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Optimization of PID parameters using BBBC for a multiarea AGC scheme in a deregulated power system

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Abstract: Automatic generation control (AGC) is an important service used for the secure and reliable operation of a power system. In this paper, a suitable AGC scheme for a deregulated environment has been studied for various load perturbation scenarios. A proportional integral derivative (PID) controller has been utilized to control the real power output of the generators. The optimal parameters of the PID controller have been determined using the big bang big crunch (BBBC) algorithm, (BBBC–PID). The performance of the BBBC–PID controller has been checked on three different sized multiarea power systems. The results obtained with the applied algorithm have also been compared with the results of other algorithms, namely imperialistic competition algorithm (ICA) and harmony search (HS). MATLAB/Simulink was used as a simulation tool for this study. The results show the superiority of the BBBC–PID over the others.

Key words: Automatic generation control, deregulation, big bang big crunch algorithm, PID controller, optimization

1. Introduction

The power system is being restructured from a vertically integrated structure into the open market system, which consists of separate entities such as Gencos (generation companies), Transcos (transmission companies), Discos (distribution companies), and ISOs (independent system operators). An ISO is an independent agent that supervises all the transactions held between Discos and Gencos. A Disco participation matrix (DPM) is used for visualization of contracts between Gencos and Discos [1]. An ISO has to perform various ancillary services for successful operation of the power system [2]. Automatic generation control (AGC) is one of the most important ancillary services. AGC is used to provide balance between generation and load demand of each area and maintain the frequency and tie-line power flow within specified limits. A detailed discussion on load frequency control issues in power system operation after deregulation is reported in [3]. Controllers play an important role in the frequency control scheme. Many control strategies have been reported in the literature in the field of AGC. Proportional integral derivative (PID) controllers are widely used to control the frequency and tie-line power because of low cost, ease of use, and robustness. Many approaches such as genetic algorithm (GA) and particle swarm optimization (PSO) have been proposed to determine the parameters of a PID controller to solve the AGC problem [4–6]. A review of various control approaches along with their advantages and limitations is given in [7].

Big bang big crunch is an optimization algorithm based on the big bang theory and big crunch theory [8].

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This paper proposes the determination of optimal values of the parameters of a PID controller for a multiarea AGC scheme in a deregulated environment using the BBBC algorithm (BBBC–PID). The minimization of mean square of area control error (ACE) is taken as an objective function. The BBBC–PID controller with optimal parameters is tested on two-area and three-area power systems [1,9]. Further the performance of the controller has also been tested on 75-bus Indian power system [10] divided into four areas of different ratings. The optimal parameters of the PID controller have also been determined using the imperialistic competition algorithm (ICA–PID) and harmony search algorithm (HS–PID). A comparative study has been carried out among the results obtained with BBBC–PID, ICA–PID, and HS–PID. The study shows that the BBBC–PID controller performs better than the others.

2. Modeling of multiarea AGC scheme

Frequency deviations occur due to mismatch between real power generation and load demand. In power systems, ACE is given as the combination of frequency deviation and the deviation of net power interchange from scheduled values [11]. For satisfactory operation of a power system, it is desirable to have frequency and tie-line power as per their scheduled values.

In a deregulated environment Gencos sell power to various Discos based on the economic criteria through poolco or mixed type transactions [10]. The distribution of ACE among Gencos is proportional to their participation in the AGC to achieve desired generation as per DPM. Coefficients that distribute ACE to several Gencos are known as ACE participation factors (αpf). Elements of DPM and p.u. MW load of a Disco forms demand signals that carry information about the Disco–Genco contract. If P_{ij} is the tie-line power flow from area–i to area–j and k is the total number of areas, the net tie-line power flow from area–i ($Ptie_i$) in a conventional power system can be written as

$$Ptie_i = \sum_{\substack{j=1 \\ j \neq i}}^{k} P_{ij} \tag{1}$$

In a deregulated scenario, tie-line power modifies due to various transactions [10]. The net scheduled tie-line power flow from area–i can be determined as

$$\Delta Ptie_i\_schd = \Delta Ptie_i + \sum_{\substack{j=1 \\ j \neq i}}^{k} Dij - \sum_{\substack{j=1 \\ j \neq i}}^{k} Dji, \tag{2}$$

where Dji is the demand of the Disco in area–i from the Genco in area–j, and Dij is the demand of the Disco in area–j from the Genco in area–i. The tie-line power error can be determined as given in Eq. (3),

$$\Delta Ptie_i\_error = \Delta Ptie_i\_actual - \Delta Ptie_i\_schd \tag{3}$$

Eq. (3) is used to generate ACE. ACE for area–i can be represented as

$$ACE_i = B_i \Delta F_i + \Delta Ptie_i\_error, \tag{4}$$

where B_i is frequency bias factor and ΔF_i is frequency deviation in area–i. There may be a number of Gencos and Discos in area–i. The block diagram of the kth Genco in area–i is shown in Figure 1. In Figure 1, pf is the Genco participation factor and R_i is the droop. G_g and G_t represent the transfer function model of the governor and turbine respectively, and are expressed as $G_g = \frac{1}{1+sT_G}$, where T_G is the governor time constant and $G_t = \frac{1}{1+sT_T}$, where T_T is the turbine time constant. The change in the total generation of area–i is ΔP_{gi}. Figure 2 represents the complete block diagram of the AGC scheme for area–i. In Figure 2, the power system block represents the power system dynamics given by $\frac{K_{pi}}{1+sT_{pi}}$, where K_{pi} is the system gain and T_{pi} is the time constant. ΔP_{Li} is change in the total load demand of the area–i.

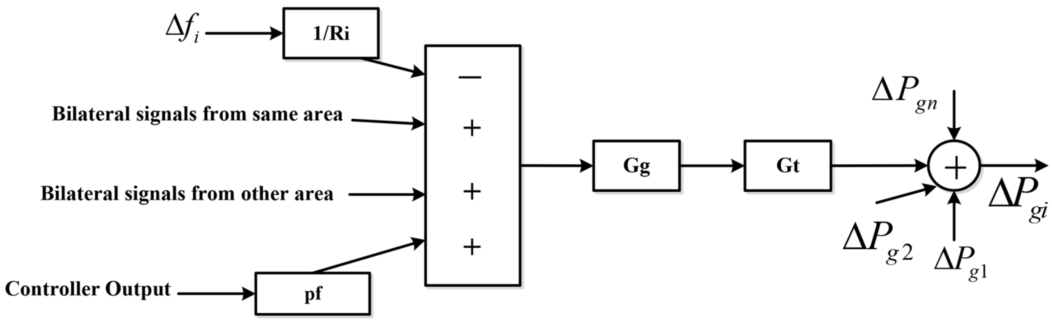

Figure 1. Block diagram of Genco–k of area–i.

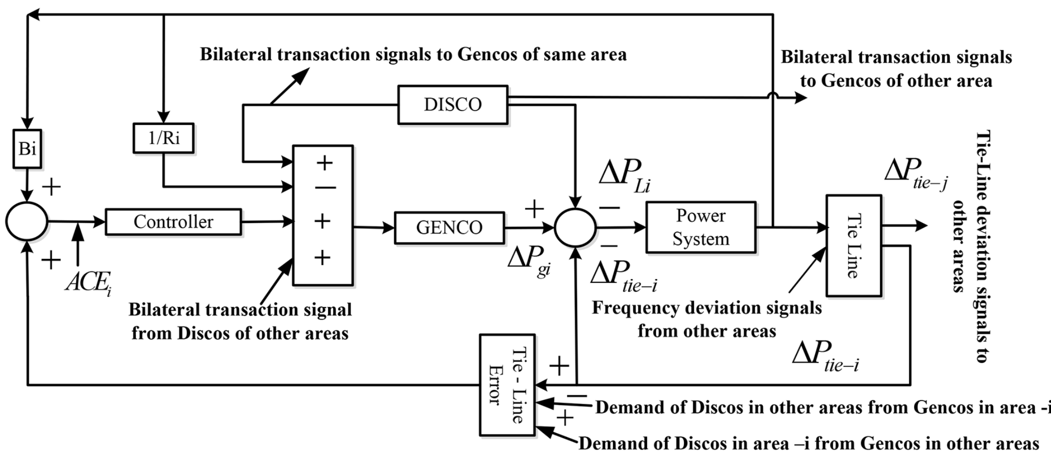

Figure 2. AGC block diagram for area–i.

3. AGC using a PID controller

In this paper, a PID controller has been used as an AGC controller. The transfer function of a PID controller can be expressed as

$$G_{PID}(s) = K_P + \frac{K_I}{s} + K_D s, \tag{5}$$

where K_P, K_I, and K_D are the proportional, integral, and derivative parameters of the controller. For the best performance of the system these parameters should be determined optimally. Here, the BBBC search algorithm is utilized to determine the optimal parameters of PID controllers with the objective to minimize mean square of area control error, which can be formulated in the following manner:

$$J = \frac{1}{k} \sum_{i=1}^{k} [(ACE_i)^2], \tag{6}$$

where k is the total number of areas in the system and J is the mean square of area control error. The optimization problem can be stated as minimizing J under the following constraints:

$$\begin{array}{l} K_{P,i}^{\min} \leq K_{P,i} \leq K_{P,i}^{\max} \\ K_{I,i}^{\min} \leq K_{I,i} \leq K_{I,i}^{\max} \\ K_{D,i}^{\min} \leq K_{D,i} \leq K_{D,i}^{\max} \end{array}, \quad (7)$$

where $K_{P,i}$, $K_{I,i}$, and $K_{D,i}$, are the proportional, integral, and derivative parameters of the PID controller of area–i. $K_{P,i}^{\min}, K_{I,i}^{\min}, K_{D,i}^{\min}$ and $K_{P,i}^{\max}, K_{I,i}^{\max}$, and $K_{D,i}^{\max}$ are the lower bounds and upper bounds of the PID controller. The ACE minimization for optimal values of PID controller coefficients has been solved using the BBBC search algorithm. The performance of the applied algorithm has also been compared with other search algorithms, i.e. ICA and HS. The search algorithms used are explained in the following section.

4. Evolutionary techniques employed

4.1. Big bang big crunch (BBBC)

Optimization is the process of making something best under the given constraints. The literature reveals many search algorithms applied for the solution of optimization problems. A recent evolutionary technique, called the big bang big crunch optimization search algorithm, has been reported in [12]; it can easily solve the optimization problem with fast convergence. The algorithm is inspired by the big bang theory. The BBBC algorithm produces random points in the search space and shrinks those points to a single solution point [13]. The algorithm is explained stepwise in the succeeding subsections.

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

$$x_{ij}^{(k)} = x_{i(\min)}^{(k)} + rand \times (x_{i(\max)}^{(k)} - x_{i(\min)}^{(k)}), \quad (8)$$

where $x = [K_P, K_I, K_D]$, represents the PID controller parameters. $k = 1, 2, 3, ...L$, represents the total number of areas. $i = 1, 2, ...q$, shows the number of each controller parameter. $j = 1, 2, ...p$, determines the population size. $x_{i(\min)}$ and $x_{i(\max)}$ are the upper and lower limit of ith parameters. This is called the big bang phase.

Step 2: Determine the objective function value as given in Eq. (6) for each population.

Step 3: This step determines the computation of the center of mass on the basis of the current position of each parameter in the population and the associated fitness function value as given by Eq. (9) (big crunch phase).

$$X_{com} = \frac{\sum_{j=1}^{p} \frac{x_{ij}^{(k)}}{F_j}}{\sum_{j=1}^{p} \frac{1}{F_j}}, \quad (9)$$

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

Step 4: This step considers the generation of a new population for each controller parameter in the vicinity of the center of mass using Eq. (10).

$$x_{ij(new)}^{k} = \beta X_{com} + (1-\beta) x_{best} + \frac{rand \times \alpha (x_{i(\max)}^{k} - x_{i(\min)}^{k})}{iteration}, \quad (10)$$

where α is the parameter limiting size of the search space and β is the parameter controlling the influence of global best solution x_{best} on the location of the new candidate solution.

Step 5: This step considers the calculation of the fitness function of these newly generated parameters and compares 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.

$$x_{ij}^{k}(next) = \min\left\{F(x_{ij}^{k}(previous)), F(x_{ij}^{k}(new))\right\} \tag{11}$$

Step 6: Calculate the difference between the new and previous fitness value for all generations $e_{ij}^{k} = x_{ij}^{k}(new) - x_{ij}^{k}(previous)$ and if $e_{ij}^{k} < 10^{-4}$ stop, otherwise return to step 2. This step gives the optimum fitness function which results the optimum parameters of the controllers.

5. Imperialist competition algorithm (ICA)

The ICA was proposed by Atasphaz-Gargari and Lucas [14]. The ICA simulates the social and political process of imperialism and imperialistic competition. Similar to the other evolutionary algorithms, this algorithm also starts with an initial population. The ICA starts with some initial population called country. Countries are divided into two types, colonies and imperialist states. The imperialist states together with their colonies form some empires. Imperialistic competition among all the empires forms the basis of the ICA. During the competition, weak empires collapse and powerful ones take possession of their colonies. At last, there exists just one empire and all the other countries are colonies of that empire [15].

6. Harmony search (HS)

HS has been proposed by Geem et al. [16]. HS is based on natural music performance processes that occur when a musician searches for a better state of harmony. In HS, harmony memory, pitch adjusting, and randomization are the three main components. In order to use this memory more effectively, harmony memory accepting or considering rate is used. The second component is the pitch adjustment determined by a pitch bandwidth and a pitch adjusting rate. Pitch adjustment is used to generate a slightly different solution in the HS. The third component is randomization, which increases the diversity of the solutions. The use of randomization can drive the system further to explore various diverse solutions so as to find the global optimality [17].

7. Results and discussion

The performance of the proposed BBBC–PID controller has been checked on two-area, three-area, and four-area deregulated power systems. The simulation for all the cases has been performed in MATLAB/Simulink R2011b environment on a personal computer with a Core i3 processor – 2350M 2.30 GHz, 4 GB DDR2 RAM.

8. Two-area system

The performance of the PID controller has been checked on a two-area power system. The parametric values of the two-area AGC scheme are given in Table 1. The applied values of the parameters of the ICA, HS, and BBBC are given in Tables 2–4, respectively. The optimal values of parameters of the PID controller determined using the BBBC, ICA, and HS are given in Table 5.

A step change of 0.2 p.u. in load demand has been considered in area–1 (0.1 p.u. in Disco_{11} and 0.1 p.u. in Disco_{12}), and a similar change of 0.2 p.u. load demand has been considered in area–2 (0.1 p.u.

in Disco_{21} and 0.1 p.u. in Disco_{22}). Area control error participation factors of each Genco are taken as $\alpha pf_{11} = 0.75, \alpha pf_{12} = 0.25, \alpha pf_{21} = 0.5$, and $\alpha pf_{22} = 0.5$. All Discos have contract with Gencos for power as per the following DPM:

Table 1. Two-area power system parameters.

Parameters, symbols (units)	Value
Governor time constant, $Tg_i(s)$	0.08
Power system time constant, $Tp_i(s)$	24
Power system gain constant, $Kp_i\,(Hz/p.u.MW)$	120
Turbine time constant, $Tt_i\,(s)$	0.3
Speed regulation, R_i	2.4
Frequency bias constant, B_i	0.425
Synchronizing constant, Ti_j	0.0707

Table 2. ICA parameters.

Parameters	Value
Number of countries	30
Number of decades	100
Number of initial imperialist	2
Assimilation coefficient	2
Assimilation angle coefficient (γ)	0.5

Table 3. HS parameters.

Parameters	Value
Size of harmony memory	30
Harmony consideration rate	0.9
Pitch adjusting rate	[0.4–0.9]
Bandwidth	[0.0001–1]
Number of variable	3

Table 4. BBBC parameters.

Parameters	Value
Initial population	30
Number of variables	3
β	0.5
α	0.1

Table 5. Optimum values for PID controllers.

	K_P	K_I	K_D
BBBC	–2	–1.1537	–2
ICA	–1	–0.6597	–1
HS	–0.9153	–0.3234	–0.9252

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

It is assumed that the change in load demand in different areas occurs at t = 0. The frequency deviation in area–1 and area–2 is shown in Figure 3a. It is seen that the deviation of frequency of area–1 and area–2 settles down to zero at steady state. The change in the tie-line power is determined by the following expression:

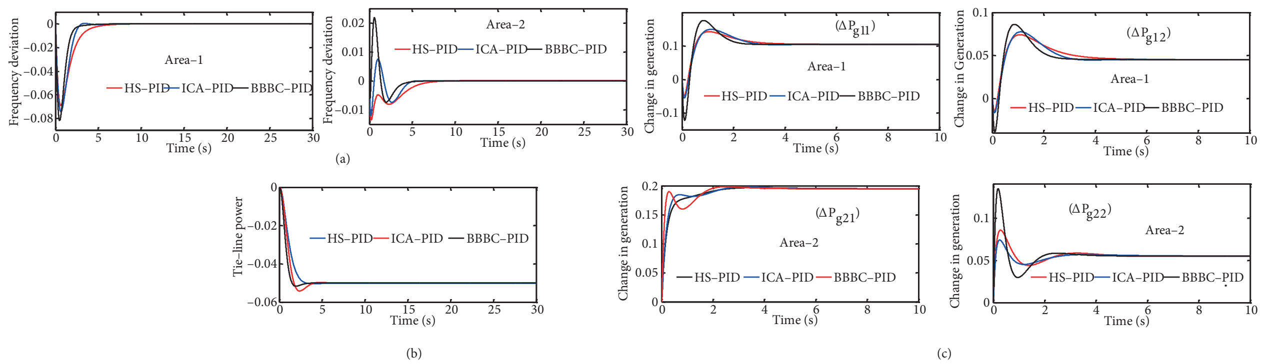

Figure 3. (a) Frequency deviations (rad/s), (b) Tie-line power (p.u.), (c) Generated power (p.u.) (two-area power system).

$$\Delta P_{tie1-2,scheduled} = \sum_{i=1}^{2}\sum_{j=3}^{4} cpf_{ij}\Delta PL_j - \sum_{i=3}^{4}\sum_{j=1}^{2} cpf_{ij}\Delta PL_j = -0.05p.u. \tag{12}$$

Tie-line power settles to –0.05 p.u., which is the change in the scheduled power on the tie-line as shown in Figure 3b. Change in the generation of all Gencos must match the additional demand of Discos at steady state. This desired generation of a Genco in p.u. can be expressed in terms of the total demand of Discos and contract participation factors (cpf) as shown in Eq. (13).

$$\Delta P_{gi} = \sum_{j} cpf_{i_j}\Delta P_{Lj}, \tag{13}$$

where ΔP_{Lj} is the total load demand of the jth Disco. For the case under consideration, the change in generation of the Gencos of area–1 can be written as $\Delta P_{g11} = 0.5(0.1) + 0.25(0.1) + 0 + 0.3(0.1) = 0.105$ p.u. and $\Delta P_{g12} = 0.045$ p.u. Similarly, the required change in generation of the area–2 Gencos is $\Delta P_{g21} = 0.195$ p.u. and $\Delta P_{g22} = 0.055$ p.u. The change in generation is shown in Figure 3c. The performance of controllers has been compared in terms of settling time as given in Table 6. It is evident from Table 6 that the BBBC–PID controller provides better settling performance than ICA–PID and HS–PID.

Table 6. Comparative study of settling time (s).

	Controller	Settling time		
		Δf_1 (s)	Δf_2 (s)	ΔP_{tie} (s)
Two area	BBBC–PID	5.3	5.3	5.5
	ICA–PID	6	5.8	7
	HS–PID	11.5	12.5	11.5

9. Three-area system

Performance of the BBBC–PID controller has also been checked on a three-area AGC scheme with a generation rate constraint (GRC) of 3% per minute. The three-area AGC scheme consists of two Discos and two Gencos in area–1, and one Disco and one Genco in area–2 and area–3 each. The considered parameters of ICA, HS, and BBBC are the same as given in Tables 2–4. The parameters of the three-area system used for the illustration are given in Table 7. The optimal values of parameters determined for the PID controller using the BBBC, ICA, and HS are given in Table 8.

Table 7. Three-area power system parameters.

Parameters, symbols (Units)	Value
Governor time constant, $Tg_i(s)$	0.08
Power system time constant, $Tp_i(s)$	20
Power system gain constant, $Kp_i\ (Hz/p.u.MW)$	120
Turbine time constant, $Tt_i\ (s)$	0.3
Speed regulation, R_i	2.4
Frequency bias constant, B_i	0.425
Synchronizing constant, Ti_j	0.545
Reheat turbine time constant, $Tr_i(s)$	10

Table 8. Optimum values for PID controllers.

	K_P	K_I	K_D
BBBC	1.4043	0.2468	0.14137
ICA	1.5932	0.3042	0.1804
HS	1.6980	0.4937	0.4150

In the case considered, the Disco's power demand is increased by 0.01 p.u. in each area. The contract participation factors for power transaction are given in the following DPM:

$$DPM = \begin{pmatrix} 0.4 & 0.3 & 0.1 & 0.2 \\ 0.2 & 0.2 & 0.3 & 0.3 \\ 0.1 & 0.3 & 0.4 & 0.2 \\ 0.3 & 0.2 & 0.2 & 0.3 \end{pmatrix}$$

The ACE participation factors in each area are taken as $\alpha pf = 0.5$. At steady state Gencos must generate real power as given in Eq. (13). To fulfill the additional demand the change in generation in each area is given by $\Delta P_g = 0.01$ p.u. (area–1), $\Delta P_g = 0.01$ p.u. (area–2), and $\Delta P_g = 0.01$ p.u. (area–3). The change in tie-line power is $\Delta P_{tie_{1-2}} = \Delta P_{tie_{2-3}} = \Delta P_{tie_{1-3}} = 0.0$ p.u. The comparison of dynamic responses of frequency deviation and change in generation using BBBC–PID, ICA–PID, and HS–PID are shown in Figures 4a and 4b, respectively. It is clearly seen that the responses with the BBBC–PID controller are much more effective and superior to those ICA–PID and HS–PID controllers in terms of settling time and oscillations.

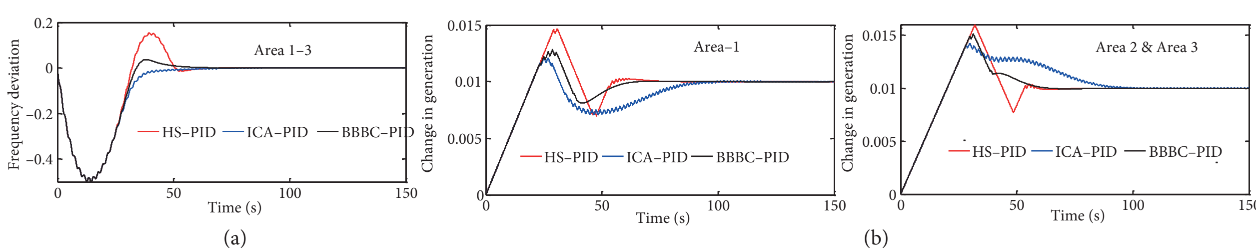

Figure 4. (a) Frequency deviations (rad/s), (b) Generated power (p.u.) (three-area power system).

In all cases change in generations and frequency deviations are stabilized at steady state and the dynamic responses obtained with ICA–PID and HS–PID controllers are more oscillatory and take a longer settling time. Table 9 shows that the BBBC–PID controller provides better settling performance than ICA–PID and HS–PID.

Table 9. Comparative study of settling time (s).

	Controller	Settling time (s)		
		Δf	ΔP_g (area–1)	ΔP_g (area–2–3)
Three area	BBBC–PID	82	90	90
	ICA–PID	110	120	135
	HS–PID	90	105	95

10. Four-area system

The performance of the proposed BBBC–PID controller has been tested on the 75–bus Indian power system. The system is divided into four areas. Area–1 is of 460 MW rating, having 3 Discos and 3 Gencos. Area–2 is of 994 MW rating and there are 5 Gencos and 3 Discos in this area. Area–3 is of 400 MW rating, having 2 Gencos and 3 Discos. Area–4 is of 4470 MW rating, having 3 Discos and 5 Gencos. Results of the BBBC–PID controller have been compared with those obtained by ICA–PID and HS–PID.

The bids (price and capacity) of Gencos and Discos of different areas for the power transaction are given in Table 10. Based on the accepted bid, the contracted power can be transacted through a poolco or bilateral transaction or a poolco plus bilateral transaction (mixed transaction) to several Discos. In the present work, poolco plus bilateral (mixed) transactions have been considered for power contract. The details are given as follows:

Table 10. Gencos and Discos bids in all areas.

Genco/Discos		Price (Rs./KWh)	Capacity (MW)
Area–1	$G_1/G_2/G_3$	5.7/5.5/6.0	15/30/30
	$D_1/D_2/D_3$	5.6/6.1/6.8	10/5/5
Area–2	$G_4/G_5/G_6/G_7/G_8$	6.0/6.4/5.6/7.0/5.4	25/40/20/30/25
	$D_4/D_5/D_6$	6.5/5.5/6.1	5/5/10
Area–3	G_9/G_{10}	4.5/4.2	25/35
	$D_7/D_8/D_9$	5/5.5/5.8	5/5/5
Area–4	$G_{11}/G_{12}/G_{13}/G_{14}/G_{15}$	4.2/5.7/4.8/6.2/4.5	25/25/50/30/25
	$D_{10}/D_{11}/D_{12}$	5.4/4.6/5.5	5/10/5

- No bilateral transaction in area–3.
- Gencos 5 (G5) of area–2 supplied 10% of area–1 load demand.
- 20% load of area–2 is provided by G11 of area–4 and 10% by G4 of area–2 itself.
- G5 provides 10% load of area–4, also 20% of area–4 load provides by G12 of area–4 itself.

Let us consider an increase in demand of area–1 by 50 MW, area–2 by 50 MW, area–3 by 50 MW, and area–4 by 100 MW. These increases in demand are met according to mixed transactions. After meeting all the demands Gencos will increase their power and Discos will reduce their power. Figure 5 shows the frequency deviations and responses of Gencos of different areas. Figure 5a shows the frequency deviation settling to zero value at steady state. Figure 5b shows the change in generating power in area–1 and area–2. It is seen that all Gencos increase their generation and settle down to the required value at steady state. Figure 5c shows that Gencos of area–3 and area–4 also settle to desired generated power at steady state. ISO sends the signals directly to Discos and not through the controller, therefore the responses of Discos are similar with all controllers (BBBC–PID, ICA–PID and HS–PID) as shown in Figure 6. The various simulated results show that the BBBC–PID controller's performance is fast, more accurate, and better than the other controllers. From Table 11 it is clear that the BBBC–PID controller provides better settling performance than do ICA–PID and HS–PID. The optimal values of parameters of the PID controller using the BBBC, ICA, and HS are given in Table 12.

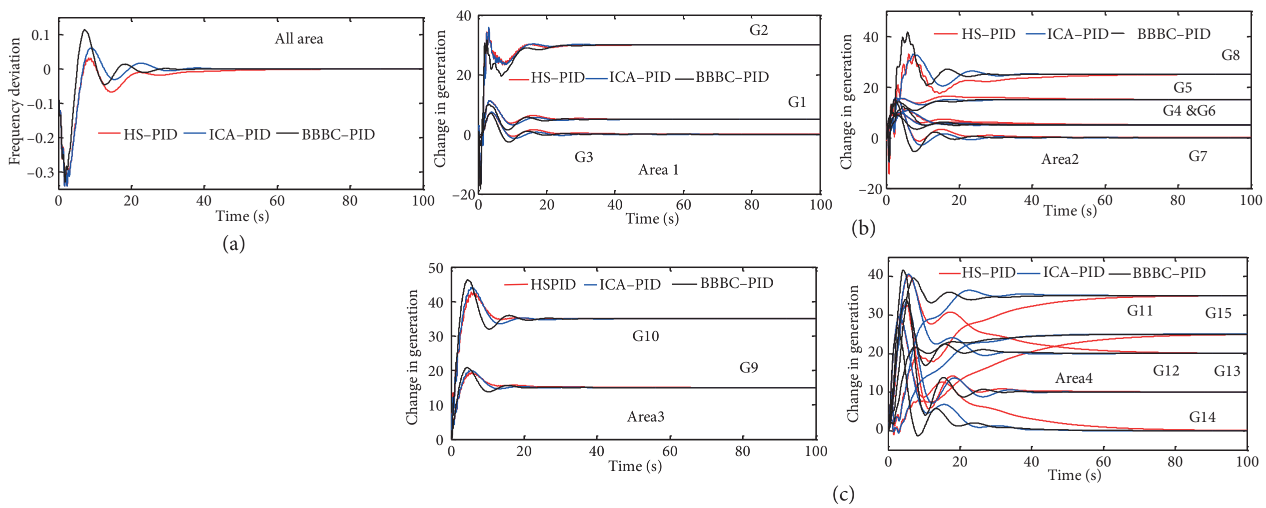

Figure 5. (a) Frequency deviations (Hz), (b) Generated power in area–1 and area–2 (MW), (c) Generated power in area–3 & area–4 (MW) (four-area power system).

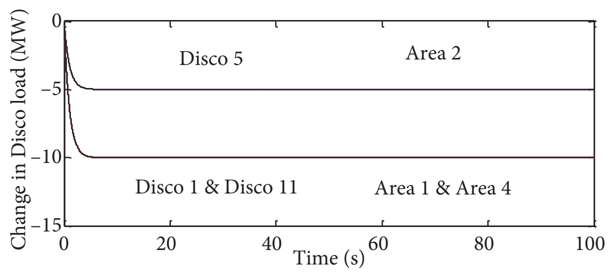

Figure 6. Change in Discos load (MW).

Table 11. Comparative study of settling time (s) of Gencos power.

Mixed transaction	G_1	G_2	G_3	G_4	G_5	G_6	G_7	G_8	G_9	G_{10}	G_{11}	G_{12}	G_{13}	G_{14}	G_{15}
BBBC–PID	45	38	45	35	35	35	45	40	40	45	40	45	40	45	50
ICA–PID	55	50	55	55	50	55	55	50	55	55	55	60	45	55	55
HS–PID	65	60	70	65	65	65	70	70	75	65	70	70	60	75	70

Table 12. Optimum values for PID controllers (four-area).

	BBBC			ICA			HS		
	K_P	K_I	K_D	K_P	K_I	K_D	K_P	K_I	K_D
Area–1	–0.7585	–0.2815	0.089	–0.755	–0.281	0.088	–0.5622	–0.4055	0.1110
Area–2	1.0413	–3.084	0.423	1.045	–3.482	0.443	0.8238	–1.8835	0.7079
Area–3	–1.018	–2.89	–0.00589	–1.0181	–2.899	–0.006	–1.9953	–1.7205	–0.2480
Area–4	0.689	0.520	0.8275	0.697	0.518	0.828	1.6520	–0.1001	1.8041

11. Conclusion

An AGC scheme for the multiarea deregulated power system at different load conditions is presented in this paper. A PID controller for the AGC scheme of the multiarea power system has been considered and the parameters of the PID were obtained based on the BBBC algorithm. Two-area, three-area, and four-area deregulated power systems have been considered as test systems. A wide range of load changes with GRC and different market transactions have been considered. The PID controller is designed in such a way that it minimizes the mean square of area control error. Results show the effective performance of the BBBC–PID controller. The results of the BBBC–PID have also been compared to the results of ICA–PID and HS–PID controllers. Comparison among various approaches shows that Gencos shared increased load demand faster with the BBBC–PID than the ICA–PID and HS–PID. Dynamic responses obtained for the ICA–PID and HS–PID are more oscillatory and take more settling time. It is seen that the BBBC–PID can be effective and a suitable choice for the multiarea AGC scheme.

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