar Gorripotu, Rabindra Kumar Sahu*, Sidhartha Panda

Department of Electrical Engineering, Veer Surendra Sai University of Technology (VSSUT), Burla 768018, Odisha, India

A R T I C L E I N F O

Article history:
Received 20 January 2015
Received in revised form
25 March 2015
Accepted 7 April 2015
Available online 15 May 2015

Keywords:
Automatic generation control (AGC)
Generation rate constraint (GRC)
Interline power flow controller (IPFC)
Redox flow batteries (RFB)
Differential evolution (DE)
Sensitivity analysis

A B S T R A C T

In this paper, Proportional Integral Derivative with Filter (PIDF) is proposed for Automatic Generation Control (AGC) of a multi-area power system in deregulated environment. Initially, a two area four units thermal system without any physical constraints is considered and the gains of the PIDF controller are optimized employing Differential Evolution (DE) algorithm using ITAE criterion. The superiority of proposed DE optimized PIDF controller over Fuzzy Logic controller is demonstrated. Then, to further improve the system performance, an Interline Power Flow Controller (IPFC) is placed in the tie-line and Redox Flow Batteries (RFB) is considered in the first area and the controller parameters are tuned. Additionally, to get an accurate insight of the AGC problem, important physical constraints such as Time Delay (TD) and Generation Rate Constraints (GRC) are considered and the controller parameters are retuned. The performance of proposed controller is evaluated under different operating conditions that take place in a deregulated power market. Further, the proposed approach is extended to a two area six units hydro thermal system. Finally, sensitivity analysis is performed by varying the system parameters and operating load conditions from their nominal values.

1. Introduction

Automatic Generation Control (AGC) is one of the important control problems in an interconnected power system design and operation. AGC is becoming more significant today due to the increasing size, changing structure, emerging renewable energy sources, new uncertainties, environmental constraints and complexity of power systems [1–3]. In a conventional power system configuration, the generation, transmission and distribution is owned by a sole entity called a Vertically Integrated Utility (VIU), which supplies power to the clients at regulated rates. In an open energy market, Generating Companies (GENCOs) may or may not participate in the AGC task as they are independent power utilities. On the other hand, Distribution Companies (DISCOs) may contract with GENCOs or Independent Power Producers (IPPs) for the transaction of power in different areas [4]. Thus, in deregulated environment, control is greatly decentralized and Independent System Operators (ISOs) are responsible for maintaining the system frequency and tie-line power flows.

The researchers in the world over are trying to propose several strategies for AGC of power systems under deregulated environment in order to maintain the system frequency and tie-line flow at their scheduled values during normal operation and also during small perturbations. Donde et al. [5] have demonstrated the concept of restructured power system and DISCO Participation Matrix (DPM). Chidambaram et al. [6] have proposed AGC strategy for a two-area multi-units power system under deregulated environment in presence of Redox Flow Batteries (RFB) and Interline Power Flow Controller (IPFC). Recently, Parmar et al. [7] have studied the multi-source power generation in deregulated power environment using optimal output feedback controller. However, in the above literature the effect of physical constraints such as Time delay (TD) and Generation Rate Constraint (GRC) are not examined which needs further comprehensive study.

Flexible AC Transmission Systems (FACTS) controllers [8] play a crucial role to control the power flow in an interconnected power system. Several studies have explored the potential of using FACTS devices for better power system control since it provides more flexibility. Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) are among the most

* Corresponding author. Tel.: +91 9439702316.
E-mail address: rksahu123@gmail.com (R.K. Sahu).
Peer review under responsibility of Karabuk University.

http://dx.doi.org/10.1016/j.jestch.2015.04.002

versatile FACTS controllers which are connected in series with the transmission line or in tie-lines respectively to control the power flow [9,10]. Both UPFC and IPFC need at least two converters. It is observed from literature that, UPFC is employed to power flow control of a single transmission line whereas the IPFC is can provide power flow control for multi-line transmission system. Therefore, IPFC is attractive for compensating multi-line systems from economical point of view. IPFC can compensate each transmission line separately or concurrently so that the power optimization of the overall system can be obtained in the form of appropriate power transfer from over-loaded lines to under-loaded lines [6]. In view of the above, an IPFC is considered in the present paper.

Balancing of power supply and demand is always a complex process particularly at peak loads. As a result, there may be serious concerns about reliable operation of power system. So, it is necessary to include Battery Energy Storage (BES) systems especially in the present deregulated scenario to improve the automatic generation control problem [11–18]. There are several types of battery energy storage systems used in power system applications such as lead acid batteries, flooded type batteries, Valve regulated (VRLA) type batteries, Sodium sulphur (NaS) batteries, Lithium ion (Li ion), Metal air and Redox Flow Batteries (RFB). Among all the batteries Redox Flow Batteries are promising for the applications which require high power and long duration storage. Redox Flow Batteries (RFB) is an active power source which can be essential not only as a fast energy compensation device for power consumptions of large loads, but also as a stabilizer of frequency oscillations [19,20]. The RFB will, in addition to load compensating, can have other applications such as power quality maintenance for decentralized power supplies. But, due to the economical reasons it is not possible to place RFB in all the areas. When IPFC and RFB are present in the system, they should act in a coordinated manner so as to control the network conditions in a very fast and economical manner.

Several advanced controller structures and techniques have been proposed in literature for AGC [4–6], [26]. But, these advanced approaches are complicated and need familiarity of users to these techniques thus reducing their applicability. Alternatively, a classical Proportional Integral Derivative (PID) controller and its variant remain an engineer's preferred choice due to its structural simplicity, reliability and the favourable ratio between performances and cost. In a PID controller, the derivative mode improves stability of the system and increases speed of the controller response but it produces unreasonable size control inputs to the plant. Also, any noise in the control input signal will result in large plant input signals which often lead to

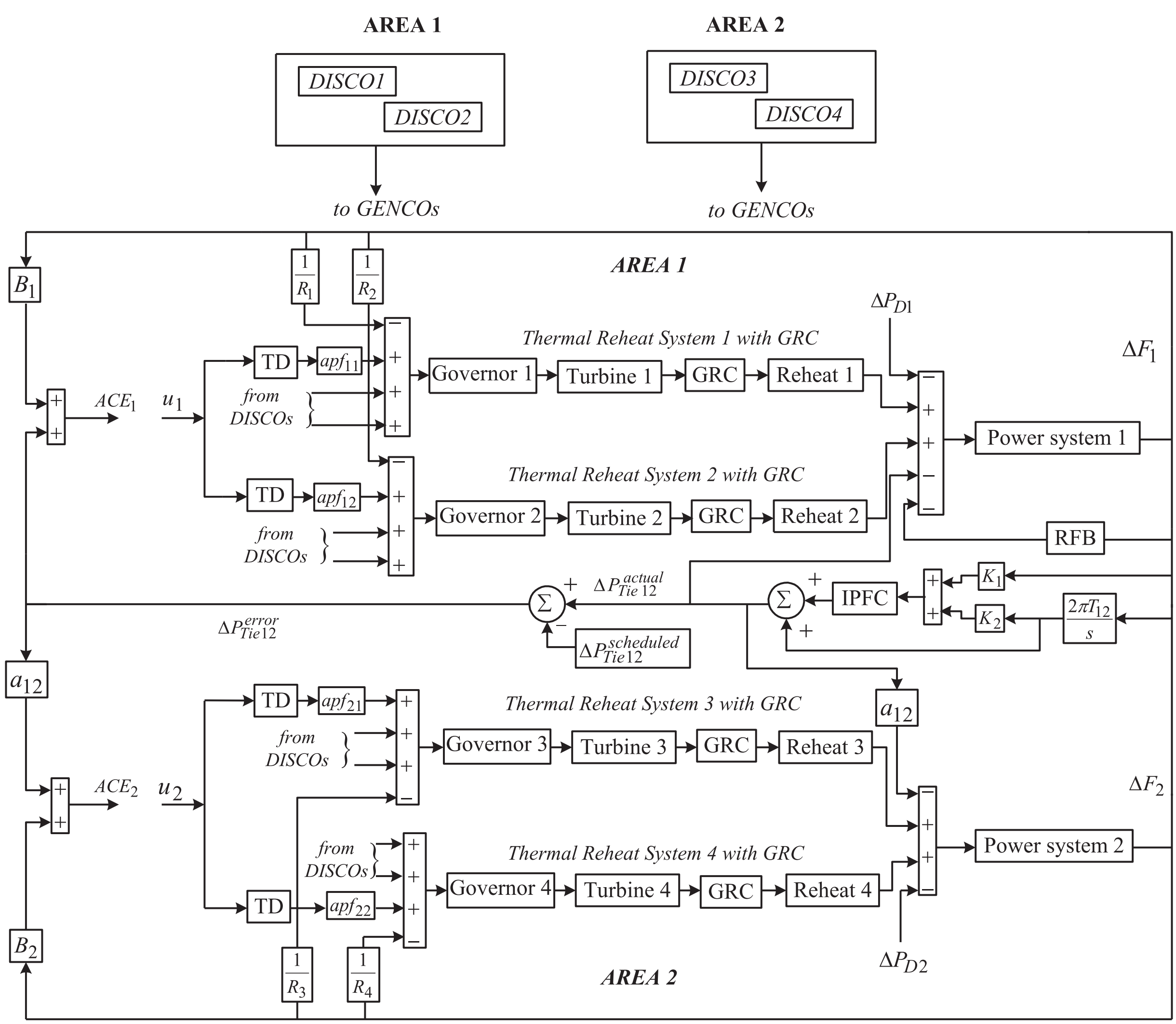

Fig. 1. Block diagram representation of two area power system with IPFC and RFB in deregulated environment.

complications in practical applications. The practical solution to these problems is to put a first filter on the derivative term and tune its pole so that the chattering due to the noise does not occur since it attenuates high frequency noise [21]. Surprisingly, in spite of these advantages, Proportional Integral Derivative with derivative Filter (PIDF) controllers structures are not attempted for the AGC under deregulated environment problems.

It is obvious from literature survey that the performance of the power system depends on the controller structure and the techniques employed to optimize the controller parameters. Hence, proposing and implementing new controller approaches using high performance heuristic optimization algorithms to real world problems are always welcome. 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 [22]. 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 [23]. Having known all this, an attempt has been made in the present paper for the DE based PIDF controller for AGC in a deregulated environment with the consideration of GRC and TD for the coordinated application of IPFC and RFB.

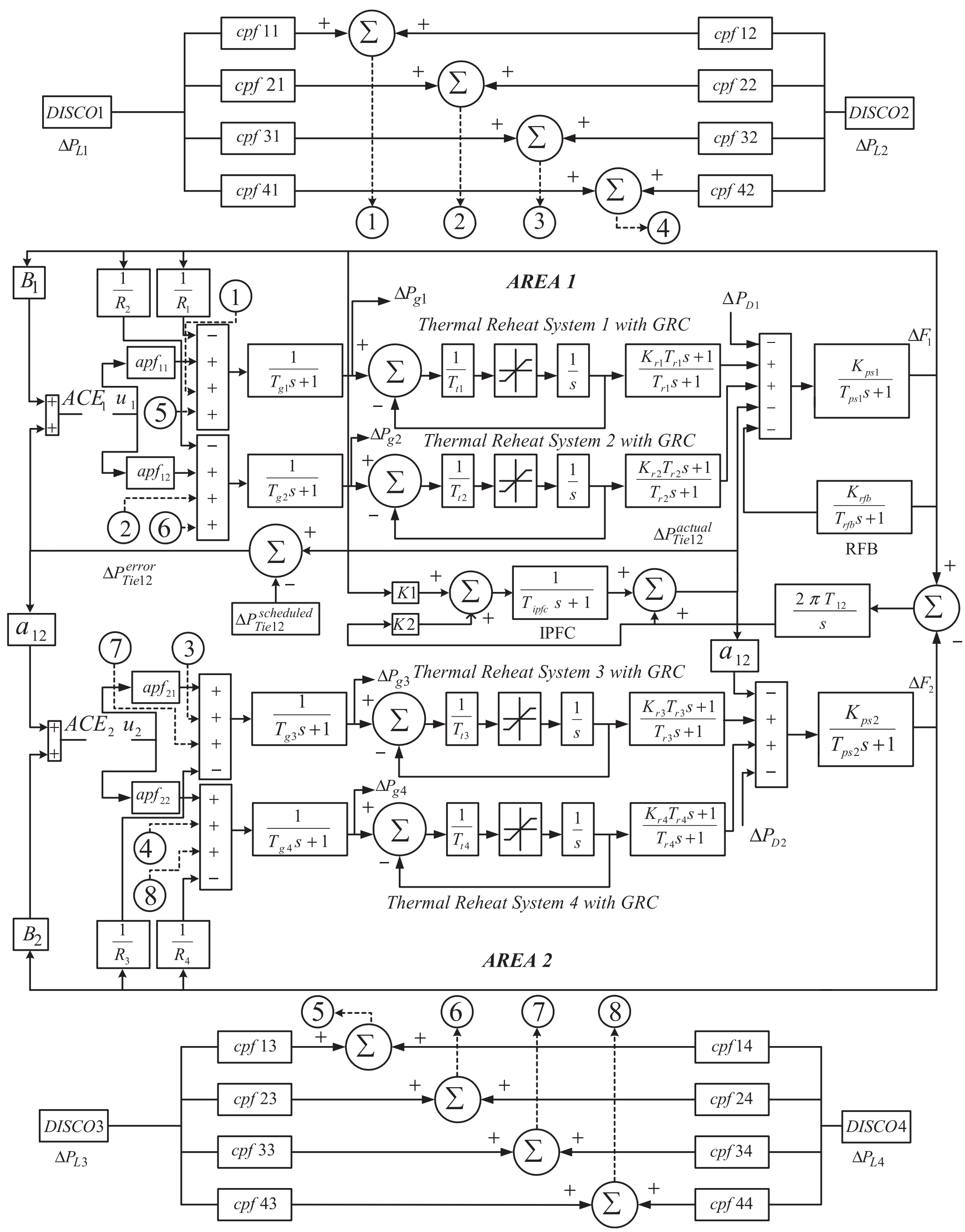

Fig. 2. Transfer function model of two area power system with IPFC and RFB in deregulated environment.

The main investigations of the present work:

i. To develop a strategy based on DE, for AGC of multi-area power system in deregulated environment.
ii. To optimize the parameters of PID controller with derivative filter and analyze the dynamic performance of power system with DE optimized PIDF controller for AGC.
iii. To study the effect of Interline Power Flow Controller (IPFC) and Redox Flow Batteries (RFB) in AGC studies.
iv. To analyze the effect of physical constraints such as Time Delay (TD) and Generation Rate Constraints (GRC) on system performance.
v. To carry out the sensitivity analysis for the proposed controllers and test its robustness to wide variations in loading pattern and system parameters as well as changes in size and locations of load perturbations.
vi. To test the effectiveness of proposed controllers in a two area six unit hydro thermal power system with IPFC and RFB.

2. Material and method

2.1. Power system model in a deregulated system

A two area multi unit interconnected power system has been proposed for AGC in deregulated environment. The system is widely used in literature for the design and analysis of AGC under deregulated scenario [6]. The block diagram representation of two area power system with IPFC and RFB in presence of GRC and TD under deregulated environment is shown in Fig. 1. Area 1 comprises of two GENCOs with thermal power system of reheat turbine and GRC combinations and two DISCOs, Area 2 comprises of two GENCOs with thermal power system of reheat turbine and GRC combinations and two DISCOs as shown in Fig. 1. A PIDF controller is considered for each area. The transfer function model of the above system is shown in Fig. 2. In Fig. 2, R_1, R_2 and R_3, R_4 are the regulation parameters of thermal units for area 1 and area 2 respectively in p.u. Hz.B_1 andB_2 represent the frequency bias parameters in p.u. MW/Hz. T_{g1} and T_{g2} are the speed governor time constants in sec for area 1; T_{g3} and T_{g4} are the speed governor time constants in sec for area 2; T_{t1} and T_{t2} are the turbine time constant in sec for area 1; T_{t3} and T_{t4} are the turbine time constant in sec for area 2; ΔP_{D1} and ΔP_{D2} are the load demand changes in p.u.; ΔP_{Tie} is the incremental change in tie-line power (p.u.); K_{Ps1} and K_{Ps2} stands for the power system gains; T_{Ps1} and T_{Ps2} represent the power system time constant in sec; T_{12} is the synchronizing coefficient in p.u. and ΔF_1 and ΔF_2 are the system frequency deviations in Hz,. For thermal plant a GRC of 3%/min [24] and a time delay of 50 ms [25] are considered in the present work. The relevant parameters are given in appendix A.

As there are several GENCOs and DISCOs in the deregulated environment, there can be various contracts between GENCOs and DISCOs. If DISCOs having contract with GENCOs of the same control area then it is known as "poolco based transaction". If DISCOs having contract with GENCOs of another area then it is known as "bilateral based transaction". If DISCOs violate the contract by demanding more than specified in the contract then it is known as "contract violation based transaction". To know the contracts between GENCOs and DISCOs the concept of DISCO Participation Matrix (DPM) is introduced [5].

DPM is a matrix in which the number of rows is equal to the number of GENCOs and the number of columns is equal to the number of DISCOs in the system. The elements of DPM are indicated with cpf_{ij} which corresponds to fraction of total load contracted by a DISCO towards a GENCO. The sum of all the entries in a column in DPM is unity i.e. $\sum_i^n cpf_{ij} = 1$. In Fig. 1 GENCO1, GENCO2, DISCO1 and DISCO2 are in area 1. GENCO3, GENCO4, DISCO3 and DISCO4 are in area 2. Then the corresponding DPM is written as [5]

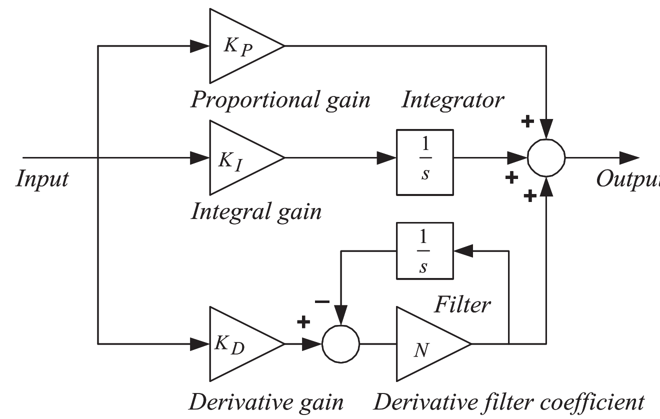

Fig. 3. Structure of PID controller with derivative filter.

$$DPM = \begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\ cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \end{bmatrix} \tag{1}$$

where cpf represents "contract participation factor" i.e. p.u. MW load of a corresponding DISCO.

The scheduled steady state power flow on the tie-line is given as [5].

$$\Delta P_{Tie12}^{scheduled} = (\text{Demand of DISCOs in area 1 to GENCOs in area 2}) - (\text{Demand of DISCOs in area 2 to GENCOs in area 1}) \tag{2}$$

The actual tie-line power is given as

$$\Delta P_{Tie12}^{actual} = \frac{2\pi T_{12}}{s}(\Delta F_1 - \Delta F_2) \tag{3}$$

At any time, the tie-line power error is given by [5].

$$\Delta P_{Tie12}^{error} = \Delta P_{Tie12}^{actual} - \Delta P_{Tie12}^{scheduled} \tag{4}$$

ΔP_{Tie12}^{error} vanishes in the steady as the actual tie-line power flow reaches the scheduled power flow. This error signal is used to generate the respective Area Control Error (ACE) signals as in the traditional scenario [5].

$$ACE_1 = B_1\Delta F_1 + \Delta P_{Tie12}^{error} \tag{5}$$

$$ACE_2 = B_2\Delta F_2 + a_{12}\Delta P_{Tie12}^{error} \tag{6}$$

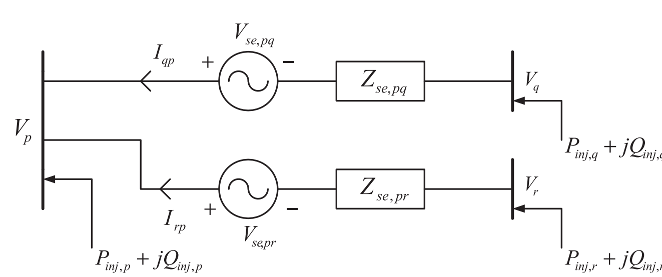

Fig. 4. The equivalent power injection model of IPFC.

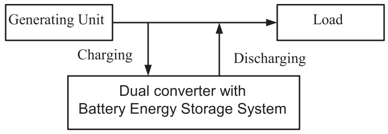

Fig. 5. General block diagram of redox flow batteries in AGC.

As there are two GENCOs in each area, *ACE* signal has to be distributed among them in proportion to their participation in the AGC. Coefficients that distribute *ACE* to GENCOs are termed as "*ACE* Participation Factors (*apfs*)". In a given control area, the sum of participation factors is equal to 1. Hence, apf_{11}, apf_{12} are considered as *ACE* participation factor in area 1 and apf_{21}, apf_{22} are in area 2.

2.2. Controller structure and objective function

In the present paper, two dissimilar PIDF controllers have been considered for the two area system [21]. The structure of PID controller with derivative filter is shown in Fig. 3 where K_P, K_I and K_D are the proportional, integral and derivative gains respectively and N is the derivative filter coefficient. The control inputs of PIDF controller are the respective ACEs and the output of PIDF controllers are the input of power system u_1 and u_2 shown in Fig. 3.

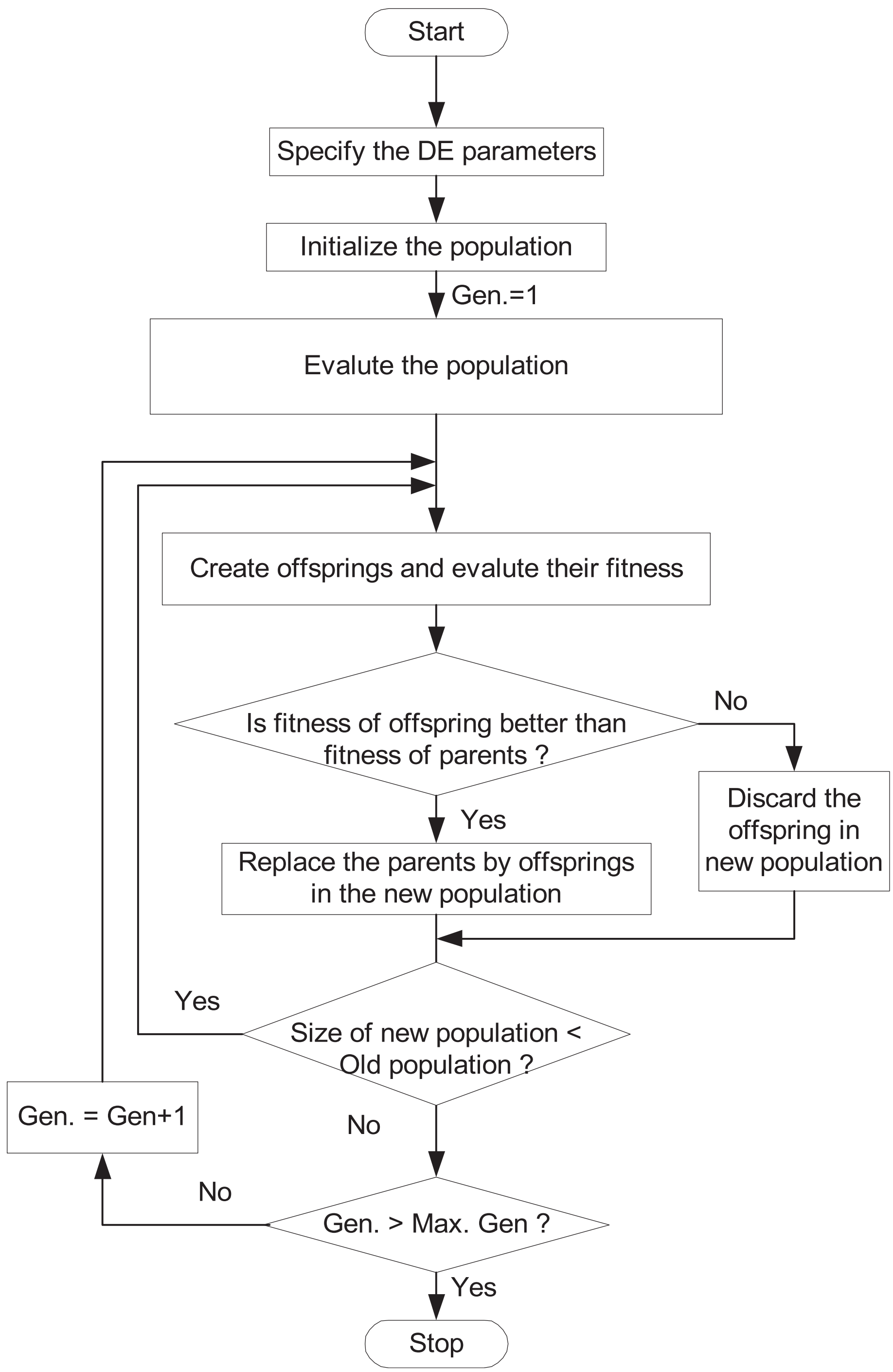

Fig. 6. Flow chart of DE optimization approach.

Table 1
Tuned controller parameters for Poolco based transaction without GRC, TD, IPFC and RFB.

Parameters and performance index		Fuzzy	PIDF
Controller parameters		$K_1 = 0.1253$	$K_{P1} = -0.8983$
		$K_2 = 0.1302$	$K_{I1} = -0.971$
		$K_3 = 0.0924$	$K_{D1} = -1.504$
		$K_4 = 0.0078$	$N_1 = 58.8709$
			$K_{P2} = 1.5299$
			$K_{I2} = -0.6979$
			$K_{D2} = -1.9265$
			$N_2 = 70.8096$
ITAE		11.7186	7.8174
Settling time T_S (sec)	ΔF_1	15.42	20.05
	ΔF_2	17.88	19.60
	ΔP_{Tie}	27.31	13.91
Peak over shoot	ΔF_1	0.0324	0.0212
	ΔF_2	0.0299	0.0169
	ΔP_{Tie}	0	0.0089

Table 2
Tuned controller parameters for Poolco based transaction without GRC, TD (with IPFC and RFB).

Parameters and performance index		With IPFC Only		With IPFC and RFB	
Controller parameters	K_{P1}	−1.7134	% Improvement	−1.7036	% Improvement
	K_{I1}	−1.5927		−1.9864	
	K_{D1}	−0.1827		−1.9948	
	N_1	57.0781		51.3204	
	K_{P2}	0.8433		−0.4245	
	K_{I2}	−0.6979		−1.1173	
	K_{D2}	−1.0405		−1.2433	
	N_2	162.3066		87.742	
ITAE		2.1414	72.6	1.8858	75.87
Settling time T_S (sec)	ΔF_1	12.59	37.21	11.05	44.88
	ΔF_2	12.93	34.03	11.94	39.08
	ΔP_{Tie}	9.09	34.65	7.83	43.71
Peak over shoot	ΔF_1	0.0115	45.75	0.01	52.83
	ΔF_2	0.0089	47.33	0.0077	54.43
	ΔP_{Tie}	0.0052	41.57	0.004	55.05

The transfer function of the controller is given by:

$$TF_{PID} = \left[K_P + K_I\left(\frac{1}{s}\right) + K_D\left(\frac{Ns}{s+N}\right)\right] \tag{7}$$

In the design of a modern heuristic optimization technique based controller, the objective function is first defined based on the desired specifications and constraints. 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). ITAE criterion reduces the settling time which cannot be achieved with IAE or ISE based tuning. ITAE criterion also reduces the peak overshoot. ITSE based controller provides large controller output for a sudden change in set point which is not advantageous from controller design point of view. It has been reported that ITAE is a better objective function in LFC studies [21,26]. Therefore in this paper ITAE is used as objective function to optimize controller parameters of PIDF controller. Expression for the ITAE objective function is depicted in Eq. (8).

Table 3
Re-tuned controller parameters for Poolco based transaction in presence of GRC and TD.

Parameters and performance index		Without IPFC and RFB	With IPFC only	With both IPFC and RFB	
Controller parameters	K_{P1}	−1.2385	0.9201	−1.5235	
	K_{I1}	−0.0424	−0.2082	−1.4186	
	K_{D1}	−0.4606	−1.6679	0.0547	
	N_1	246.9947	72.3479	220.3304	
	K_{P2}	0.6672	0.5333	−0.276	
	K_{I2}	−0.1205	−0.0748	−1.602	
	K_{D2}	−1.4102	−0.0109	−1.2598	
	N_2	41.9896	172.8689	21.1966	
ITAE		433.19	177.99	17.63	Without re-tuning 39.2789
Settling time T_S (sec)	ΔF_1	unstable	54.86	15.52	20.90
	ΔF_2	unstable	44.60	18.05	21.44
	ΔP_{Tie}	unstable	48.13	15.07	21.41
Peak over shoot	ΔF_1	1.0468	0.6920	0.0855	0.1058
	ΔF_2	1.088	0.7047	0.1622	0.118
	ΔP_{Tie}	0.0358	0.0252	0.0416	0.0463

$$J = ITAE = \int_{0}^{t_{sim}} (|\Delta F_1| + |\Delta F_2| + |\Delta P_{Tie}|) \cdot t \cdot dt \tag{8}$$

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

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

$$\text{Minimize } J \tag{9}$$

Subject to

$$K_{P\min} \le K_P \le K_{P\max}, \;\; K_{I_{\min}} \le K_I \le K_{I_{\max}}, \;\; K_{D_{\min}} \le K_D \le K_{D_{\max}}, \;\; N_{\min} \le N \le N_{\max} \tag{10}$$

Where J is the objective function and $K_{PIDF\min}$ and $K_{PIDF\max}$, are the minimum and maximum value of the PIDF control parameters. The minimum and maximum values of PID controller parameters

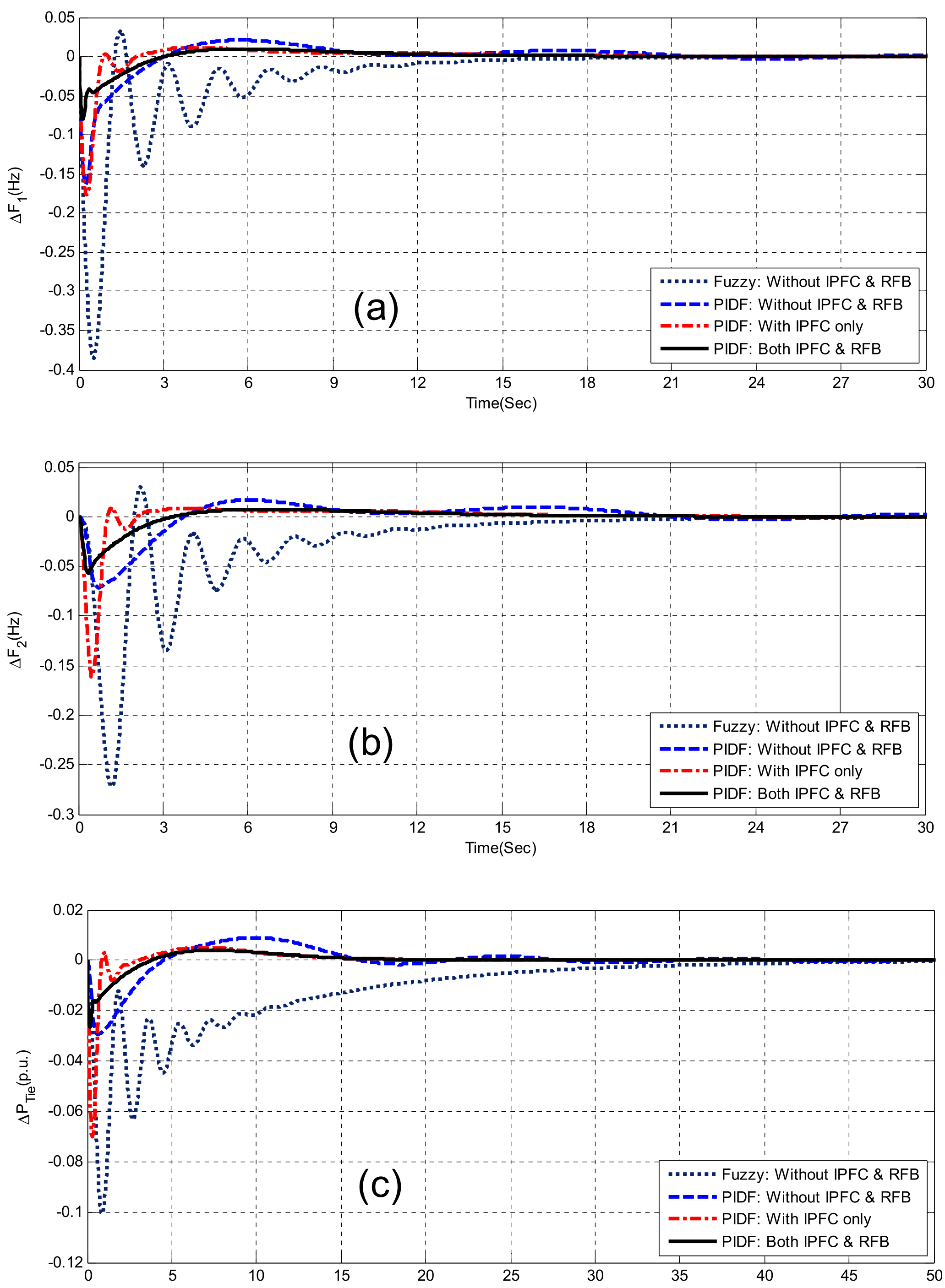

Fig. 7. Dynamic responses of the system for poolco based transaction without TD & GRC (a) Frequency deviation of area 1 (b) Frequency deviation of area 2 (c) Tie-line power deviation.

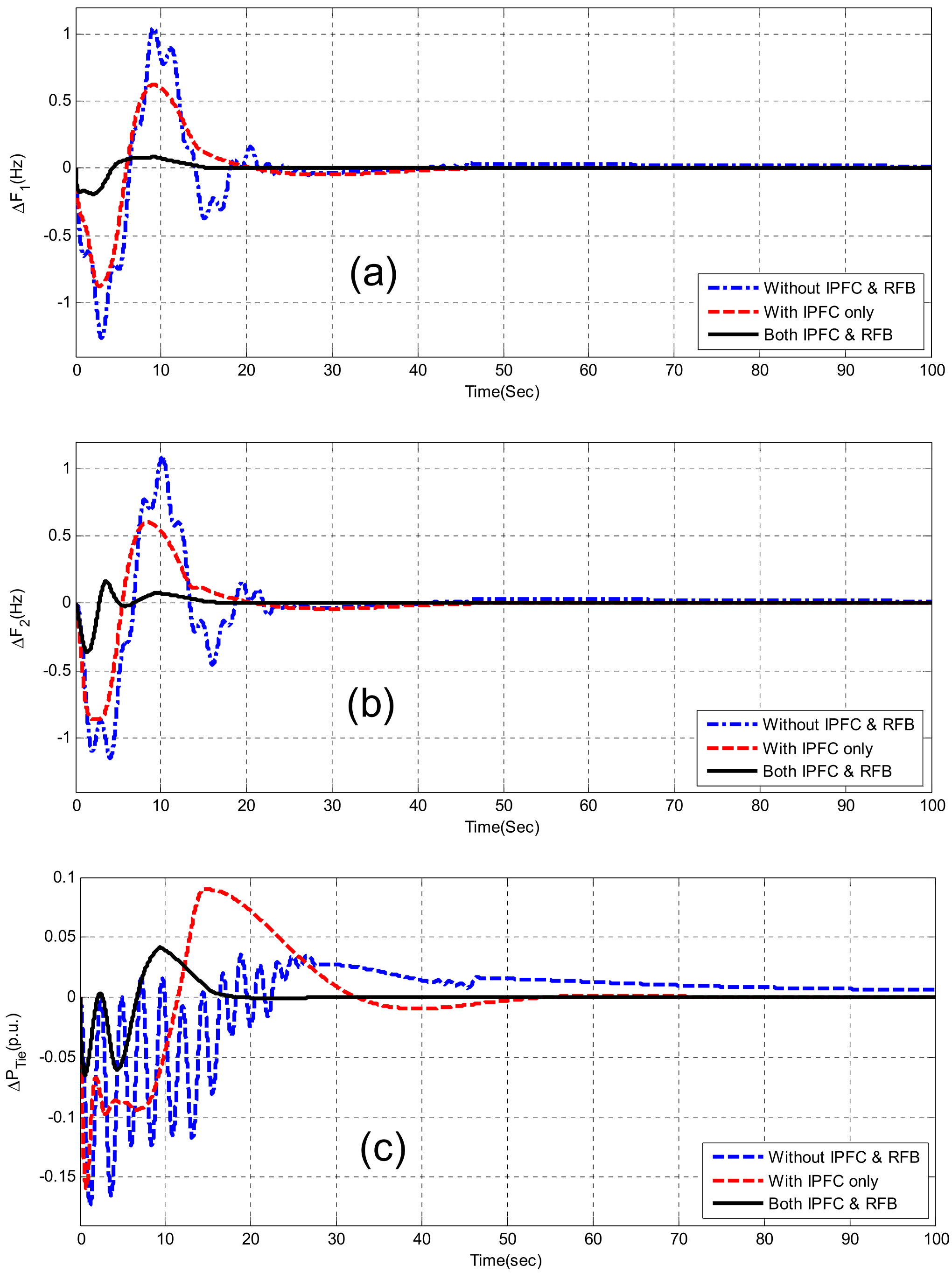

Fig. 8. Dynamic responses of the system for poolco based transaction (a) Frequency deviation of area 1 (b) Frequency deviation of area 2 (c) Tie-line power deviation.

are chosen as −2.0 and 2.0 respectively. The range for filter coefficient N is selected as 1 and 300.

2.3. Modelling of IPFC in AGC

The modelling of IPFC and RFB has been done in the same way as given in ref. [6]. However, in ref. [6] only an integral controller was used whose gain consists of products of a conventional control gain and fuzzy gain whereas in the present study a PIDF controller is proposed which increases the capabilities of IPFC and RFB in automatic generation control. Also, in the present manuscript the capabilities of IPFC and RFB are evacuated in the presence of physical constraints such as Time Delay (TD) and Generation Rate Constraint (GRC).

The equivalent power injection model of IPFC is shown in Fig. 4 [6]. IPFC is a combination of two or more SSSCs which are coupled via a common DC link. With this scheme, IPFC has the capability to provide an independently controllable reactive series compensation for each individual line and also to transfer real power between the compensated lines. There has been growing interest recently in studying the IPFC modelling, its basic function to control power flow among transmission lines and oscillation damping. The IPFC installed in series with a tie-line and provides damping of oscillations the tie-line power. In Fig. 4, V_{se} is the series voltage magnitude and φ_{se} is the phase angle of series voltage. The shunt converter

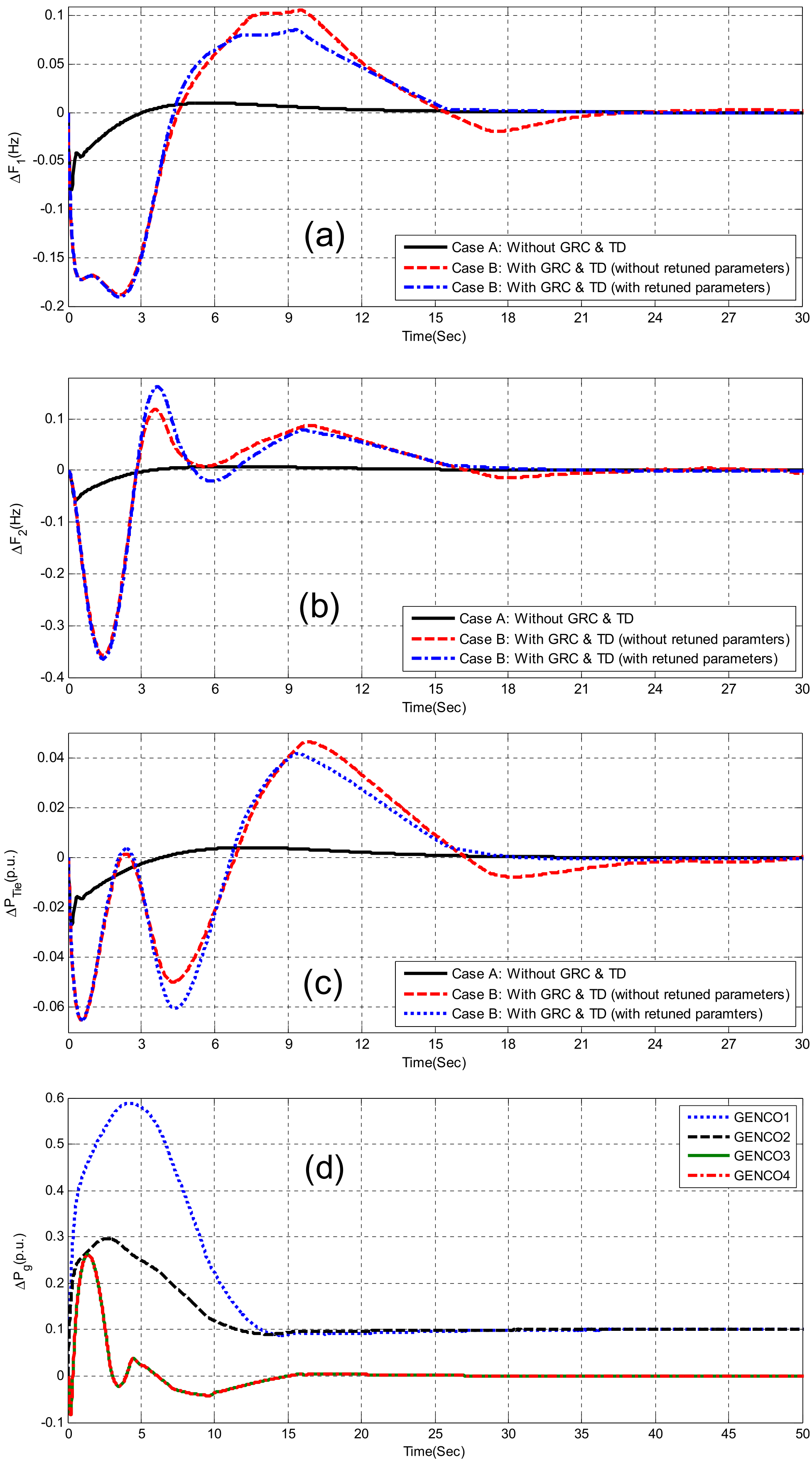

Fig. 9. Dynamic responses of the system for poolco based transaction with both IPFC & RFB (a) Frequency deviation of area 1 (b) Frequency deviation of area 2 (c) Tie-line power deviation (d) Change in generated powers of different GENCOs.

Table 4
Tuned PIDF controller parameters for Bilateral based transaction with TD & GRC.

Cases/Parameters	K_{P1}	K_{P2}	K_{I1}	K_{I2}	K_{D1}	K_{D2}	N_1	N_2
Without IPFC & RFB	−0.3619	1.6064	−0.0620	−0.1213	−1.3287	−1.6686	193.6168	100.8839
With IPFC only	−0.3619	1.6064	−0.0620	−0.1213	−1.3287	−1.6686	193.6168	100.8839
Both IPFC & RFB	−1.9760	−1.6497	−1.0010	−0.9535	−1.5502	−0.0209	146.4745	165.4745

injects controllable shunt voltage such that the real component of the current in the shunt branch balance the real power demanded by the series converter. It is clear from Fig. 4 that, the active and reactive power injections at the buses can be written as

$$P_{inj,p} = \sum_{n=q,r} V_p V_{se,pn} b_{pn} \sin(\theta_p - \theta_{se,pn}) \tag{11}$$

$$Q_{inj,p} = -\sum_{n=q,r} V_p V_{se,pn} b_{pn} \cos(\theta_p - \theta_{se,pn}) \tag{12}$$

$$P_{inj,n} = -\sum_{n=q,r} V_n V_{se,pn} b_{pn} \sin(\theta_n - \theta_{se,pn}) \tag{13}$$

$$Q_{inj,n} = \sum_{n=q,r} V_n V_{se,pn} b_{pn} \cos(\theta_n - \theta_{se,pn}) \tag{14}$$

where, $V_{se,pn} = |V_{se,in}| \angle \theta_{se,in}$ and $n = q,r$

2.4. Modelling of RFB in AGC

In an interconnected power system during the presence of small load perturbations and with optimized controller gains, the frequency deviations and tie-line power changes exist for long time durations. During such conditions the governor may not able to absorb the frequency deviations due to slow response and non-linearities present in the system. So, in order to reduce the frequency deviations and change in tie-line power, an active power source with quick response such as RFB can be expected to the most effective one [6,27]. The RFB are found to be superior over the other energy storage devices like superconducting magnetic energy storage (SMES) because of its easy operating at normal temperature, very small losses during operating conditions and have long service life [20]. As RFB are capable of ensuring a very quick response [6], ΔF_1 is being used directly as the input command signal for RFB to control frequency. A general block diagram of the RFB used for AGC in the interconnected power system is shown in the Fig. 5 [27]. During very low load duration battery charges and delivers the energy to the system during sudden load changes. The dual converter performs both rectifier and inverter action. For sudden step load perturbation the change of output of a RFB is given as [6].

$$\Delta P_{rfb} = \frac{K_{rfb}}{1 + sT_{rfb}} \Delta F_1 \tag{15}$$

where K_{rfb} is gain of a RFB and T_{rfb} is time constant of RFB in Sec.

3. Overview of differential evolution algorithm

Differential Evolution (DE) algorithm is a population-based stochastic optimization algorithm recently introduced [22]. Advantages of DE are: simplicity, efficiency & real coding, easy use 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 flow chart of DE approach is shown in Fig. 6. The DE algorithm is explained in more detail in [24].

4. Simulation results and discussion

4.1. Implementation of DE

The simulations are carried out on an Intel, Core i-5 CPU of 2.5 GHz, 8 GB, 64-bit processor computer in the the MATLAB 7.10.0.499 (R2010a) environment. The model of the system under study shown in Fig. 2 is developed in MATLAB/SIMULINK environment and DE program is written (in.m file). Initially, dissimilar PIDF controllers are considered for each area without considering the physical constraints (time delay, generation rate constraints), IPFC and RFB under poolco based transaction. The developed model is simulated in a separate program (by.m file using initial population/controller parameters) considering a 20% step load increase in area 1. The objective function is calculated in the.m file and used in the optimization algorithm. In the present study, a population size of $N_P = 100$, 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 pre specified 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

Table 5
Performance index values under Bilateral based transaction.

Parameters		Without IPFC & RFB	With IPFC only	Both IPFC & RFB
ITAE		3028.6	2930.5	64.2
T_S (sec)	ΔF_1	unstable	unstable	25.34
	ΔF_2	unstable	unstable	27.23
	ΔP_{Tie}	unstable	unstable	25.37
Peak over shoot	ΔF_1	3.0347	2.8912	0.2314
	ΔF_2	3.0427	2.9121	0.4542
	ΔP_{Tie}	0.2339	0.2054	0.2050

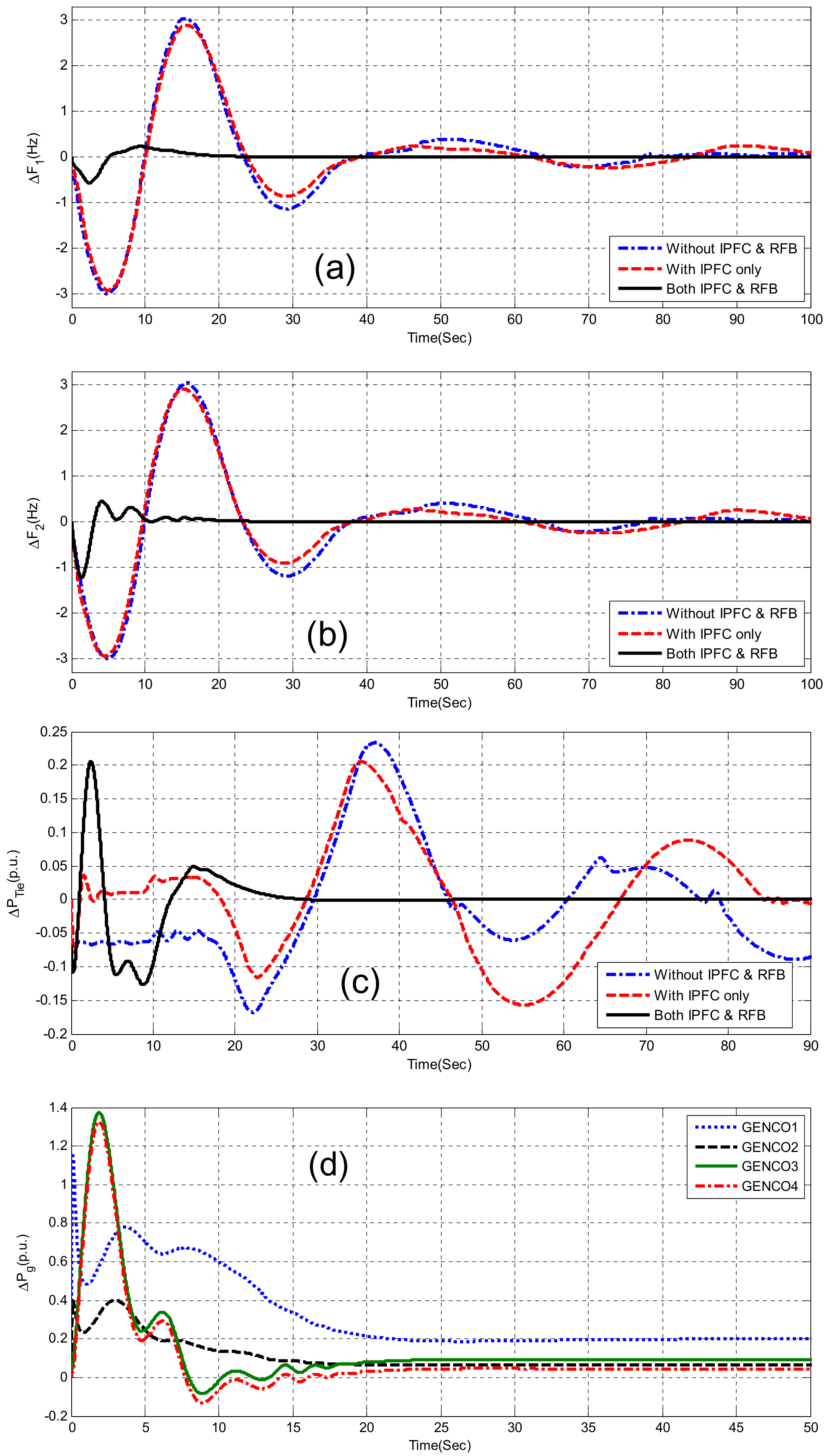

Fig. 10. Dynamic responses of the system for bilateral based transaction (a) Frequency deviation of area 1 (b) Frequency deviation of area 2 (c) Tie-line power deviation (d) Change in generated powers of different GENCOs.

Table 6
Tuned PIDF controller parameters for Contract violation based transaction with TD & GRC.

Cases/Parameters	K_{P1}	K_{P2}	K_{I1}	K_{I2}	K_{D1}	K_{D2}	N_1	N_2
Without IPFC & RFB	−0.2122	1.8576	−0.1506	−0.0160	−1.9138	−1.2309	270.4589	122.8947
With IPFC only	−0.0498	1.6603	−0.0407	−0.0628	−0.9035	−1.6356	203.1226	46.4113
Both IPFC & RFB	−1.6370	0.1720	−0.8080	−0.4726	0.1355	−0.2939	77.2905	18.2415

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. The optimization was repeated 50 times and the best final solution among the 50 runs is chosen as controller parameters.

In the present study, the controller parameters are tuned at three transactions that take place in a deregulated environment i.e. Poolco, Bilateral and Contract violation based transactions. Under each transaction scenario, three cases are considered i.e. without IPFC & RFB, with IPFC only and with both IPFC & RFB. Initially, a two area power system without any physical constraints is considered and the PIDF controller parameters are optimized under Poolco based transition. The superiority of PIDF over fuzzy controller is demonstrated in this case. Then physical constraints such as GRC and time delay are included in the system model and the PIDF controller parameters are retuned for different cases. To show the robustness of proposed approach, sensitivity analysis is performed under varied loading and system parameter conditions. The process is repeated i.e. the PIDF controller parameters are tuned under Bilateral and Contract violation based transactions in presence of physical constraints. Finally, the proposed approach is extended to a two area six unit hydro thermal power system with IPFC and RFB considering the physical constraints.

4.2. Case I: Poolco based transaction

In this scenario DISCOs have contract with GENCOs of the same area. It is assumed that the load disturbance occurs only in area 1. There is 0.1 (p.u. MW) load disturbance in DISCO1 and DISCO2, i.e. $\Delta P_{L1} = 0.1$ (p.u. MW), $\Delta P_{L2} = 0.1$ (p.u. MW), $\Delta P_{L3} = \Delta P_{L4} = 0$ (p.u. MW) as a result of the total load disturbance in area 1 i.e. $\Delta P_{D1} = 0.2$ (p.u. MW). Considering that there is an equal participation of GENCOs.

$$\therefore DPM = \begin{bmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

GENCO participates in load frequency control as defined as following area participation factors i.e. $apf_{11} = 0.75$; $apf_{12} = 0.25$; $apf_{21} = 0.5$; $apf_{22} = 0.5$. The scheduled tie-line power in this case is zero. In steady sate, generation of GENCOs must match the demand of the DISCOs in contract with it. The generated power or contracted power supplied by the GENCOs is given as

$$\Delta P_{gi} = \sum_{j=1}^{4} cpfij\ P_{Lj} \tag{16}$$

By using Eq. (16) the values for ΔP_{g1} can be calculated as

$$\Delta P_{g1} = cpf11P_{L1} + cpf12P_{L2} + cpf13P_{L3} + cpf14P_{L4}$$
$$= (0.5)*(0.1) + (0.5)*(0.1) + (0)*(0) + (0)*(0) = 0.1 \text{ (p.u. MW)}.$$

Similarly, the values of ΔP_{g2}, ΔP_{g3} and ΔP_{g4} are obtained as 0.1 (p.u. MW), 0 (p.u. MW) and 0 (p.u. MW) respectively.

In order to investigate the significance of considering the physical constraints, two cases (Case A and Case B) are considered. In Case A, Time delay and Generation Rate Constraints are neglected. In Case B, Time delay and Generation Rate Constraints are considered. Initially, the physical constraints and IPFC & RFB are not considered in the system model. The final PIDF controller parameters for the above case are obtained as explained in Section 4.1 and given in Table 1. For comparison the results are compared with fuzzy logic controller (FLC). In case of FLC, ACE and its derivative are taken as input to the fuzzy logic controller and triangular membership functions are used [28]. The membership functions are used with five fuzzy linguistic variables such as NB (negative big), NS (negative small), Z (zero), PS (positive small) and PB (positive big) for both the inputs and the output. The input scaling factors (K_1, K_2, K_3 and K_4) of FLC are optimized using DE optimization technique employing the same ITAE objective function. The optimized parameters are given in Table 1. The performance index in terms of ITAE value, and settling times (2% band) in frequency and tie line power deviations are also shown in Table 1. It is clear from Table 1 that, with the same system (without GRC, TD, IPFC and RFB) a less ITAE value is obtained with PIDF controller (ITAE = 7.817) compared to fuzzy controller (ITAE = 11.7186). The overall system performance in terms of settling times and peak over shoots are also greatly improved with proposed DE optimized PIDF controller compared to fuzzy controller. Hence it can be conclude that PIDF controller outperform fuzzy controller.

Then an IPFC is incorporated in the tie-line to analyze its effect on the power system performance. Finally, Redox Flow Batteries (RFB) is installed in the area 1 and coordinated with IPFC to study their effect on system performance. The optimized controller parameters and the corresponding performance index are provided in Table 2. It is clear from Tables 1 and 2 that, ITAE value is further reduced to 2.1414 with only IPFC controller and smallest ITAE value (ITAE = 1.8858) is obtained with the coordinated application of IPFC and RFB. The corresponding performance indexes in terms of

Table 7
Performance index values under Contract violation based transaction.

Parameters		Without IPFC & RFB	With IPFC only	Both IPFC & RFB
ITAE		30043.0	7803.4	109.4
T_S (sec)	ΔF_1	unstable	unstable	32.59
	ΔF_2	unstable	unstable	34.16
	ΔP_{Tie}	unstable	unstable	28.80
Peak over shoot	ΔF_1	3.5134	3.4846	0.2480
	ΔF_2	3.5142	3.5134	0.3874
	ΔP_{Tie}	0.2021	0.4126	0.2171

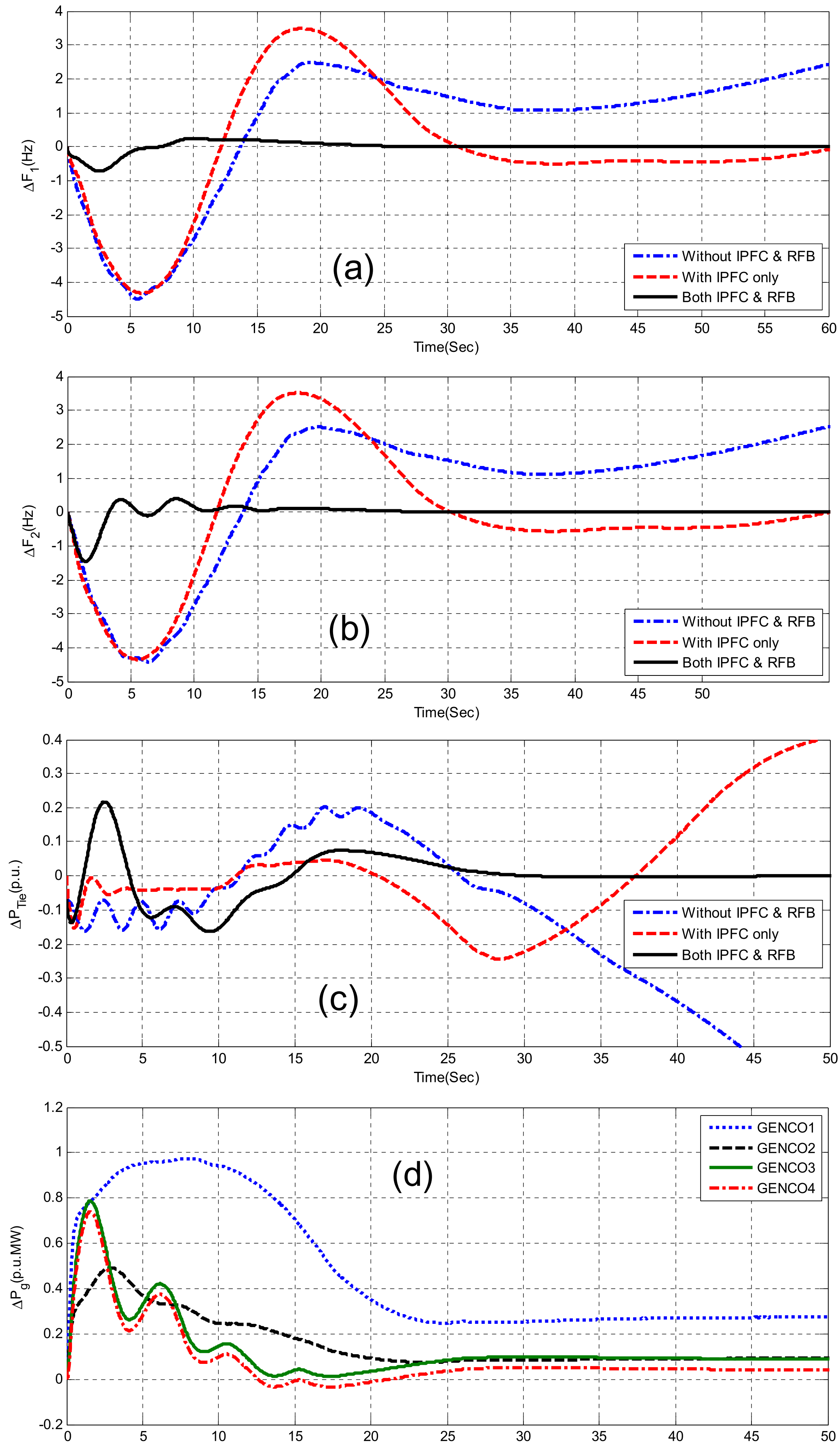

Fig. 11. Dynamic responses of the system for contract violation based transaction (a) Frequency deviation of area 1 (b) Frequency deviation of area 2 (c) Tie-line power deviation (d) Change in generated powers of different GENCOs.

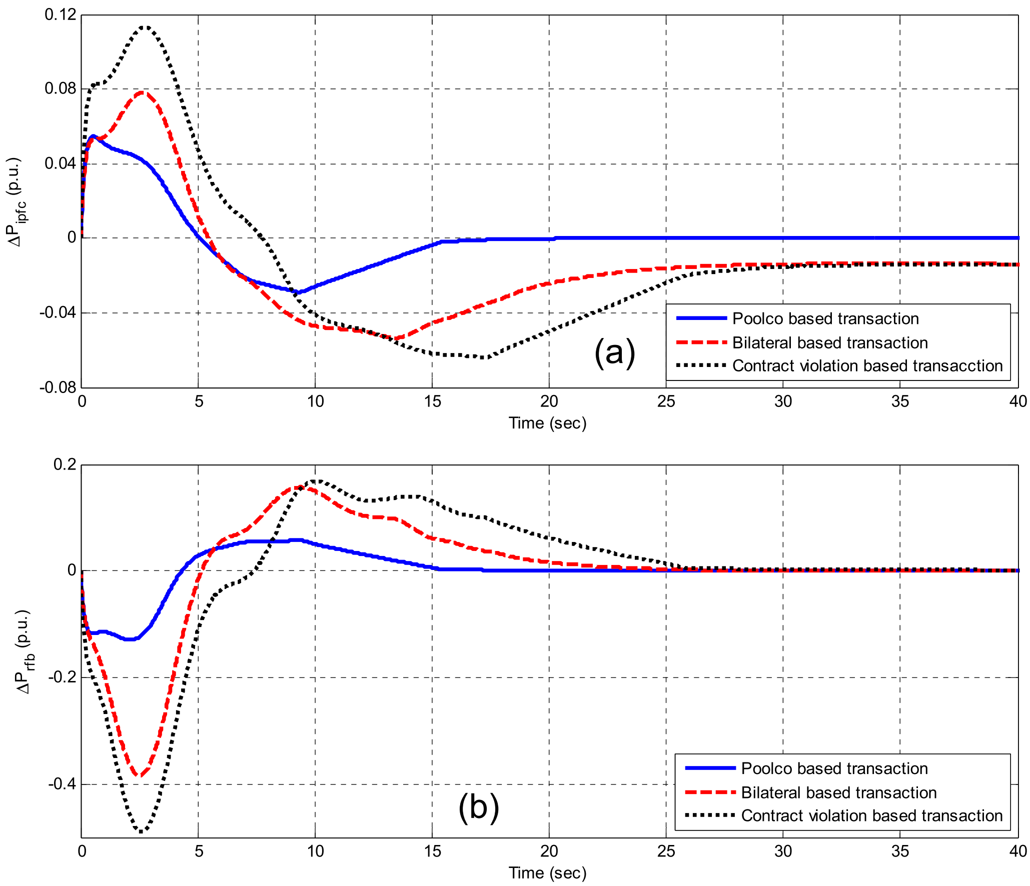

Fig. 12. Dynamic performances of system with both IPFC and RFB (a) Power deviation of IPFC under different transactions (b) Power deviation of RFB under different transactions.

settling time and peak overshoots are accordingly reduced. The percentage improvements with IPFC only and with coordinated application of IPFC and RFB compared the system without IPFC and RFB are also provided in Table 2. It can be seen from Table 2 that system performance improves IPFC only and significant improvements are achieved with coordinated application of IPFC and RFB.

In the next step, physical constraints GRC and TD are included in the system model and the results are shown in Table 3. For comparison, the performance indexes without re-tuning the controller parameters are also provided in Table 3. It can be observed from Tables 1–3 that the system performance degrades when GRC and TD are included in the system model. This is due to the reason that, when GRCs are considered, the generation can only be changed at a certain rate. Similarly, due to the presence of TD, the controller action is delayed and hence the system performance deteriorates.

The dynamic performance of the system without GRC and TD for 20% step increase in load in area 1 is shown in Fig. 7(a–c). It can be seen from Fig. 7(a–c) that the system is oscillatory with fuzzy controller. It is also evident from Fig. 7(a–c) that oscillations are quickly suppressed with proposed DE optimized PIDF controllers. The system performance further improves with IPFC and the best dynamic performance is obtained with coordinated application of IPFC and RFB.

Fig. 8(a–c) show the dynamic performance of the system with GRC and TD with/without IPFC and RFB for the above disturbance. It can be seen from Fig. 8(a–c) that the system is highly oscillatory without IPFC and RFB in presence of GRC and TD. The dynamic performance is improved with IPFC and significant improvement in system performance is obtained with coordinated application of IPFC and RFB.

Table 8
Sensitivity analysis under poolco based transaction.

Parameter variation	% Change	Settling time in (Sec)			Peak over shoot			ITAE
		ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}	
Nominal	0	15.52	18.05	15.07	0.0855	0.1622	0.0416	17.63
Loading condition	+25	15.55	18.06	15.70	0.0850	0.1377	0.0407	17.35
	−25	15.51	18.04	15.70	0.0851	0.1468	0.0410	17.48
T_g	+25	15.47	17.94	15.62	0.0854	0.1702	0.0419	17.89
	−25	16.12	18.16	15.82	0.0855	0.1532	0.0412	17.61
T_t	+25	15.48	18.01	15.63	0.0862	0.1620	0.0420	17.66
	−25	15.58	18.09	15.80	0.0849	0.1623	0.0412	17.75
T_{12}	+25	16.37	17.89	15.52	0.0844	0.1154	0.0424	17.32
	−25	15.39	18.33	16.00	0.0846	0.2245	0.0424	18.95

Table 9
System eigen values under parameter variation with poolco based transaction.

Loading condition		T_g		T_t		T_{12}	
+25%	−25%	+25%	−25%	+25%	−25%	+25%	−25%
−220.32	−220.32	−220.33	−220.32	−220.33	−220.32	−220.32	−220.32
−98.04	−98.04	−98.05	−98.01	−98.05	−98.02	−98.04	−98.03
−25.85	−25.85	−24.73	−27.95	−25.13	−26.95	−25.81	−25.88
−15.45	−15.44	−13.40	−19.06	−14.92	−16.27	−15.43	−15.44
−4.37 ± 7.02i	−4.37 ± 7.02i	−3.65 ± 6.58i	−5.4 ± 7.41i	−4.18 ± 5.68i	−4.48 ± 8.62i	−4.17 ± 6.94i	−4.52 ± 7.07i
−3.21 ± 4.55i	−3.20 ± 4.55i	−2.95 ± 4.41i	−3.47 ± 4.65i	−3.23 ± 3.96i	−3.27 ± 5.31i	−3.24 ± 4.56i	−3.15 ± 4.54i
−0.68 ± 0.67i	−0.68 ± 0.68i	−0.69 ± 0.67i	−0.69 ± 0.70i	−0.69 ± 0.62i	−0.67 ± 0.74i	−1.12	−0.67 ± 0.74i
−0.77	−0.76	−0.77	−0.72	−0.91	−0.66	−0.66 ± 0.64i	−0.46
−0.24 ± 0.08i	−0.24 ± 0.08i	−0.24 ± 0.08i	−0.24 ± 0.08i	−0.24 ± 0.08i	−0.24 ± 0.08i	−0.24 ± 0.08i	−0.24 ± 0.07i
−0.24	−0.24	−0.24	−0.24	−0.24	−0.24	−0.24	−0.27
−12.50	−12.50	−10.00	−16.67	−12.50	−12.50	−12.50	−12.50
−12.50	−12.50	−10.00	−16.67	−12.50	−12.50	−12.50	−12.50
−3.33	−3.33	−3.33	−3.33	−2.67	−4.44	−3.33	−3.33
−3.33	−3.33	−3.33	−3.33	−2.67	−4.44	−3.33	−3.33
−0.10	−0.10	−0.10	−0.10	−0.10	−0.10	−0.10	−0.10
−0. 10	−0. 10	−0. 10	−0.10	−0. 10	−0. 10	−0. 10	−0. 10

To evaluate the effect of GRC and TD and to show the need for retuning the controller parameters in presence of physical constraints, the system dynamic responses with IPFC and RFB for both the cases (without GRC and TD: Case A and with GRC and TD: Case B) without/with retuned controller parameters are shown in Fig. 9(a–c). It can be seen from Fig. 9(a–c) and Table 3 that better dynamic responses in terms of peak over shoots and settling times are obtained when the controller parameter are retuned in presence of physical constraints. For this case, the improvements in ITAE value are 58.92% with IPFC only and 95.93% with coordinated application of IPFC and RFB. The change in actual generated powers of various GENCOs in response to contract with DISCOs is shown in Fig. 9 (d). It is clear from Fig 9 (d) that the GENCO1 and GENCO2 contribute 0.1 p.u. each and the sum of power generations of GENCOs in control area-1 matches with load demand of 0.2 pu MW.

4.3. Case II: bilateral based transaction

In this type of transactions, DISCOs have the freedom to contract with any of the GENCOs within own area or with another area. Now the DISCO participation matrix can be express as

$$DPM = \begin{bmatrix} 0.4 & 0.25 & 0.75 & 0.3 \\ 0.3 & 0.2 & 0 & 0.25 \\ 0.2 & 0.2 & 0.25 & 0.25 \\ 0.1 & 0.35 & 0 & 0.2 \end{bmatrix}$$

There is a load disturbance in DISCO1 is 0.15 (p.u. MW) and 0.05 (p.u. MW), 0.15 (p.u. MW), 0.05 (p.u. MW) in DISCO2, DISCO3, DISCO4 respectively. In this case, from Eq. (2) the scheduled tie-line power can be calculated as 0.0675 (p.u. MW).

Similarly from Eq. (16) the values of steady state power generated by the GENCOs are given as $\Delta P_{g1} = 0.2$ (p.u. MW), $\Delta P_{g2} = 0.0675$ (p.u. MW), $\Delta P_{g3} = 0.09$ (p.u. MW), $\Delta P_{g4} = 0.0425$ (p.u. MW).

The tuned PIDF controller parameters for Bilateral based transaction with GRC and TD are given in Table 4. The various performance indexes (ITAE, settling time and peak overshoot) under bilateral based transaction case are given in Table 5. It is clear from Table 5 that minimum ITAE value is obtained with coordinated application of IPFC and RFB (ITAE = 64.2) compared to only IPFC (ITAE = 2930.5) and without IPFC and RFB optimized PIDF controller (ITAE = 3028.6). The improvements in ITAE value for above case are 3.24% with IPFC only and 97.88% with coordinated application of IPFC and RFB. Consequently, better system performance in terms minimum settling times in frequency and tie-line power deviations is achieved with proposed IPFC and RFB optimized PIDF controller compared to others as shown in Table 5. Hence it can be concluded that in this case also, the coordination of IPFC and RFB works satisfactorily.

It is worthwhile to mention that, in this example the values of GRC and TD as well as the magnitude of disturbance is so chosen that the system becomes unstable with IPFC for a better illustration of coordinated application of IPFC and RFB. However, in the realistic system, IPFC may be enough to stabilize the system. The dynamic performance of the system for the above case is shown in Fig. 10(a–c). Critical analysis of the dynamic responses clearly reveals that coordinated application of IPFC and RFB significantly improves the dynamic performance of the system. Improved results in settling times and peak overshoots of ΔF_1, ΔF_2 and ΔP_{Tie} are obtained with proposed DE optimized PIDF controller with coordinated application of IPFC and RFB compared to others. Fig. 10 (d) shows the change in actual generated powers of various GENCOs for the above case. It is clear from Fig 10 (d) that the steady state values of GENCOs are matching with the calculated values.

It is worthwhile to mention here that IPFC in general improves the AGC performance by controlling the tie-line power flow. In case of Bilateral based transactions, the scheduled tie-line power flow is 0.0675 (p.u. MW) as calculated according to the DPM matrix where as the load disturbance is 0.2 p.u. As the tie-line power flow is fixed to its scheduled value, the role of IPFC which controls the tie-line power flow is very limited for Bilateral based transactions. Due to the above reason a small improvement in ITAE value is obtained with IPFC only compared to the case when both IPFC and RFB are absent.

4.4. Case III: contract violation based transaction

In this case, there is a violation of contracts by demanding more power than that of specified in the contract. Considering Case II again with a modification that 0.1 (p.u. MW) of excess power demanded by DISCO1. Now ΔP_{D1} becomes $\Delta P_{D1} = \Delta P_{L1} + \Delta P_{L2} + \Delta P_{uc1} = 0.3$ (p.u. MW) and ΔP_{D2} is unchanged. In this case, as contract violation done by DISCO1 the values of ΔP_{g1} and ΔP_{g2} can be calculated as.

$$\Delta P_{g1,violation} = \Delta P_{g1} + apf_{11} * \Delta P_{uc1} = 0.275 \ \text{(p.u. MW)}$$
$$\Delta P_{g2,violation} = \Delta P_{g2} + apf_{12} * \Delta P_{uc1} = 0.0925 \ \text{(p.u MW)}$$

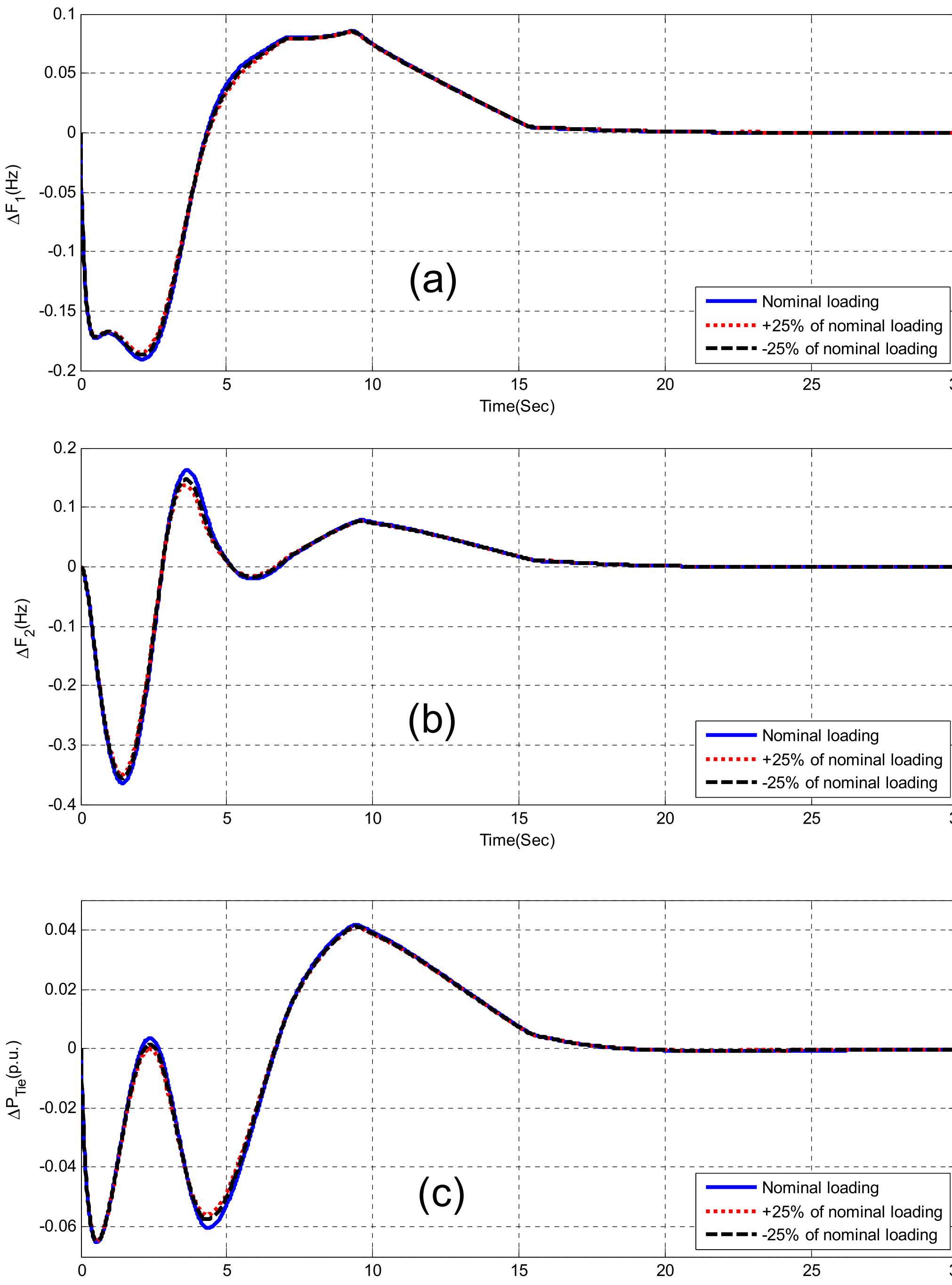

Fig. 13. Dynamic responses of the system with variation of nominal loading (a) Frequency deviation of area 1 (b) Frequency deviation of area 2 (c) Tie-line power deviation.

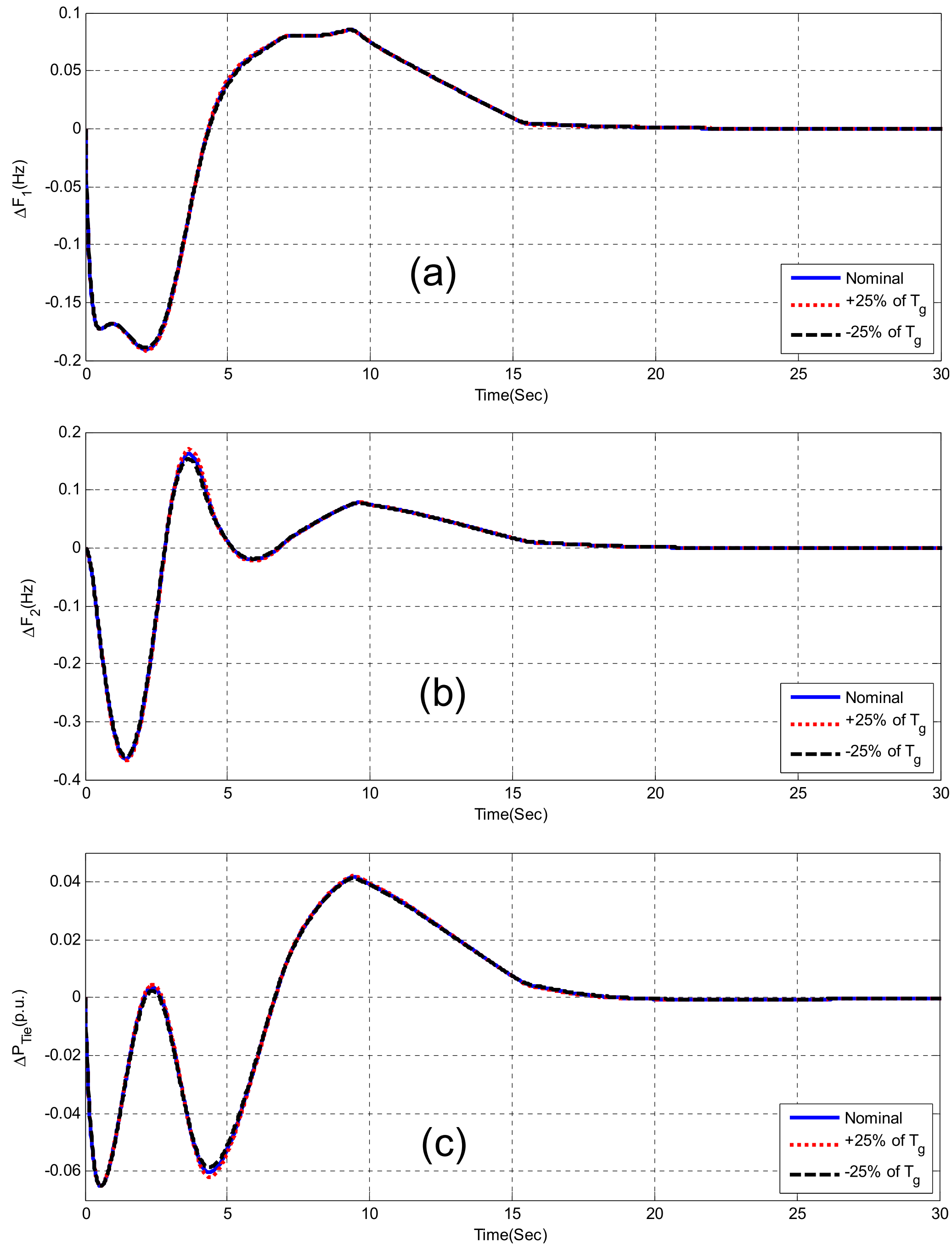

Fig. 14. Dynamic responses of the system with variation of T_g (a) Frequency deviation of area 1 (b) Frequency deviation of area 2 (c) Tie-line power deviation.

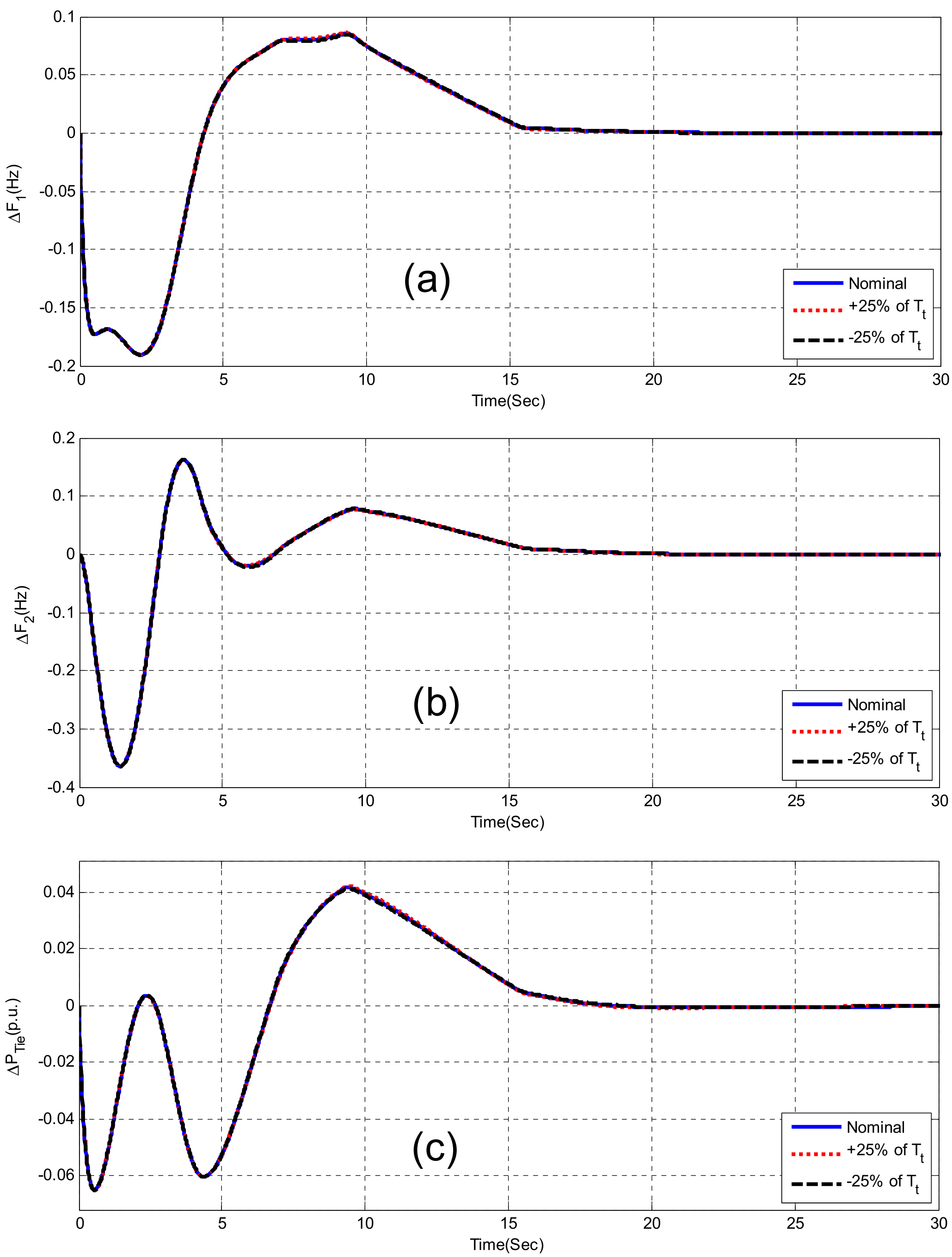

Fig. 15. Dynamic responses of the system with variation of T_t (a) Frequency deviation of area 1 (b) Frequency deviation of area 2 (c) Tie-line power deviation.

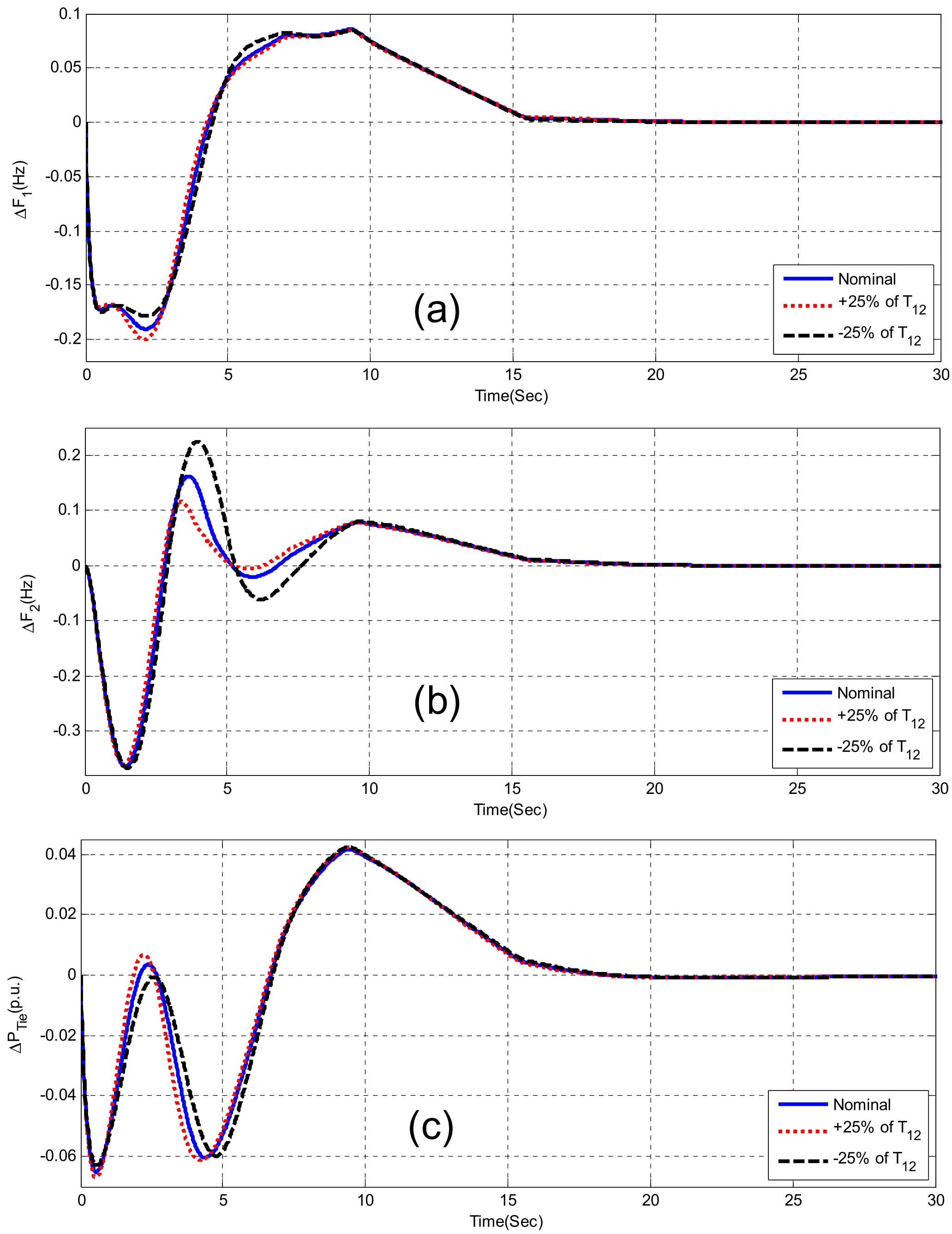

Fig. 16. Dynamic responses of the system with variation of T_{12} (a) Frequency deviation of area 1 (b) Frequency deviation of area 2 (c) Tie-line power deviation.

The values of ΔP_{g3} and ΔP_{g4} are same as in Case II because contract violation is assumed in area 1.

Table 6 gives the tuned PIDF controller parameters for contract violation based transaction with GRC and TD. The various performance indexes in terms of ITAE, settling time and peak overshoot for the above case are given in Table 7. It can be seen from Table 7 that improved results are obtained with coordinated application of IPFC and RFB compared to others. The improvements in ITAE value for contract violation based transaction are 74.02% with IPFC only and 99.6% with coordinated application of IPFC and RFB. The frequency deviations and tie-line power are shown in Fig. 11(a–c). It is evident from Fig. 11(a–c) that the system is unstable without IPFC and RFB as well as with IPFC only. This due to the reason that the situation in Case II is further worsened by demanding excess power in area 1. It is also evident from Fig. 11 (a–c) that the system is stable with coordinated application of IPFC and RFB and the oscillations are quickly damped out. The change in actual generated powers of various GENCOs for contract violation based transaction is shown in Fig. 11 (d) from which it can be seen that all the GENCOs contributes and their individual power generation matches with the calculated values. The output curves of IPFC and RFB for the above transactions are provided in Fig. 12(a–b). It is clear from Fig. 12(a–b) that both IPFC and RFB actively participate and contribute to the improvement of AGC.

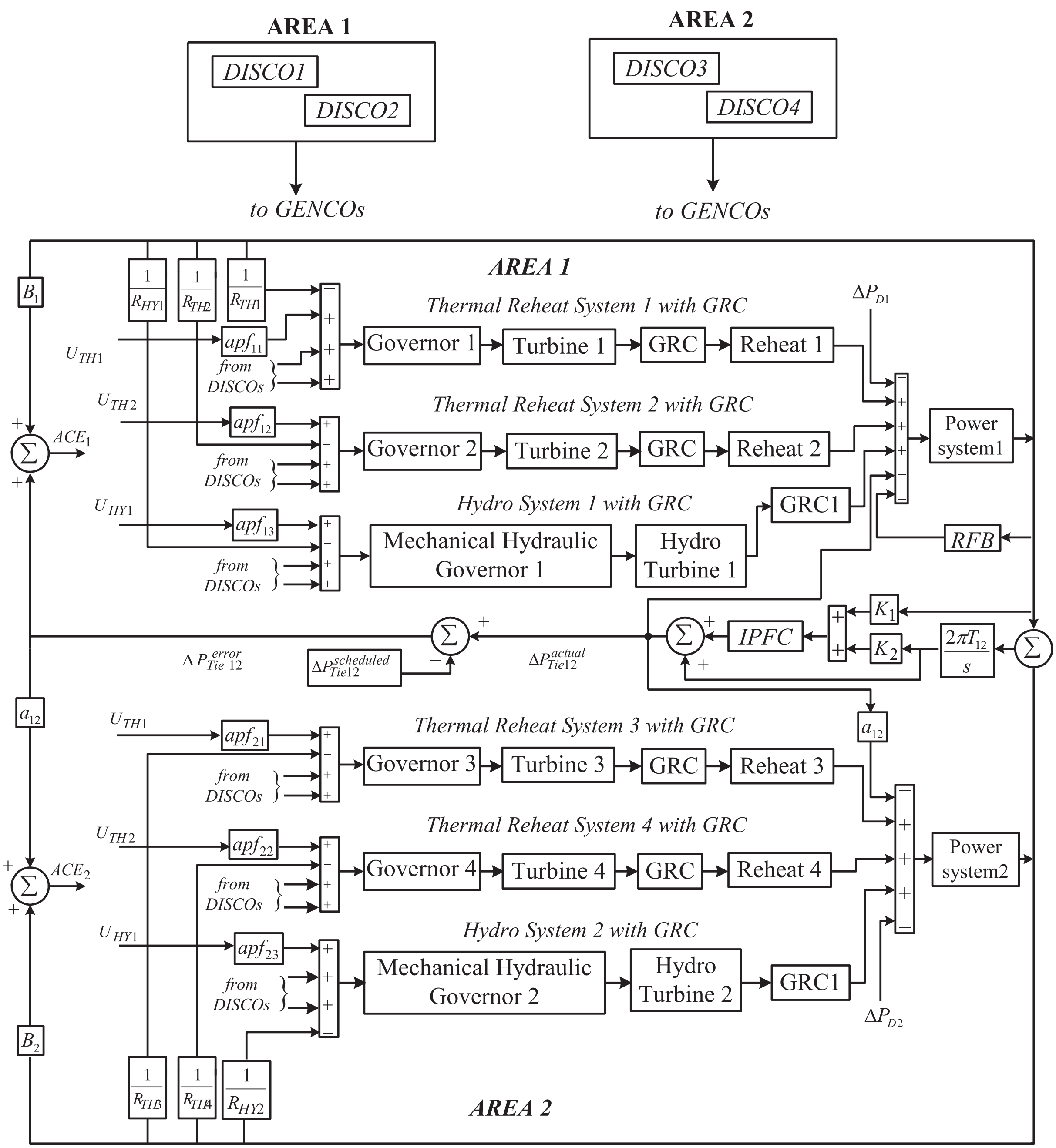

Fig. 17. Block diagram representation of the two area six unit hydro thermal power system with IPFC and RFB.

4.5. Sensitivity analysis

Sensitivity analysis is done to study the robustness the system to changes in the operating conditions and system parameters like speed governor time constant (T_g), Turbine time constant (T_t), Synchronizing time constant (T_{12}) in the range of +25% to −25%. The performance index under normal and varied conditions is shown in Table 8. Table 9 gives performance of the system under varied operating load condition and system parameters with proposed DE optimized PIDF controller employing both IPFC and RFB. Poolco based transaction with IPFC and RFB is considered for the sensitivity analyses as minimum ITAE value is obtained in that case compared to other cases. Critical examination of Table 8 clearly shows that the performance indexes are more or less same and the effect of the variation in operating loading conditions and system time constants on the system performance is negligible. It is also evident from Table 9 that the eigen values lie in the left half of s-plane for all the cases thus maintain the stability. Hence it can be concluded that, the proposed control approach provides a robust and stable control satisfactorily. To complete the analysis, the dynamic performance of the system with the varied conditions of loading, T_g, T_t and T_{12} are shown in Figs. 13–16. It can be observed from Fig. 13(a–c) that the effect of the variation of loading condition on the system performance is negligible. Also from Figs. 14(a–c), 15 (a–c) and 16 (a–c) clearly reveals that the effect of system parameters (T_g,T_t and T_{12}) on the system performance is negligible.

Table 10
Tuned PIDF controller parameters for two area six units system under Poolco based transaction.

Cases/Parameters	Without IPFC & RFB	With IPFC only	Both IPFC & RFB
K_{P1}	−1.0714	−1.1570	−0.4925
K_{P2}	0.6782	1.1109	−0.3676
K_{P3}	−0.8396	1.0238	−1.7358
K_{I1}	−0.2927	−0.7070	−1.8303
K_{I2}	0.2313	0.1535	−1.3551
K_{I3}	0.2416	0.1499	−1.3448
K_{D1}	−0.6553	−0.0486	−1.1918
K_{D2}	−1.8126	−1.5941	−0.9436
K_{D3}	0.7453	−0.8191	−0.0594
N_1	168.1922	53.5930	68.4587
N_2	182.8122	157.4710	42.9118
N_3	42.1501	187.6362	162.7192

4.6. Extension to two are six unit hydro thermal system

To demonstrate the ability of the proposed approach to cope with different sources of power generation, the study is further extended to a two area six unit hydro thermal power system with Generation Rate Constraint (GRC), time delay, IPFC and RFB as shown in Fig. 17. For thermal units a generation rate constraints (GRC) of 3%/min is considered. For hydro unit, GRC's of 270%/min for raising generation and 360%/min for lowering generation are considered [29]. Time delays can degrade a system's performance and even cause system instability. In the present paper, a time delay of 50 ms is considered [25]. The relevant parameters are given in Appendix B.

In this case only Poolco based transaction is considered. The area participation factors (apfs) of 0.4 for each thermal unit and 0.2 for hydro unit are assumed. A particular case of Poolco based transaction is simulated based on the following DPM:

$$DPM = \begin{bmatrix} 0.35 & 0.35 & 0 & 0 \\ 0.35 & 0.35 & 0 & 0 \\ 0.30 & 0.30 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

By using Eq. (16), the changes in generated powers of different GENCOs are obtained as follows:

$$\Delta P_{g1} = \Delta P_{g2} = 0.07 \text{ p.u. MW}, \ \Delta P_{g3} = 0.06 \text{ p.u. MW}, \ \Delta P_{g4} = \Delta P_{g5} = \Delta P_{g6} = 0 \text{ p.u. MW}$$

Initially, the system without IPFC and RFB is considered and dissimilar PIDF controllers are chosen for each unit. A step load disturbance of 20% is applied in area-1 and the final controller parameters of PIDF controller for the Poolco based transaction are obtained as explained in Section 4.1. In the next step, an IPFC installed in the tie-line to analyze its effect on the power system performance. Finally, RFB is placed in area-1 and coordinated with IPFC to study their effect on system performance. All the above conditions are tuned separately to obtain final controller parameters for PIDF controller and provided in Table 10. The corresponding performance indexes are shown in Table 11. It can be seen from Table 11 that minimum ITAE value is obtained with coordinated application of IPFC and RFB (ITAE = 17.5927) compared to the cases when only IPFC is present (ITAE = 201.7875) and without IPFC and RFB (ITAE = 331.3957). The improvements in ITAE value for above case are 39.11% with IPFC only and 94.69% with coordinated application of IPFC and RFB. Similar improvements are also observed in the settling times and peak overshoots.

The dynamic response of the system is shown in Fig. 18(a–c). It is clear from Fig. 18(a–c) that in all the cases the system is stable as the magnitude of applied disturbance is small. However, responses are oscillatory without IPFC and RFB. The system performance improves with the application of IPFC. Further, significant improvements in system performance are obtained with coordinated application of IPFC and RFB. Fig. 18 (d) shows the change in actual generated powers of all the GENCOs for the above case from which it can be seen that the GENCO1, GENCO2 and GENCO3 of area 1 contribute 0.07, 0.07 and 0.06 p.u. MW respectively as calculated.

Finally sensitivity analysis for two area six unit hydro thermal system under poolco based transaction is performed as explained before and the results are summarized in Table 12. It can be observed from Table 12 that settling time, peak overshoots and ITAE values vary within acceptable ranges and are nearby equal to the respective values obtained with nominal system parameter. Hence, it can be concluded that the proposed controllers are robust and perform satisfactorily when system parameters changes in the range ±25%.

The novel contributions of the present work are:

(i) PID controller with derivative filter (PIDF) is proposed for AGC in a deregulated power environment. A filter is used in derivative block to overcome the adverse affects of noise on PID controller.
(ii) Important physical constraints such as generation rate constraints and time delay are included in the system model and PIDF controller parameters are optimized employing DE technique.
(iii) IPFC is then installed in the tie-line between the interconnected areas for high speed control of tie-line power through the interconnections and to stabilize the area frequency oscillations quickly. The effect of presence of IPFC on the system performance is investigated.
(iv) In order to further improve the system performance, Redox Flow Batteries (RFB) which is an active power source with fast response characteristics is used. The impacts of IPFC and RFB on the dynamic performance have been investigated.
(v) Sensitivity analysis is performed by varying the operating load condition and system parameters in the range of ±25% from their nominal values.

Table 11
Performance index values for two area six units system under Poolco based transaction.

Parameters		Without IPFC & RFB	With IPFC only	Both IPFC & RFB
ITAE		331.3957	201.7875	17.5927
T_S (sec)	ΔF_1	unstable	59.27	15.19
	ΔF_2	unstable	51.23	17.05
	ΔP_{Tie}	unstable	40.37	15.44
Peak over shoot	ΔF_1	1.0151	0.8122	0.1034
	ΔF_2	1.0609	0.8716	0.1628
	ΔP_{Tie}	0	0.0763	0.0403

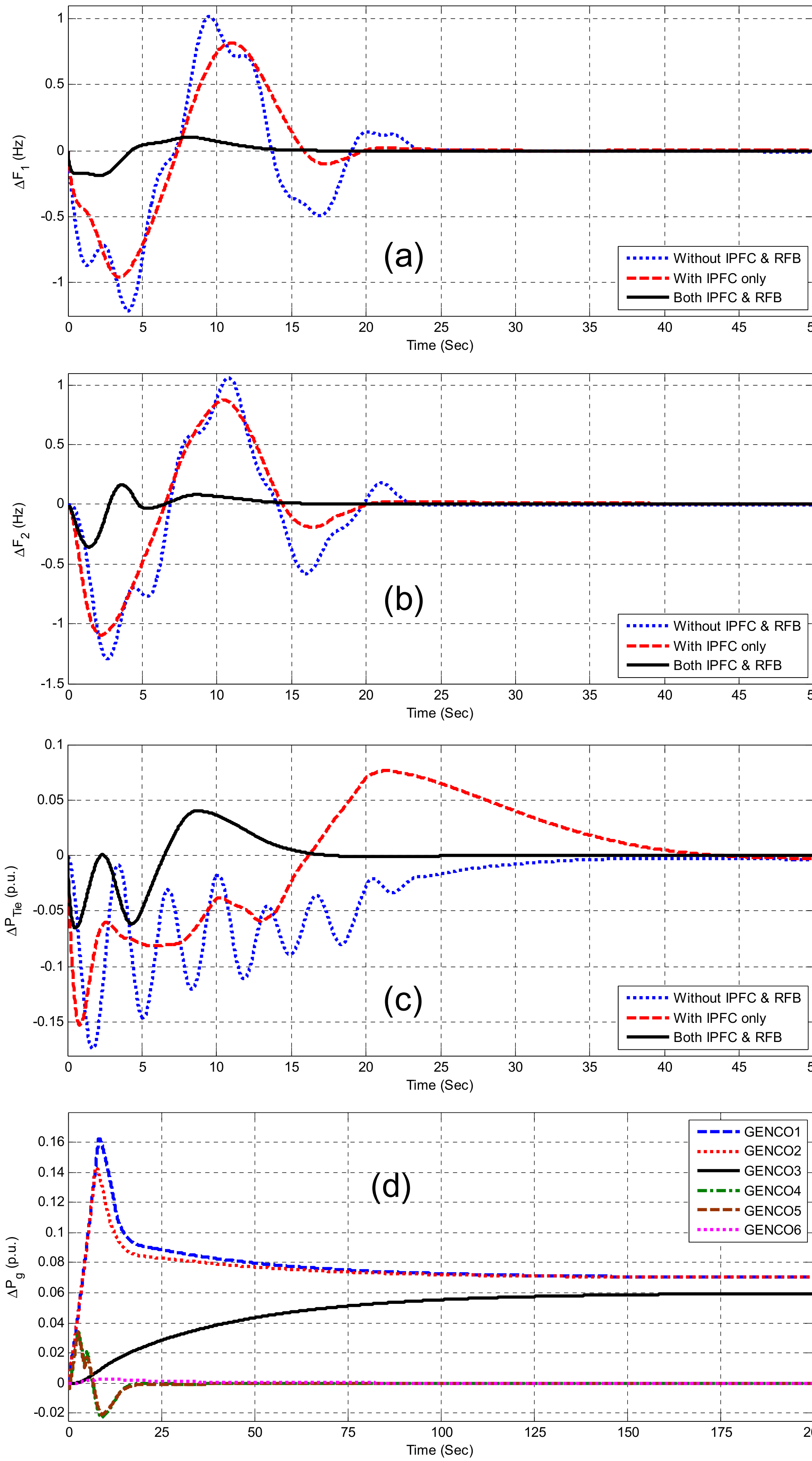

Fig. 18. Dynamic responses of the system under poolco based transaction (a) Frequency deviation of area 1 (b) Frequency deviation of area 2 (c) Tie-line power deviation (d) Change in generated powers of different GENCOs.

Table 12
Sensitivity analysis for two area six units system under poolco based transaction.

Parameter variation	% Change	Settling time in (Sec)			Peak overshoot			ITAE
		ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}	
Nominal	0	15.19	17.05	15.44	0.1034	0.1628	0.0403	17.5927
Loading condition	+25	15.24	17.08	15.45	0.1032	0.1567	0.0401	17.4978
	−25	15.12	17.02	15.44	0.1036	0.1690	0.0406	17.7026
T_{SG}	+25	15.04	16.96	15.38	0.1036	0.1705	0.0408	17.6946
	−25	15.32	17.14	15.51	0.1031	0.1539	0.0399	17.4899
T_T	+25	14.91	16.90	15.32	0.1044	0.1628	0.0405	17.5920
	−25	15.47	17.23	15.59	0.1023	0.1627	0.0401	17.6237
T_{RH}	+25	15.26	17.11	15.45	0.1029	0.1619	0.0402	17.8214
	−25	15.04	16.94	15.41	0.1040	0.1641	0.0405	17.4003
T_{GH}	+25	15.22	17.06	15.44	0.1028	0.1619	0.0401	17.8788
	−25	15.09	17.01	15.44	0.1043	0.1642	0.0406	17.0249
T_{12}	+25	15.47	16.90	15.32	0.1035	0.1185	0.0401	17.1093
	−25	14.57	17.22	15.57	0.1015	0.2214	0.0430	18.7608
R	+25	14.04	16.14	15.40	0.1089	0.1585	0.0395	17.7816
	−25	17.20	18.09	15.36	0.0978	0.1682	0.0418	17.8693

5. Conclusions

In this paper, a Differential Evolution Algorithm (DE) optimized PID controller with derivative filter (PIDF) has been proposed for Automatic Generation Control of multi area power system. Initially, a two area four unit thermal system is considered and the gains of PIDF controller parameters are optimized by employing DE technique. It is observed that better dynamic performance are obtained with proposed DE optimized PIDF controller compared to a fuzzy logic controller. Time Delay (TD) and Generation Rate Constraints (GRC) have been considered to have a more realistic power system. To get better insight of AGC problem, inclusion of GRC and TD is important for the dynamic performance study of the system. The system has been investigated all possible of power transactions that take place under deregulated environment. Interline power flow controller (IPFC) is then added in the tie-line for improving the system performance. As the tie-line power flow is fixed to its scheduled value, the role of IPFC which controls the tie-line power flow is very limited for bilateral based transactions. Due to the above reason a small improvement in ITAE value is obtained with IPFC only compared to the case when both IPFC and RFB are absent. Additionally, Redox Flow Batteries (RFB) is included in area 1 along with IPFC in order to improve the system performance. It is observed that in all the cases (poolco based, bilateral based and contract violation based) the deviation of frequency becomes zero in the steady state with coordinated application of IPFC and RFB which assures the AGC requirements. The proposed approach is also extended to a two-area six unit hydro thermal system. Sensitivity analysis is performed for both test systems under study by varying the system parameters and operating load conditions from their nominal values. From the simulation results it is observed that effect of system parameters and loading condition on the dynamic response of the power system is negligible.

Appendix

Nominal parameters of the system investigated are:

A .Data for two area four unit thermal system [6].

Rated frequency = *60* Hz, *Rating of each area* = *2000* MW, *Base power* = *2000* MVA, $R_1 = R_2 = R_3 = R_4 = 2.4$ Hz/p.u.MW, $B_1 = B_2 = 0.425$ p.u.MW/Hz, $T_{g1} = T_{g2} = T_{g3} = T_{g4} = 0.08$s, $T_{r1} = T_{r2} = T_{r3} = T_{r4} = 10$ s, $T_{t1} = T_{t2} = T_{t3} = T_{t4} = 0.3$ s, $K_{p1} = K_{p2} = 120$ Hz/p.u. MW, $T_{p1} = T_{p2} = 20$s, $K_{r1} = K_{r2} = K_{r3} = K_{r4} = 0.5$; $a_{12} = -1$, $2\pi T_{12} = 0.545$ p.u.MW/Hz.

B .Data for two area six unit hydro thermal system

$B_1 = B_2 = 0.425$ p.u. MW/Hz; $K_{PS1} = K_{PS2} = 120$ Hz/p.u. MW; $T_{PS1} = T_{PS2} = 20$ s; $R_{TH1} = R_{TH2} = R_{TH3} = R_{TH4} = R_{HY1} = R_{HY2} = 2.4$ Hz/p.u.; $T_{T1} = T_{T2} = T_{T3}\ T_{T4} = 0.3$ s; $T_{SG1} = T_{SG2} = T_{SG3} = T_{SG4} = 0.08$ s; $K_{R1} = K_{R2} = K_{R3} = K_{R4} = 0.5$; $T_{R1} = T_{R2} = T_{R3} = T_{R4} = 10$ s; $T_{12} = 0.0433$; $T_{GH1} = T_{GH2} = 48.7$ s; $T_{W1} = T_{W2} = 1$ s; $T_{RS1} = T_{RS2} = 0.513$; $T_{RH1} = T_{RH2} = 10$; $a_{12} = -1$.

C .Data for RFB and IPFC [6].

$K_{rfb} = 0.6787$, $T_{rfb} = 0$ s, $T_{ipfc} = 0.01$ s, $K_1 = -0.3$, $K_2 = -0.2622$.

D .MATLAB Programme to find system eigen values:

[A, B, C, D] = linmod ('Model'); % Model is the SIMULINK model of system.
Eigen_Values = eig(A); %Computes the system eigen values.

References

[1] O.I. Elgerd, Electric Energy Systems Theory: An Introduction, McGraw-Hill, New York, 1982.
[2] P. Kundur, Power System Stability and Control, McGraw-Hill, New York, 1994.
[3] H. Bervani, T. Hiyama, Intelligent Automatic Generation Control, CRC Press, 2011.
[4] P. Bhatt, R. Roy, S.P. Ghoshal, Optimized multi-area AGC simulation in restructured power systems, Int. J. Electr. Power Energy Syst. 32 (1) (2010) 311–322.
[5] V. Donde, M.A. Pai, I.A. Hiskens, Simulation and optimization in an AGC system after deregulation, IEEE Tran. Power Syst. 16 (3) (2010) 311–322.
[6] I.A. Chidambaram, B. Paramasivam, Optimized load-frequency simulation in restructured power system with redox flow batteries and interline power flow controller, Int. J. Electr. Power Energy Syst. 50 (2013) 9–24.
[7] K.P.S. Parmar, S. Majhi, D.P. Kothari, LFC of an interconnected power system with multi-source power generation in deregulated power environment, Int. J. Electr. Power Energy Syst. 57 (2014) 277–286.
[8] N.G. Hingorani, L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission System, IEEE Press., 2000.
[9] A.V. Naresh Babu, S. Sivanagaraju, C.H. Padmanabharaju, T. Ramana, Power flow analysis of a power system in presence of interline power flow controller (IPFC), ARPN J. Eng. Appl. Sci. 5 (10) (2010) 1–4.
[10] L. Gyugyi, K.K. Sen, C.D. Schavder, The interline power flow controller concept: a new approach to power flow management in transmission system, IEEE Trans. Power Deliv. 14 (3) (1989) 1115–1123.
[11] D. Kottick, M. Balu, D. Edelstein, Battery energy storage for frequency regulation in an island power system, IEEE Trans. Energy Convers. 8 (3) (1993) 455–459.
[12] H.J. Kunisch, K.G. Kramer, H. Dominik, Battery energy storage, another option for load frequency control and instantaneous reserve, IEEE Trans. Energy Conversions 1 (3) (1986) 41–46.
[13] Lu Chun-Feng, Liu Chun-Chang, Wu Chi-Jui, effect of battery energy storage system on load frequency control considering governor dead band and generation rate constraint, IEEE Trrans. Energy Convers. 10 (3) (1995) 555–561.

[14] L.H. Walker, 10 MW GTO converter for battery peaking service, IEEE Trans. Ind. Appl. 26 (1) (1990) 63–72.
[15] S.K. Aditya, D. Das, Battery energy storage for load frequency control of an interconnected power system, Electr. Power Syst. Res. 58 (3) (2001) 179–185.
[16] S.K. Aditya, D. Das, Application of battery energy storage system to load frequency control of an isolated power system, Int. J. Energy Res. 23 (3) (1999) 247–258.
[17] S.K. Aditya, D. Das, Load frequency control of an interconnected hydro-thermal power system with new area control error considering battery energy storage facility, Int. J. Energy Res. 24 (6) (2000) 525–538.
[18] R.J. Abraham, D. Das, A. Patra, Load following in a bilateral market with local controllers, Int. J. Electr. Power Energy Syst. 33 (10) (2011) 1648–1657.
[19] S. Tetsuo, K. Toshihisa, E. Kazuhiro, Study on load frequency control using redox flow batteries, IEEE Trans. Power Syst. 19 (1) (2004) 660–667.
[20] K. Enomoto, T. Sasaki, T. Shigematsu, H. Deguchi, Evaluation study about redox flow battery response and its modeling, IEEE J. Trans. Power Eng. 122 (4) (2002) 545–560.
[21] R.K. Sahu, S. Panda, S. Padhan, Optimal gravitational search algorithm for automatic generation control of interconnected power systems, Ain Shams Eng. J. 5 (3) (2014) 721–733.
[22] R. Stron, K. Price, Differential evolution—a simple and efficient adaptive scheme for global optimization over continuous spaces, J. Glob. Optim. 11 (4) (1995) 341–359.
[23] S. Das, P.N. Suganthan, Differential evolution: a survey of the state-of-the-art, IEEE Trans. Evol. Comput. 15 (1) (2011) 4–31.
[24] R.K. Sahu, S. Panda, U.K. Rout, DE optimized parallel 2-DOF PID controller for load frequency control of power system with governor dead-band nonlinearity, Int. J. Electr. Power Energy Syst. 49 (2013) 19–33.
[25] S. Panda, N.K. Yegireddy, S. Mahapatra, Hybrid BFOA-PSO approach for coordinated design of PSS and SSSC-based controller considering time delays, Int. J. Electr. Power Energy Syst. 49 (2013) 221–233.
[26] H. Shabani, B. Vahidi, M. Ebrahimpour, A robust PID controller based on imperialist competitive algorithm for load-frequency control of power systems, ISA Trans. 52 (1) (2013) 88–95.
[27] K.P.S. Parmar, Load frequency control of multi-source power system with redox flow batteries: an analysis, Int. J. Comput. Appl. 88 (8) (2014) 46–52.
[28] R.K. Sahu, S. Panda, N.K. Yagireddy, A novel hybrid DEPS optimized fuzzy PI/PID controller for load frequency control of multi-area interconnected power systems, J. Process Control 24 (01) (2014) 1596–1608.
[29] S.R. Khuntia, S. Panda, Simulation study for automatic generation control of a multi-area power system by ANFIS approach, Appl. Soft Compt. 12 (1) (2012) 333–341.