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Application of Fractional Order PID Controller for AGC Under Deregulated Environment

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Abstract: In this paper, a fractional order proportional integral derivative (FOPID) controller for multiarea automatic generation control (AGC) scheme has been designed. FOPID controller has five parameters and provides two additional degrees of flexibility in comparison to a proportional integral derivative (PID) controller. The optimal values of parameters of FOPID controller have been determined using Big Bang Big Crunch (BBBC) search algorithm. The designed controller regulates real power output of generators to achieve the best dynamic response of frequency and tie-line power on a load perturbation. The complete scheme for designing of the controllers has been developed and demonstrated on multiarea deregulated power system. The performance of the designed FOPID controllers has been compared with the optimally tuned PID controllers. It is observed from the results that the FOPID controller shows a considerable improvement in the performance as compared to the conventional PID controller.

Keywords: Automatic generation control (AGC), deregulation, Big Bang Big Brunch (BBBC) algorithm, fractional order proportional integral derivative (FOPID) controller, optimization.

1 Introduction

Now a days power system is in its restructuring phase, it is being restructured from conventional structure to open market system which consists Gencos (generation companies), Transcos (transmission companies), Discos (distribution companies), and ISO (independent system operator). The control of such a large and complex power system is the most challenging problem. The main objectives of automatic generation control (AGC) are to keep the frequency deviation and interconnected tie-line power within the scheduled limits. In a deregulated environment, ISO has to procure various ancillary services for the stable and secure operation of power system[1−2]. Frequency regulation using AGC is one of the most important ancillary services among all. AGC is used to provide the balance between generation and load demands of each area and maintain the frequency and tie-line power flow within the specified limits. Load frequency control issues under deregulated environment have been reported in [3].

Controller plays an important role in AGC scheme, therefore various control strategies for AGC scheme have been proposed in the literature over the past decades, however proportional integral derivative (PID) controller has been used mostly. Different methods to determine the optimal parameters of PID controller such as genetic algorithm (GA), particle swarm optimization (PSO), bacterial foraging optimization (BFO) and artificial bee colony (ABC) have been proposed[4−7]. GA is an effective approach for AGC but deficiency such as premature convergence may degrade its performance, as reported in [5]. Authors in [6] have proved the superiority of the craziness based PSO in terms of convergence, robustness and precision. Gozde et al.[7] discussed that ABC gives better solution than PSO for AGC problem. A detailed study of various control strategies for AGC is given in [8−9]. PID controllers are simple in design and have good performance such as low percentage overshoot and small settling time. Since the operating point of power system keep changing, therefore, PID controllers are required to be tuned time to time.

The performance of PID controllers can be improved by using the fractional calculus. In fractional order (FO) controllers, the order of integral and derivative terms is not an integer[10]. The main advantage associated with FO controllers is flexibility in controlling purpose which helps to design a robust control system. FO controllers have excellent capability of handling parameter uncertainty, elimination of steady state error and better stability[11]. Fractional order proportional integral derivative (FOPID) controllers are being used in different fields of engineering, such as stabilizing fractional order time delay systems[12], automatic voltage regulator system[13], etc. To design an optimal FOPID controller, the optimal value of the controller parameters such as K_{P_f} (proportional gain), K_{I_f} (integral gain), K_{D_f} (derivative gain), λ (non-integer integral order) and μ (non-integer derivative order) are to be determined. A number of algorithms have been used in literature to determine these parameters[14−16]. In [14], authors have proposed FOPID controller utilizing BFO technique for deregulated three area thermal power system. The performance of FOPID controller has been compared with other controllers. In [15], the superiority and advantage of two degree fractional order controller along with the firefly algorithm concept has been explored in the AGC

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scheme of three area conventional power systems. The performance of FOPID controller tuned by chaotic algorithm has been compared with PID controller for two-area load frequency control (LFC) in [16]. In [17], FOPID controller is introduced for interconnected and isolated power system but the authors have not addressed the effects of deregulated scenario, generation rate constraint (GRC) and reheat turbine. FOPID controller has been extended in deregulated power system in [18]. The parameters of controller have been determined by genetic algorithm-firefly algorithm (GA-FA) algorithm. Performance of FOPID controller has also been compared with PID controller. However authors have not considered the effects of nonlinearities. A comparison of FOPID controller with artificial neural networks (ANN), fuzzy logic and GA, for two area interconnected power system is investigated in [19] which reveals that the AGC scheme based on FOPID is more robust than others.

The complexity of AGC problems and its optimization reveal the necessity for an efficient search algorithm. A new Meta heuristic algorithm called Big Bang Big Crunch algorithm (BBBC) based on the Big Bang theory[20, 21] has been successfully applied to solve different engineering problems[22−24]. A design methodology of interval type-2 fuzzy PID (IT2FPID) controllers for the LFC problem using BBBC algorithm is proposed in [22]. It is shown that BBBC has low computational cost and high convergence speed. PID controller design for the AGC scheme in multiarea power system using BBBC algorithm is presented in [23, 24]. In [24], it is shown that BBBC algorithm, have better performance over PSO and differential evolution (DE) algorithms for the AGC-AVR system. In the present work, parameters determined using BBBC have been applied to design FOPID and PID controllers. The designed controller is tested on two similar area power systems[25] and 75-bus Indian power system[26]. 75-bus Indian power system is divided into four control areas. All the four areas are of different ratings. The performance of FOPID controllers has been compared with PID controllers.

2 Modeling of multiarea AGC scheme

Detailed mathematical model of multiarea conventional AGC scheme has been given in [27]. In the present work, this model has been modified for deregulated scenario. The block diagram of the AGC scheme for i-th area of n areas power system is shown in Fig. 1. Gg and Gt represent the transfer functions model of governor and turbine respectively, and are expressed as, $G_g = \frac{1}{1+sT_G}$, and $G_t = \frac{1}{1+sT_T}$ where, T_G is the governor time constant and T_T is the turbine time constant. The transfer function of power system is represented by $\frac{K_{pi}}{1+sT_{pi}}$ where, K_{pi} and T_{pi} represent power system gain and power system time constant respectively. There may be m Gencos and l Discos in i-th area therefore the total change in generation of *area-i* is, $\Delta P_g = \Delta P_{g1} + \Delta P_{g2} + \cdots + \Delta P_{gk} + \cdots + \Delta P_{gm}$.

Similarly the net change in load demand of Discos can be written as, $\Delta P_L = \Delta P_{L1} + \Delta P_{L2} + \cdots + \Delta P_{Lp} + \cdots + \Delta P_{Ll}$. In a deregulated electricity market different transactions can take place such as poolco based transaction, bilateral transaction and the combination of these two transactions[26]. The term poolco means transactions governed by the ISO. Both the Genco and the Disco submit their bids to ISO, that clears the bids and provides regulation. In case of bilateral transaction the change in the tie-line power can be modified as

$$\Delta Ptie_{i\text{-}new} = \Delta Ptie_i + \sum_{\substack{j=1\\j\neq i}}^{m} D_{ij} - \sum_{\substack{j=1\\j\neq i}}^{m} D_{ji} \tag{1}$$

where D_{ij} is the demand of Disco in the *area-j* from the Genco in *area-i*, D_{ji} is the demand of Disco in the *area-i* from the Genco in *area-j*, $\Delta Ptie_i$ is change in tie-line power when no bilateral transaction is considered. The change in tie-line power error can be represented as

$$\Delta Ptie_{i\text{-}error} = \Delta Ptie_{i\text{-}actual} - \Delta Ptie_{i\text{-}new}. \tag{2}$$

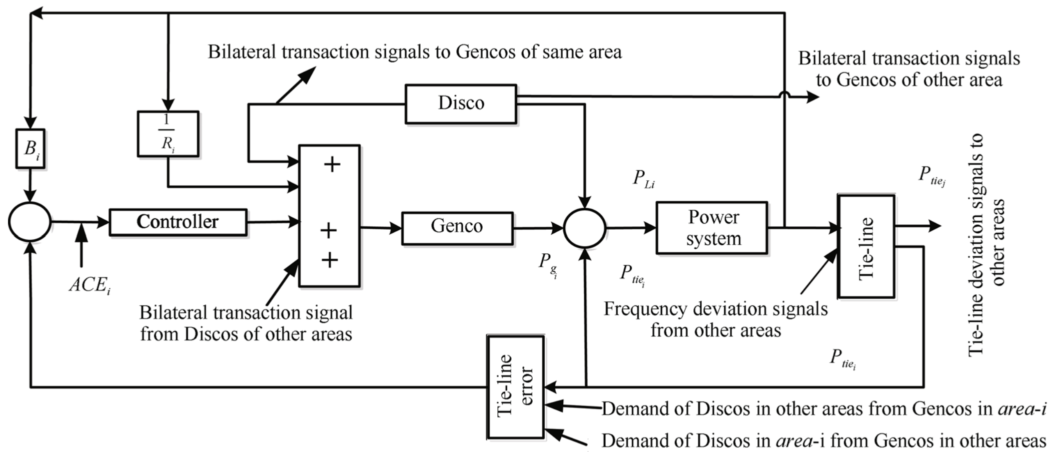

Fig. 1 AGC block diagram for *area-i*

Tie-line power and system frequency can be used to determine area control error (ACE), which can be written as

$$ACE_i = B_i \Delta f_i + \Delta Ptie_{i\text{-}error} \tag{3}$$

where B_i and Δf_i are the frequency bias factor and frequency deviation, respectively for i-th area. ACE in transient state varies as the deviations of frequency and tie-line power vary but when these both settle down ACE also settles down to zero (in steady state). Bilateral transaction can be implemented utilizing the Disco participation matrix (DPM)[25, 26].

3 FOPID controller design for multi-area AGC scheme

In this paper, FOPID and PID controllers have been used as supplementary controllers. Fractional order controllers use non integer differential and integral calculus and provide a larger range of control action which helps in designing a more effective controller[28−30]. The commonly used equations for non-integer order integral and derivative is given by Riemann-Liouville[14, 28−30]. The input output relation for FOPID can be written as[31, 32]

$$u(t) = K_P e(t) + K_I D^{-\lambda} e(t) + K_D D^{\mu} e(t) \tag{4}$$

where $e(t)$ and $u(t)$ are input and output and D represents $\frac{\mathrm{d}}{\mathrm{d}t}$. The transfer function of a FOPID controller can be expressed as

$$G_{FOPID}(s) = K_{P\_f} + \frac{K_{I\_f}}{s^{\lambda}} + K_{D\_f} s^{\mu} \tag{5}$$

where $K_{P\_f}, K_{I\_f}, K_{D\_f}$ are the proportional, integral and derivative gains of the FOPID controller, λ and μ are the non-integer order of integrator and differentiator respectively. For effective action of FOPID controller, its parameters should be determined optimally. In this paper BBBC algorithm is utilized to determine the optimal parameters of FOPID controller. Mean square of ACE is taken as the optimization function and formulated in the following manner: Minimize

$$F = \frac{1}{n} \sum_{i=1}^{n} (ACE_i)^2$$

or

$$F = \frac{1}{n} \sum_{i=1}^{n} (B_i \Delta f_i + \Delta Ptie_{i\text{-}error})^2. \tag{6}$$

Constraints,

$$\begin{aligned} K_{P\_f}^{\min} &\leq K_{P\_f} \leq K_{P\_f}^{\max} \\ K_{I\_f}^{\min} &\leq K_{I\_f} \leq K_{I\_f}^{\max} \\ K_{D\_f}^{\min} &\leq K_{D\_f} \leq K_{D\_f}^{\max} \\ \lambda^{\min} &\leq \lambda_i \leq \lambda^{\max} \\ \mu^{\min} &\leq \mu_i \leq \mu^{\max} \end{aligned} \tag{7}$$

where superscripts min and max indicate the lower bound and upper bound of the parameters of FOPID controller for i-th area. One FOPID controller is considered in each area:

$$G_{PID}(s) = K_{P\_c} + \frac{K_{I\_c}}{s} + K_{D\_c} s \tag{8}$$

where $K_{P\_c}, K_{I\_c}, K_{D\_c}$ represent proportional gain, integral gain and derivative gain of PID controller respectively. The same optimization problem given in (6) has been used to determine the parameters of PID controller with the constraints as follows:

$$\begin{aligned} K_{P\_c}^{\min} &\leq K_{P\_c} \leq K_{P\_c}^{\max} \\ K_{I\_c}^{\min} &\leq K_{I\_c} \leq K_{I\_c}^{\max} \\ K_{D\_c}^{\min} &\leq K_{D\_c} \leq K_{D\_c}^{\max} \end{aligned} \tag{9}$$

where superscripts min and max indicate the lower bound and upper bound of the parameters of PID controller for i-th area.

The main steps of BBBC search algorithm to design FOPID controller are given in following section.

3.1 Big Bang Big Crunch (BBBC) algorithm

BBBC optimization method is reported in [20], which has the advantage of high convergence speed, and low computational cost[20, 28]. BBBC has gained popularity among researchers due to its high speed and accuracy in finding solution of optimization problems. This algorithm is based on the formation of the universe stated by Big Bang theory which is given in [20, 21]. The major steps involved to determine the optimal FOPID parameters using BBBC algorithm are given below.

Step 1. For each area one FOPID controller is considered. For each controller, population for each parameter can be generated as

$$x_{ij}^{(k)} = x_{i(\min)}^{(k)} + \mathrm{rand}(x_{i(\max)}^{(k)} - x_{i(\min)}^{(k)}) \tag{10}$$

where $x = [K_P, K_I, K_D, \lambda, \mu]$ represents FOPID controller parameters, $k = 1, 2, 3, \cdots, n$, number of areas, $i = 1, 2, \cdots, q$, number of each controller parameters and $j = 1, 2, \cdots, p$ population size. $x_{i(\max)}$ and $x_{i(\min)}$ are upper and lower limits of i-th parameters. Therefore $(p \times (n \times q))$ is the total population size generated. This is called Big Bang phase.

Step 2. Determine the fitness function value F_j for $(j = 1, 2, \cdots, p)$ as given in (6) for each population.

Step 3. Compute of the center of mass on the basis of the current position of each parameter in population as given by (11) and the associated fitness function value:

$$X_{com} = \frac{\sum\limits_{j=1}^{p} \frac{x_{ij}^{(k)}}{F_j}}{\sum\limits_{j=1}^{p} \frac{1}{F_j}} \tag{11}$$

where X_{com} is the position vector of the center of mass.

Step 4. This step considers the generation of new population for each controller parameters in the vicinity of the center of mass using (12).

$$x^k_{ij(new)} = X_{com} + \frac{r \times \alpha(x^k_{i(\max)} - x^k_{i(\min)})}{K} \tag{12}$$

where α is the parameter that limits the size of the search space, r is the normal random number, and K is the iteration step.

Step 5. Determine the fitness function using newly generated parameters by (12) and compare it with the previous fitness function value. Finally the minimum fitness value will be retained and the parameters corresponding to the minimum fitness function will be chosen as the next parameters.

$$x^k_{ij}(next) = \min\{F(x^k_{ij}(previous)), F(x^k_{ij}(new))\}. \tag{13}$$

Step 6. Calculate the difference between the new and previous fitness value for all generations $e^k_{ij} = x^k_{ij}(new) - x^k_{ij}(previous)$ and if $e^k_{ij} < 10^{-6}$, stop, otherwise return to Step 2. This step gives the optimum fitness function which results the optimum parameters of the controllers. In this work, ACE minimization problem has been solved using BBBC algorithm, but for the comparative analysis the parameters of FOPID and PID have also been determined using imperialistic competition algorithm (ICA) and GA search algorithm for the same optimization problem.

4 Results and discussion

The performance of FOPID controller has been evaluated on two different systems. First system is a two area non-reheat thermal power system[25], while second system is a 75-bus Indian power system which is divided into four unequal areas in this work[26]. The parameters of BBBC, ICA and GA used in two area and four area power system are given in Tables 1 to 3.

Table 1 BBBC parameters

Parameters	2 area	4 area
Initial population	30	40
Number of variables	6 and 10	12 and 20
α	10	10

Table 2 ICA parameters

Parameters	2 area	4 area
Initial country	30	40
Number of variables	6 and 10	12 and 20
Assimilation coefficient	2	
Assimilation angle	0.5	
Number of decade	100	

Table 3 GA parameters

Parameters	2 area	4 area
Initial population	30	40
Number of variables	6 and 10	6 and 10
Elite count	2	2

4.1 Two area system

To check the performance of the FOPID controller, two area AGC scheme, shown in Fig. 1 has been considered. A deregulated scenario as described in Section 2 has also been considered for the simulation study in Matlab environment. Both the areas are assumed to be identical. The governor-turbine units in each area are also assumed to be identical. Two Gencos and two Discos are considered in each control area.

Fig. 2 compares the convergence rate of BBBC, ICA and GA for two area system. It is clear from Fig. 2 that the convergence of BBBC algorithm is faster than ICA and GA. BBBC algorithm converges and gives optimal parameters after 15 generations while ICA and GA converges after 45 and 60 generations.

The comparative analysis of these three algorithms for two area system is given in Table 4.

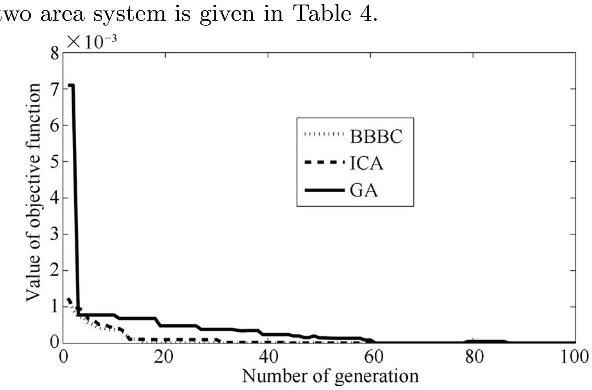

Fig. 2 Comparison of convergence characteristics of BBBC with ICA and GA

Table 4 Comparison of BBBC, ICA and GA algorithms

	2 area power system		
	GA	ICA	BBBC
Average fitness	3.802×10^{-4}	1.021×10^{-4}	$7.130\,9 \times 10^{-5}$
Worst fitness	0.006 814	0.001 246	0.001 232
Best fitness	$4.701\,3 \times 10^{-5}$	$1.901\,5 \times 10^{-6}$	1.402×10^{-6}
Standard deviation	0.000 989 68	0.000 231 96	0.000 206 44
Convergence of iteration	60	45	15

Based on convergence and statistical comparison of all the three algorithms, the parameters determined using BBBC algorithm have been used to design FOPID and PID controllers in two area power system case. The parameters of two area AGC scheme are given in Table 5.

Table 5 Two area power system parameters

Parameter	Symbol (unit)	Value
Governor time constant	T_{gi} (s)	0.08
Power system time constant	T_{pi} (s)	24
Power system gain constant	K_{pi}(Hz/pu MW)	120
Turbine time constant	T_{ti}(s)	0.3
Speed regulation	R_i	2.4
Frequency bias constant	B_i	0.425
Synchronizing constant	T_{ij}	0.545

The controller parameters have been determined under the following conditions.

1) No contract has been considered.

2) Only generators are responding to the loads.

3) 0.2 pu load change has been considered in each area.

The optimal parameters of FOPID and PID controller, determined using BBBC are given in Table 6.

Table 6 Optimum values for FOPID and PID controllers

	PID			FOPID				
	K_P	K_I	K_D	K_P	K_I	K_D	λ	μ
area-1	−3.61	−2.79	−4.29	−1	−0.002 6	−1	1.8	1.4
area-2	−1.98	−1.995	−3.985	−1	−0.002 6	−1	1.8	1.4

In two area system, a load demand change of 0.2 pu in *area*-1 (0.1 pu in Disco_{11} and 0.1 pu in Disco_{12}), and 0.2 pu in *area*-2 (0.1 pu in Disco_{21} and 0.1 pu in Disco_{22}) has been considered. The bilateral contracts have been implemented using the given DPM. The elements of DPM are known as contract participation factors (cpf) and given as

$$DPM = \begin{bmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 0.25 & 0 & 0 \end{bmatrix}.$$

At $t = 0$, the demand change takes place in form of a step in each Discos of *area*-1 and *area*-2. At steady state, change in the generation of all Gencos must match the Discos demand. The desired generation of a Genco (in pu) can be expressed in terms of contract participation factors and the total demand of Discos. The change in the generation of the i-th Genco can be expressed as

$$\Delta P_{Gi} = \sum_j cpf_{ij} \Delta P_{Lj} \tag{14}$$

where ΔP_{Gi} and ΔP_{Lj} are the changes in generation of i-th Genco and the total load demand of j-th Disco respectively. cpf_{ij} is the contract participation factor of i-th Genco and j-th Disco. For the case under consideration (14) can be represented as

$$\Delta P_{Gi} = cpf_{i1}\Delta P_{L1} + cpf_{i2}\Delta P_{L2} + cpf_{i3}\Delta P_{L3} + cpf_{i4}\Delta P_{L4}. \tag{15}$$

Therefore, the net change in generation using (15), can be determined as

$\Delta P_{G11} = 0.5(0.1) + 0.25(0.1) + 0 + 0.3(0.1) = 0.105$ pu

$\Delta P_{G12} = 0.045$ pu (*area*-1)

$\Delta P_{G21} = 0.195$ pu

$\Delta P_{G22} = 0.055$ pu (*area*-2).

The change in the tie-line power of the two area system is determined by (16) which should be settled at −0.05 pu at steady state.

$$\Delta Ptie_{i-new} = \sum_{i=1}^{2}\sum_{j=3}^{4} cpf_{ij}\Delta P_{Lj} - \sum_{i=3}^{4}\sum_{j=1}^{2} cpf_{ij}\Delta P_{Lj}. \tag{16}$$

The frequency deviations in *area*-1 and *area*-2 are given in Fig. 3. The change in the tie-line power is shown in Fig. 4. The change in the generation of different Gencos in *area*-1 and *area*-2 are shown in Fig. 5. It is seen that change in generation of *area*-1 and *area*-2 settles down to the desired value at steady state.

It is clear from the obtained results that the frequency and tie-line power settle more quickly with FOPID controller than PID controller. The performance parameters, namely maximum undershoot and settling time for frequency deviations are given in Table 7 which show that the undershoots and settling time are smaller in case of FOPID controllers.

Table 7 Performance parameters for frequency deviations: (Two area system)

	area-1		*area*-2	
	PID	FOPID	PID	FOPID
Max. undershoot	−0.101 4	−0.073	−0.012 3	−0.012
Settling time (s)	15	6	16	8

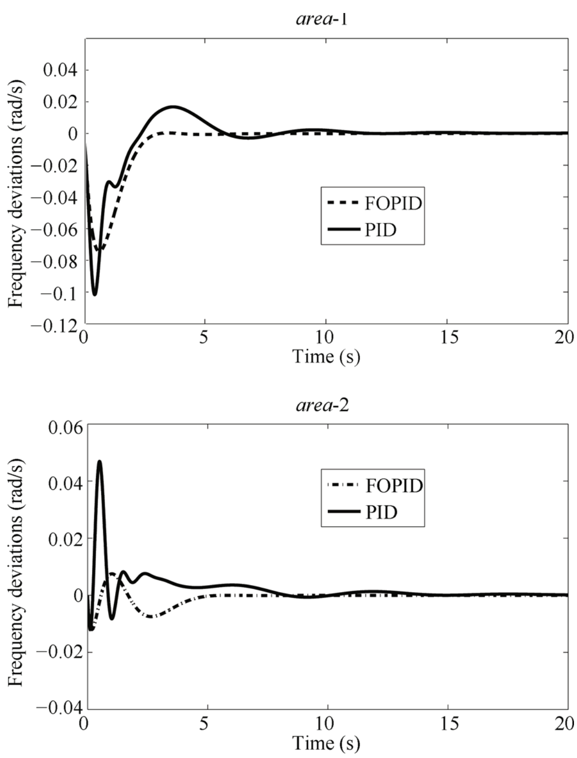

Fig. 3 Frequency deviations (rad/s)

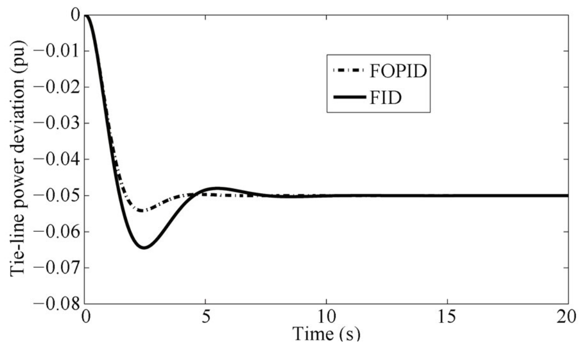

Fig. 4 Tie-line power (pu)

4.2 Four area system

The FOPID controller for a multi area power system has also been tested on 75-bus Indian power system which is divided into four control areas[26]. Control *area*-1 is of 460 MW rating, having 3 Gencos (G1, G2, G3) and 3 Discos (D1, D2, D3). Control *area*-2 is of 994 MW rating, having 5 Gencos (G4, G5, G6, G7, G8) and 3 Discos (D4, D5, D6). Control *area*-3 is of 400 MW rating, having 2 Gencos (G9, G10) and 3 Discos (D7, D8, D9), and control *area*-4 is of 4 470 MW rating, having 5 Gencos (G11, G12, G13, G14, G15) and 3 Discos (D10, D11, D12). Fig. 6 shows the convergence curve of BBBC, ICA and GA algorithms for four area system. Table 8 determines the performance parameters of BBBC, ICA and GA search algorithms for four area power system.

Price and capacity of different Gencos and Discos for 75-bus system are given in Table 9.

Consider a change in load demand of *area*-1 by 50 MW, *area*-2 by 50 MW, *area*-3 by 50 MW, and *area*-4 by 100 MW. Different bilateral transactions considered are given below,

1) Genco 5 (G5) of *area*-2 provided 10 % of *area*-1 load demand and 10 % of *area*-4 load demand.

2) No bilateral transaction in *area*-3.

3) 20 % of *area*-4 load is provided by $G12$ of *area*-4 itself.

4) 20 % of *area*-2 load is provided by $G11$ of *area*-4 and 10 % by $G4$ of *area*-2 itself.

Table 8 Comparison of BBBC, ICA and GA algorithms

	4 area power system		
	GA	ICA	BBBC
Average fitness	9.978×10^{-4}	4.488×10^{-4}	2.682×10^{-5}
Worst fitness	0.007 104	0.010 935	0.010 434
Best fitness	8.724×10^{-5}	6.152×10^{-6}	5.153×10^{-6}
Standard deviation	0.002 301	0.001 885	0.001 457 8
Convergence of iteration	80	65	35

The changes in load demand are met according to their bilateral and poolco transactions. After meeting out all the load demands Gencos will increase their power and Discos will reduce their power. The various responses obtained using FOPID and PID controller have been compared to show the effectiveness of the FOPID controller in AGC scheme.

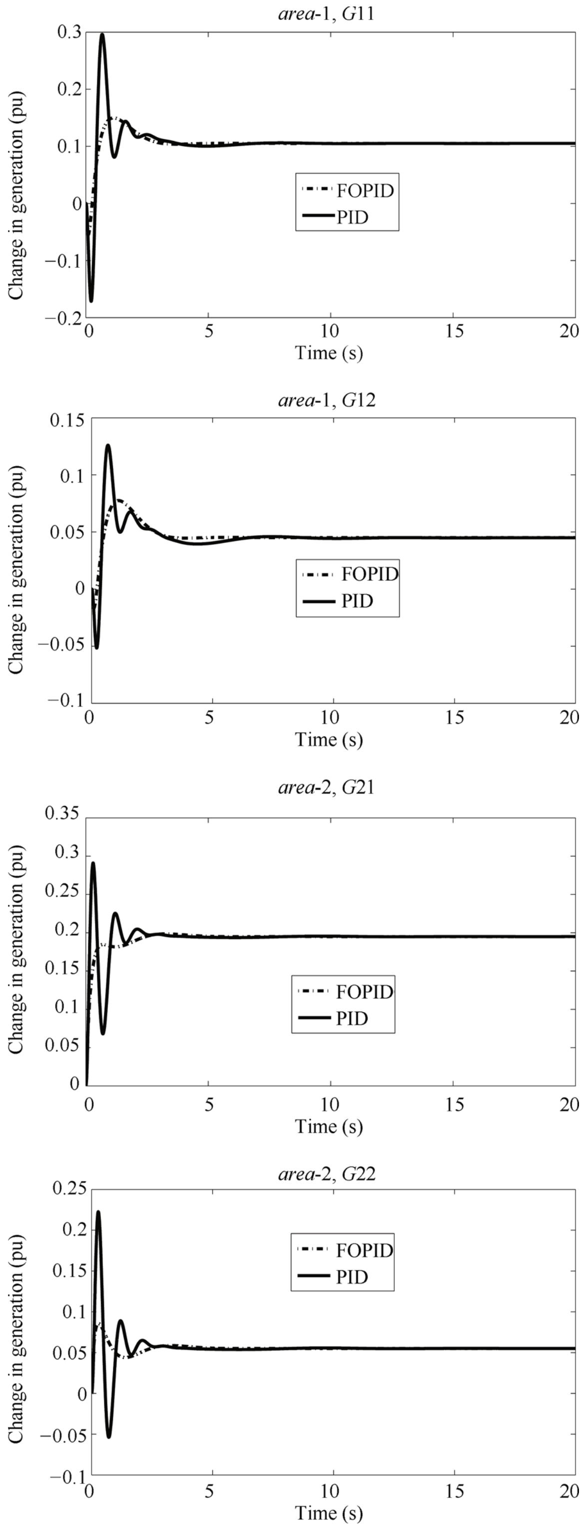

Fig. 5 Generated power (pu)

The frequency deviations in *area*-1 and *area*-4 are shown in Fig. 7. Since ISO sends the signal directly to Discos and not through the controller the responses of Discos are similar with FOPID, and PID controller as shown in Fig. 8.

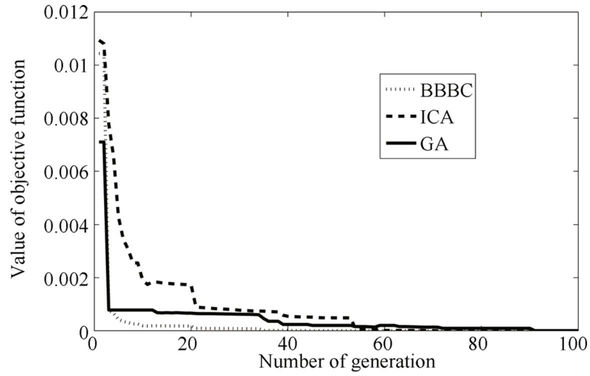

Fig. 6 Comparison of BBBC, ICA and GA algorithms

Table 9 Gencos and Discos bids in *area*-1 to *area*-4

	Gencos/Discos	Price (Rs./KWh)	Capacity (MW)
area-1	$G1/G2/G3$	5.7/5.5/6.0	15/30/30
	$D1/D2/D3$	5.6/6.1/6.8	10/5/5
area-2	$G4/G5/G6/$	6.0/6.4/5.6/	25/40/20/
	$G7/G8$	7.0/5.4	30/25
	$D4/D5/D6$	6.5/5.5/6.1	5/5/10
area-3	$G9/G10$	4.5/4.2	25/35
	$D7/D8/D9$	5/5.5/5.8	5/5/5
area-4	$G11/G12/G13/$	4.2/7.4/4.8/	25/25/50/
	$G14/G15$	6.2/4.5	30/25
	$D10/D11/D12$	5.4/4.6/5.5	5/10/5

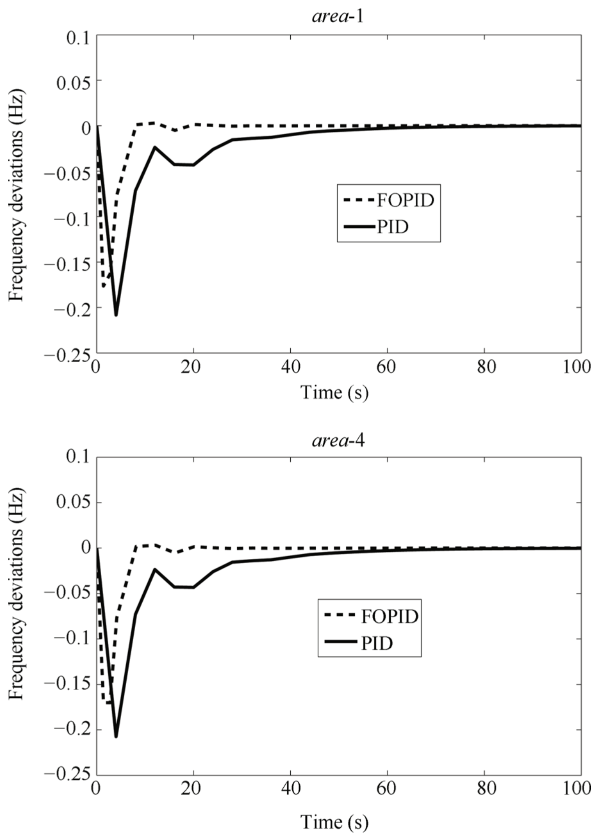

Fig. 7 Frequency deviation (Hz)

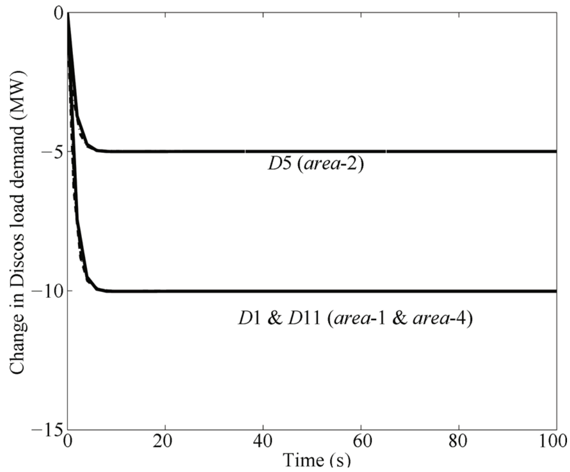

Fig. 8 Change in Discos load (MW)

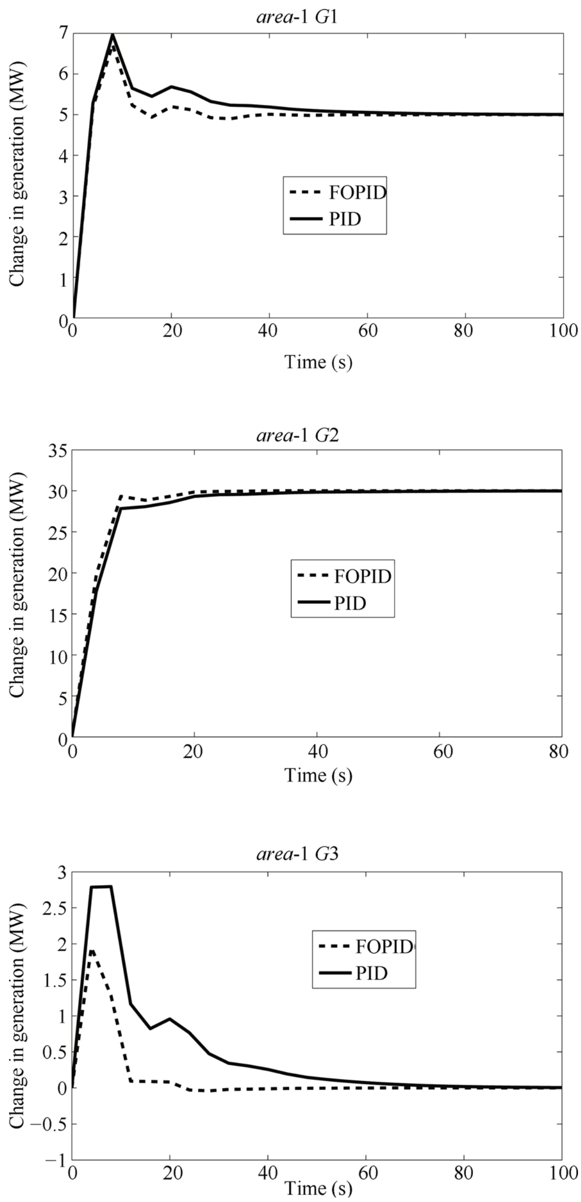

Fig. 9 Change in generation in Gencos in *area*-1

The change in generation of *area*-1 Gencos ($G1$, $G2$ and $G3$) is shown in Fig. 9. Due to bilateral transactions, excess power of 5 MW flows from *area*-2 to *area*-1 as shown in Fig. 10. Tie-line power deviations in *area*-3 and *area*-4 settle down to zero as shown in Fig. 11. Results have also been obtained for frequency deviations, change in the generation and tie-line power deviations for other areas, but not shown in this paper. The given results show that the frequency deviations become zero at their steady state and all Gencos and Discos change their power according to the poolco and bilateral transactions.

The performance evaluated by maximum undershoots and settling time of FOPID and PID controllers are compared in Table 10. It is clear from these results that the FOPID controller reduces the undershoot and settling time effectively in four area power system case too.

Table 10 Performance parameters for frequency deviations: (Four area system)

	area-1		*area*-4	
	PID	FOPID	PID	FOPID
Max. undershoot	−0.233 7	−0.176 4	−0.193 9	−0.17
Settling time (s)	65	40	55	40

After all the demand settlement (using poolco and bilateral transactions), the net power of Gencos and Discos in all areas can be written as given in Table 11. The optimal parameters obtained for FOPID and PID controller are given in Table 12.

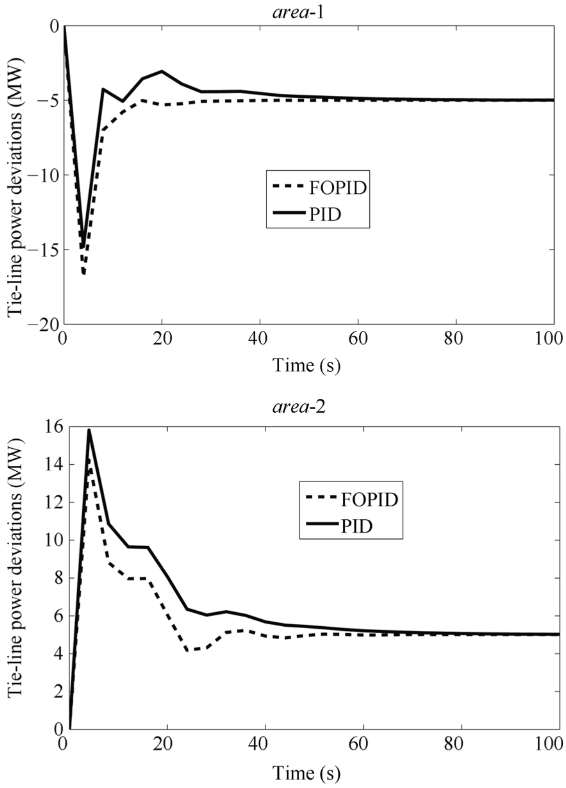

Fig. 10 Change in tie-line power flow (*area*-1, *area*-2)

Table 11 Different transaction in different areas

Areas	Bilateral transaction	Poolco transaction	Total change in power
area-1	10% of load i.e., 5 MW by $G5$	$G2$ increases power by 30 MW	
		$D1$ reduces its power by 10 MW	50 MW
		$G1$ increases its power by 5 MW	
area-2	20% of load i.e., 10 MW by $G11$	$G8$ increases power by 25 MW	
	10 % of load i.e., 5 MW by $G4$	$D5$ reduces its power by 5 MW	50 MW
		$G6$ increases its power by 5 MW	
area-3	none	$G10$ increases power by 35 MW	
		$G9$ increases its power by 15 MW	50 MW
		$G11$ increases its power by 25 MW	
area-4	10% of load i.e., 10 MW by $G5$	$G15$ increases power by 25 MW	
	20 % of load i.e., 20 MW by $G12$	$D11$ reduces its power by 10 MW	100 MW
		$G13$ increases its power by 10 MW	

Table 12 Optimum value for FOPID and PID controllers

	PID			FOPID				
Mixed transactions	KP	KI	KD	KP	KI	KD	λ	μ
area-1	−0.754 7	−0.499 4	0.044 8	−1.789	−1.578	2.984	1.155	0.047
area-2	0.339 7	−3	−0.015 1	−5.746	−1.287	−1.534	0.98	1.168
area-3	−1.019 7	−2.999 6	−0.095 7	−9.935	−2.957	−6.203	0.514	1.466
area-4	−0.228 6	−0.532 3	−0.623 8	−0.42	−1.363	0.326	1.484	1.578

5 Conclusions

In this paper, FOPID controller has been proposed for the deregulated multiarea AGC scheme. The BBBC algorithm has been used to determine the optimal parameters of the FOPID controller. The convergence of the BBBC algorithm is faster compared to other search algorithms like ICA and GA. The use of the FOPID controller provides larger control range compared to PID controller. The proposed FOPID controller has been tested on two area and four area power systems. The results of FOPID controller have been compared with the results of PID controller. The results show that FOPID controller has better performance and it improves system responses more effectively compared to PID controller.

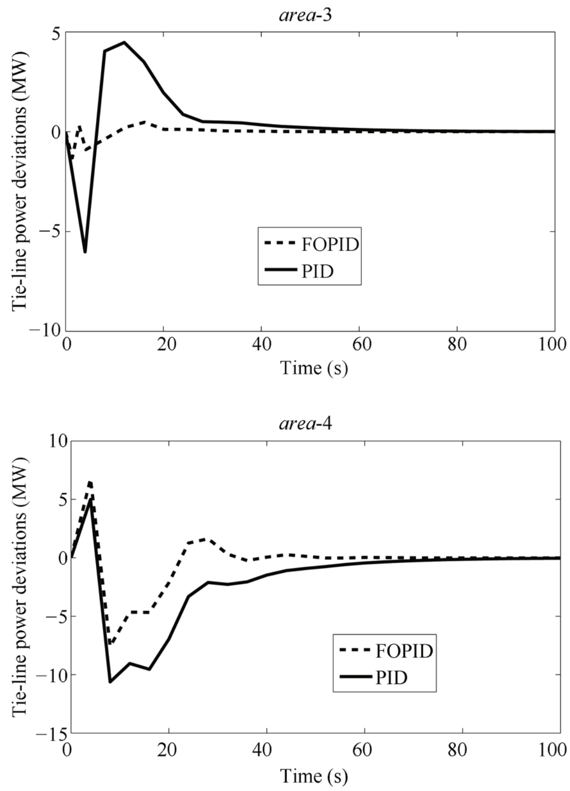

Fig. 11 Change in tie-line power flow (*area*-3, *area*-4)

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