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Application of soft computing techniques for multi source deregulated power system

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In this paper, an interconnected power system is proposed for Automatic Generation Control (AGC) in restructured power environment. The customized AGC scheme is projected in deregulated environment for multi-source combination of hydro, reheat thermal and gas generating units in entire area. Proportional integral derivative controller is offered for AGC scheme and the gains are optimised through soft computing techniques such as Hybrid Chaotic Particle Swarm Optimization (HCPSO) algorithm, Real Coded Genetic Algorithm (RCGA) and also with Artificial Neural Network (ANN). The PSO chosen here carves out the AGC problem through the addition of adaptive inertia weight factor and adaptive constriction factors. The intense trend in deregulated system leads to the aggressiveness in frequency and tie line power deviations. It is observed that the chaos mapping of PSO enhance the rate of convergence using logistics map sequence. The proposed algorithms are tested on three area power system for different electricity contracted scenarios under various operating conditions with Generation Rate Constraint (GRC). Analysis reveals that proposed HCPSO improves significantly the dynamical performances of system such as settling time and overshoot. The comparative results show the robust performance of HCPSO against parametric uncertainties for a wide range of load demands and disturbances.

Key words: Automatic generation control (AGC), hybrid chaotic particle swarm optimisation (HCPSO), proportional integral derivative (PID), restructured power system.

INTRODUCTION

In restructured situation, Automatic generation control (AGC) is one of the essential subsidiary services to be maintained for diminishing frequency deviations (Abraham et al., 2011; Tan, 2011; Shayeghi, 2008). The requirement for improving the efficiency of power production and delivery with intense participation of independent power producers stimulates restructuring of the power sector. The demand being fluctuating and increasing one, it is necessary to maintain the same constraint with the combination of various sources of generation and hence an attempt on research is made on the three area power system with various combinations of hydro, thermal and gas generation. Many researchers have been made their contribution in analyzing the restructured system (Ibrabeem and Kothari, 2005; Bevrani et al., 2005; Shayeghi and Shayanfar, 2005;

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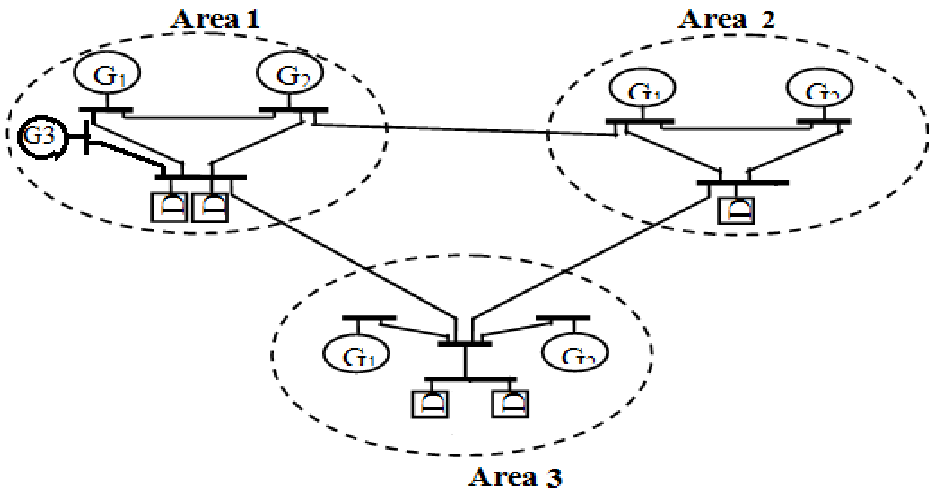

Figure 1. Three area restructured power system.

Menniti et al., 2004; Bevrani et al., 2004). Various control strategies have been opted for the better performance of the open market system (Demiroren and Zeynelgil, 2007; Shayeghi et al., 2006). The restructured three area power system is shown in Figure 1. Now-a-days the electric power industry has been transformed from Vertically Integrated Utilities (VIU) providing power at regulated rates to an industry that will incorporate competitive companies selling unbundled power at lower rates (Shayeghi et al., 2009). In the new power system structure, Load Frequency Control (LFC) acquires a fundamental role to enable power exchanges and to provide better conditions for electricity trading (Sedghisigarchi et al., 2002; Bevrani, 2002; Donde et al., 2001). Since to maintain the area control error to be zero so as to assure the generation and demand to be same, LFC are required for the power system (Christie and Bose, 1996; Lim et al., 1996). To keep the dynamic response of the power system to be stable, a controller like HCPSO (Cheshta and Verma, 2011) is required so as to perform the LFC of system shown in Figure 1. Under open market system (deregulation) the power system structure changed in such a way that would allow the evolving of more specialized industries for Generation (GENCOs), Transmission (TRANSCOs) and Distribution (DISCOs) (Tan, 2010). The concept of Independent System Operator (ISO) is an unbiased coordinator who has to balance the consumer and power generators reliably and economically (Bhatt et al., 2010; Rakhshani and Sadeh, 2010; Tan, 2009).

The AGC task is done through the error signal produced during generation and net interchange between the areas, that error is known as Area Control Error (ACE) (Liu et al., 2003).

$$ACE = \sum_j(\Delta P_{tie,i,j} + b_i \Delta f_i) \quad (1)$$

Where b_i be the frequency bias coefficient of the ith area, Δf be the frequency error of the ith area, $\Delta P_{tie,i,j}$ be the tie line power flow error between ith area and jth area.

The DISCO Participation Matrix (DPM) is proposed here to carry out the electricity contracts, the conventional control uses the integral of ACE as the control signal (Abraham et al., 2011; Tan, 2010, 2011; Shayeghi, 2008) and it has been found that the ACE which is used as a control signal results in reduction in frequency and tie line power error to zero in steady state (Tan, 2011). From the literature it is pointed out that very few of them concentrates on AGC problem in restructured environment. Since Proportional Integral Derivative (PID) holds the better results and hence, RCGA and HCPSO (Shayeghi et al., 2006), Artificial Neural Network (ANN) algorithm are introduced to independently determine optimal gain parameters of three area multi source AGC problem. In all PSO algorithms, inertial, cognitive and communal behaviour governs the movement of a particle. In HCPSO, an extra feature is introduced to ensure that the particle would have a predefined probability to maintain the diversity of the particles. The HCPSO algorithm converges to the best optimization results consistently and moderately rapid for all the test cases. The proposed work compares the performances for scenarios with ANN algorithm and RCGA-PID, while comparing the algorithms, the optimizing performance of HCPSO algorithm has been established to be the best for all the test cases with the controllers.

SYSTEM ANALYZED

The three area multi source generating system is considered here, in which each area has different combinations of GENCOs and DISCOs. Area 1 comprises of two DISCOs and three GENCOs with thermal reheat turbine, mechanical hydraulic turbine and gas turbine, Area 2 includes one DISCO and two GENCOs with hydro and thermal turbines and Area 3 consists of two GENCOs with thermal and Gas turbines combination with two DISCOs as shown in Figure 3. In this restructured environment, any GENCO in one area may supply DISCOs in the same area as well as DISCOs in other areas. In other words, for restructured system having several GENCOs and DISCOs, any DISCO may contract with any GENCO in another control area independently. This is termed as bilateral transaction.

The transactions have to be carried out through an Independent System Operator (ISO). The main purpose of ISO is to control many ancillary services, one of which is AGC. In open access scenario, any DISCO has the freedom to purchase MW power at competitive price from different GENCOs, which may or may not have contract with the same area as the DISCO (Shayeghi et al., 2009). The contracts of GENCOs and DISCOs described by 'DISCO participation matrix' (DPM). In DPM, 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. Any entry of this matrix is a fraction of total load power contracted by a DISCO towards a GENCO. The sum of total entries in a column corresponds to one DISCO be equal to one. The DPM for the nth area power system is as follows:

$$DPM = \begin{bmatrix} cpf_{11} & cpf_{12} \dots & cpf_{1n} \\ cpf_{21} & cpf_{22} \dots & cpf_{2n} \\ \vdots & \vdots & \vdots \\ cpf_{n1} & cpf_{n2} \dots & cpf_{nn} \end{bmatrix} \tag{2}$$

$$\sum_{j=1}^{n} cpf_{ij} = 1$$

$$AGPM = \begin{bmatrix} AGPM_{11} & .. & AGPM_{1N} \\ \vdots & \vdots & \vdots \\ AGPM_{N1} & .. & AGPM_{NN} \end{bmatrix} \tag{3}$$

Where, $AGPM_{ij} = \begin{bmatrix} gpf_{(si+1)(zj+1)} & .. & gpf_{(si+1)(zj+mj)} \\ \vdots & \vdots & \vdots \\ gpf_{(si+ni)(zj+1)} & .. & gpf_{(si+ni)(zj+mj)} \end{bmatrix}$

For i,j=1,2,....N, and $s_i = \sum_{k=1}^{i-1} n_i$; $z_j = \sum_{k=1}^{j-1} m_j$;$s_1 = z_1 = 0$

In the above, ni and mj are the number of GENCOs and DISCOs in area i and gpf_{ij} refer to 'generation participation factor' and shows the participation factor GENCOi in total load following the requirement of DISCOj based on the possible contract. The Equation (3) shows the Augmented Generation Participation Matrix (AGPM), which depicts the effective participation of DISCO with various GENCOs in all the areas with Generation Rate Constraint (GRC).

The sum of all entries in each column of AGPM is unity. To demonstrate the effectiveness of the modeling strategy and proposed control design, a three control area power system is considered as a test system with GRC. As there are many GENCOs in each area, the ACE signal has to be distributed among them due to their ACE participation factor in the AGC task. The scheduled contracted power exchange is given by (Shayeghi et al., 2009):

$\Delta P_{tieij}^{scheduled}$= (Demand of DISCOs in area j from GENCOs in area i) - (Demand of DISCOs in area i from GENCOs in area j)

$$d_i = \Delta P_{loc,i} + \Delta P_{di} \tag{4}$$

Where, $\Delta P_{loc,i} = \sum_{j=1}^{mi} \Delta P_{Lj-i}$, $\Delta P_{d,i} = \sum_{j=1}^{mj} \Delta P_{ULj-i}$,

$$\eta_i = \sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij} \Delta f_j, \tag{5}$$

$$\xi_i = \Delta P_{tie,ik,sch} \sum_{\substack{k=1 \\ k\neq i}}^{mj} \Delta P_{tie,ik,sch}, \tag{6}$$

$$\Delta P_{tie,ik,sch} = \sum_{j=1}^{ni} \sum_{t=1}^{mk} apf_{(si+j)(zk+t)} \Delta P_{Lt-k} - \sum_{t=1}^{nk} \sum_{j=1}^{mi} apf_{(sk+t)(zi+j)} \Delta P_{Lj-1} \tag{7}$$

$$\Delta P_{tie,i,error} = \Delta P_{tie,i-actual} - \xi_i \tag{8}$$

$$\rho_i = [\rho_{1i} \ \dots \rho_{ki} \dots \rho_{nii}]^T \tag{9}$$

$$\rho_{ki} = \sum_{j=1}^{N} \left[\sum_{t=1}^{mj} gpf_{(si+k)(zj+t)} \Delta P_{Lt-j} \right]^T ; \Delta P_{m,k-i} = P_{ki} + apf_{ki} \sum_{j=1}^{mj} \Delta P_{ULj-i} \tag{10}$$

Where k=1,2.....n_i

In a power system having steam plants, power generation can change only at a specified maximum rate. The structure for ith area in the presence of GRC is shown in Figure 2. A typical value of the GRC for thermal unit is 3%/min, that is, GRC for the thermal system be $\Delta PGt(t) \leq 0.0005 p.u.MW/s$ .Two limiters, bounded by±0.0005 are employed within the AGC of the thermal and gas system to prevent the excessive control action. Likewise, for hydro plant GRC of 270%/min. for raising generation and 360%/min. for lowering generation has been deemed.

HCPSO-PID controller strategy

The Proportional-Integral-Derivative (PID) controller is intended for this multi area multi source generation system. Since this controller provides zero steady state deviation with good dynamic response of frequency and tie-line power in a multi area power system. The control vector is given by:

$$U_i = -[K_{pi} + ACE_i + K_{Ii} \int ACE_i\, dt + K_{di} \frac{dACE_i}{dt}] \tag{11}$$

Where K_{pi}, K_{di}, K_{ii} are the proportional, derivative and integral gains of PID controller.

In PID controller, the tie line power deviation and frequency deviation are weighted together as a linear combination to a single variable called ACE, which is given as control signal to governor set point in each area. Here, ITAE is used as a performance criterion. To achieve a preeminent performance and to improve the dynamics of LFC in a deregulated power system, Hybrid Chaotic Particle Swarm Optimization Algorithm is used to optimize the gains of PID controller. The evaluation of proposed controller has been made by simulating the same structure using RCGA optimization (Demiroren and Zeynelgil, 2007) and ANN has been trained through Back Propagation Algorithm (Demiroren, 2001) for ACE and Differentiation of ACE.

Hybrid chaotic particle swarm optimisation

In conventional approach, it involves more number of iterations to

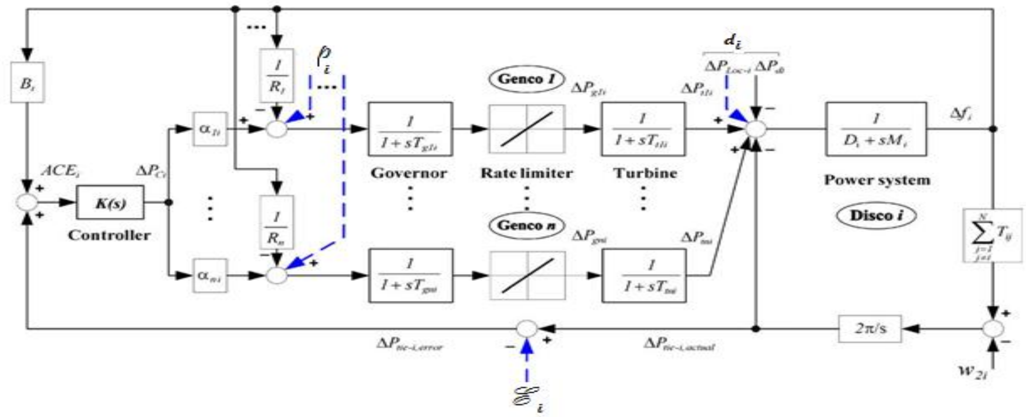

Figure 2. Control structure with GRC for ith area.

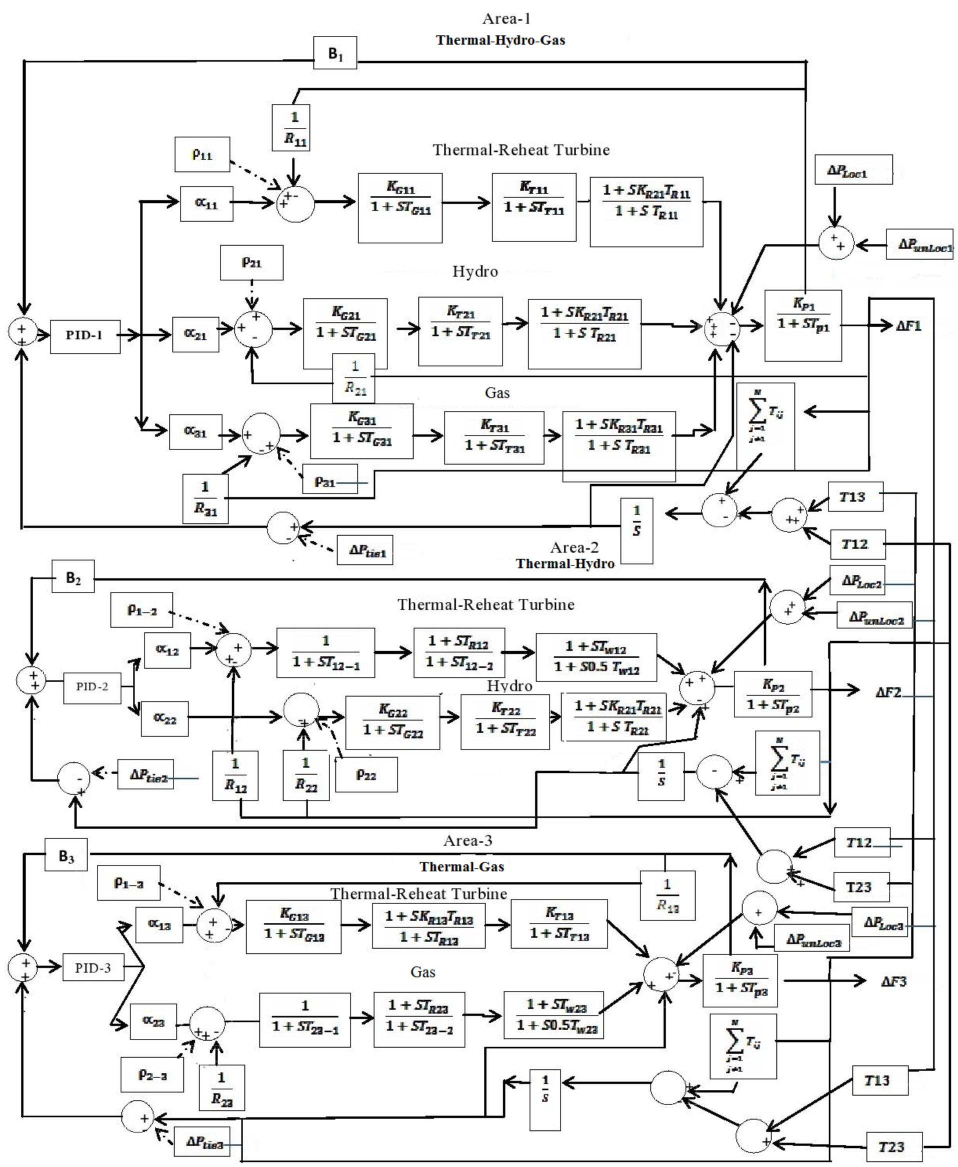

Figure 3. Three area restructured control area.

Table 1. Fitness value (ITAE) comparison.

Scenario	Fitness function		
	HCPSO-PID	RCGA-PID	ANN
1	4.5236	4.5099	4.8932
2	8.3976	9.0656	9.8035
3	8.111	9.4837	10.1235

optimize the objective function and hence it is a time consumable one (Cheshta and Verma, 2011; Shayeghi and Shayanfar, 2006; Barjeev and Srivastava, 2003; Rerkpreedapong and Feliache, 2002). To conquer this intricacy, Hybrid Chaotic Particle Swarm Optimization is proposed to optimise the gains of PID Controller. In general PSO depends on its parameter and after certain iterations, the parameter sets are approximately identical (Cheshta and Verma, 2011). To enhance the performance of particle swarm optimization algorithm the application of adaptive inertia weight factor and adaptive constriction factors is proposed. The extreme trend in deregulated power system leads to the aggressiveness in frequency and tie line power deviations. It is observed that the chaos mapping upgrade the rate of convergence using logistics map sequence and Chaotic based optimisation offers diversity in population. A chaotic sequence for inertia weight and constriction factor for optimization is as follows:

Adaptive inertia weight factor (AIWF)

The rate of inertia weight is set for the entire particles be similar for all iteration (Cheshta et al., 2011). Therefore difference among particles is omitted. This adaptive method declares that the better particle should have a tendency to utilize its neighbour particles. This strategy provides the huge selection pressure. The AIWF is obtained as (Cheshta et al., 2011):

$$w_i^k = w_{min} + f_{pbest}^k \mid f_i^k \cdot f_{pbest}^k \mid / f_i^k \mid f_i^k \cdot f_{gbest}^k \mid \qquad (12)$$

Where w_i^k be inertia weight of i^{th} population at k^{th} iteration, w_{min} be minimum inertia weight, f_{pbest}^k be fitness function of pbest solution at k^{th} iteration, f_i^k be fitness function of i^{th} population at k^{th} iteration and f_{gbest}^k be fitness function of gbest solution at k^{th} iteration.

Adaptive constriction factors

Constriction factor are extremely depend on fitness function of current iteration (that is) pbest and gbest solution and c1 and c2 controls the utmost step size. This factor can be determined as:

$$c1_i^k = \sqrt{f_i^k / f_{pbest}^k} \qquad (13)$$

$$c2_i^k = \sqrt{f_i^k / f_{gbest}^k} \qquad (14)$$

The velocity up gradation of particle modified as:

$$v_i^{k+1} = w_i^k v_i^k + c1_i^k z1_i^k \left(pbest_i^k - x_i^k\right) + c2_i^k z2_i^k \left(gbest_i^k - x_i^k\right) \qquad (15)$$

Where, v_i^k be the velocity of the i^{th} population at k^{th} iteration, z_i^k be Chaotic sequence based on logistic map for i^{th} population at k^{th} iteration, x_i^k be position of particle of i^{th} at k^{th} iteration.

The position of each particle is updated using the velocity vector that is:

$$x_i^{k+1} = x_i^k + v_i^{k+1} \qquad (16)$$

Fitness-objective function

The focal intention of this effort is to reduce the frequency deviation and tie line power flow deviations and these parameters are weighted together as ACE. The fitness function is taken along with an optional penalty factor to take care of transient responses; the fitness function is given by:

$$\text{ITAE}=\int_0^{tsim} t|e(t)|dt \qquad (17)$$

Where *e(t)* be error considered.

The fitness function to be minimized is given by:

$$j = \int_0^{tsim} (\beta_1|\Delta f_1| + \beta_2|\Delta f_2| + |\Delta p_{tie12}^{error}|)dt + FD \qquad (18)$$

Where, FD=α_1OS+α_2ST ; Where Overshoot (OS) and settling time (ST) for 2% band of frequency deviation in all three areas are considered for evaluation of the Frequency Discrimination (FD), by adjusting the values of α_1 and α_2 the frequency discrimination can be obtained. The fitness value for all the three scenarios are listed Table 1.

Pseudo code

Step 1: Choose the population size and number of iteration.
Step 2: Generate randomly 'n' particles for gains and frequency biases with uniform probability over the optimized parameter search space [x_{min}, x_{max}], similarly generate initial velocities of all particles , v^i which is given by: $v^i = 0.4\, rand(v_{max} - v_{min})$
Step 3: Run AGC model and calculate the fitness function for each particle (Equation18) at k^{th} iteration.
Step 4: Calculate gbest value and pbest value.
Step 5: Calculate fitness function at gbest and pbest solution.
Step 6: Calculate AIWF (Equation 12), constriction factor (Equations 13-14) and z1, z2 (Equation 10).
Step 7: Update velocity of each particle (Equation 15).
Step 8: Based on updated velocities, each particle changes its position according to Equation (16).

If particle infringes the position limit in any dimension, set its position at the proper limit.
Step 9: If the last change of the best solution is greater than a pre

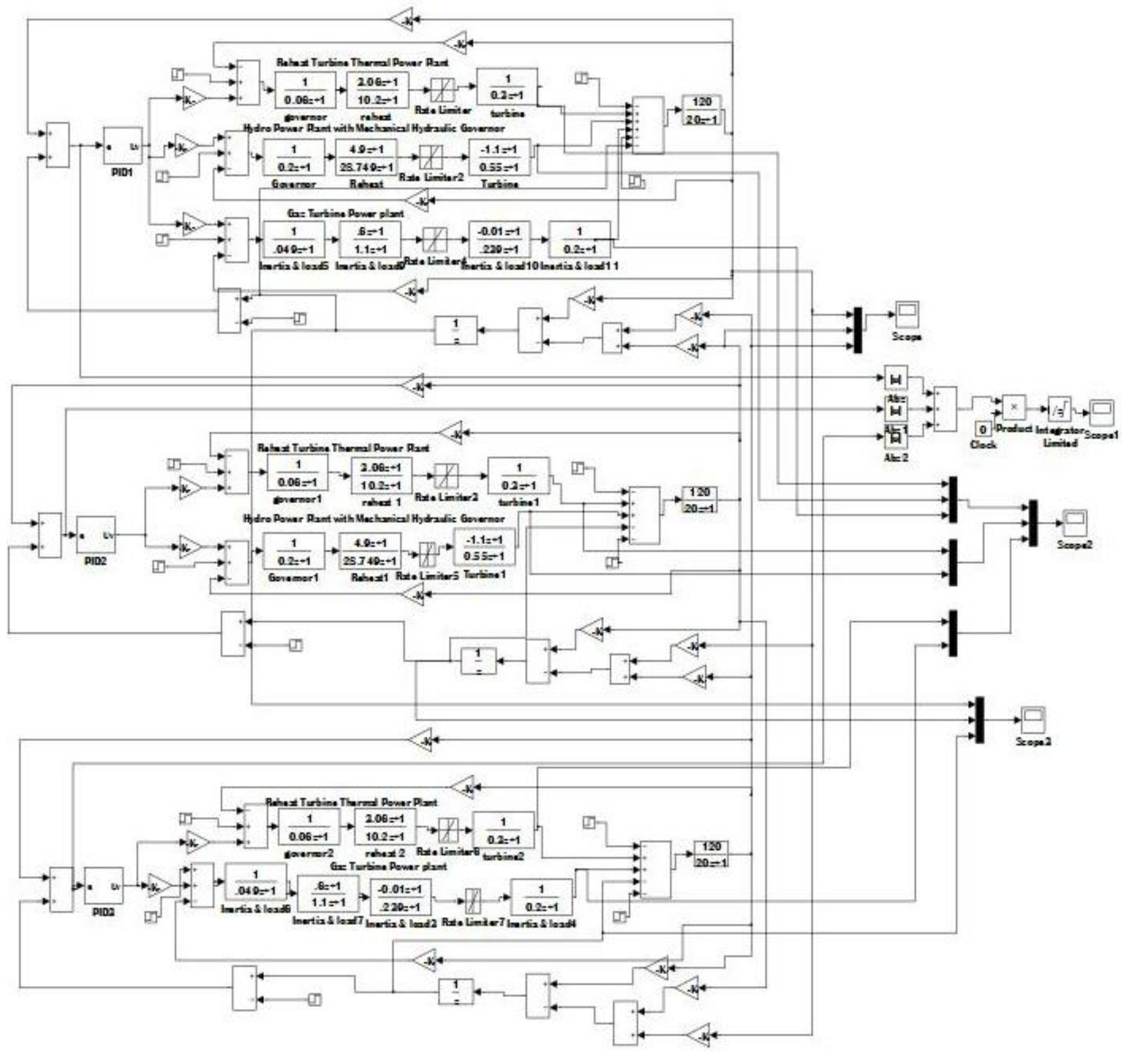

Figure 4. Simulink model.

specified number or the number of iteration reaches the maximum iteration, stop the process, otherwise go to Step 3.

RESULTS AND DISCUSSION

The three area control structure with GRC considering multi source generation has been simulated for restructured structure as shown in Figure 4. To demonstrate the robustness of proposed control strategy against parametric suspicions and contract variations, simulations are carried out for three scenarios of possible contracts under various operating conditions and large load demands. The plant parameters for three area deregulated power system is presented in Table 2. Performance of the proposed controller is compared with RCGA-PID (Demiroren and Zeynelgil, 2007) and ANN (Demiroren, 2001) controller. The parameters of the controllers are given in appendix (Table 3).

Scenario1 poolco based transactions

In this scenario, GENCOs participate only in the load following control of their areas. It is assumed that a large step load 0.1 pu is demanded by each DISCOs in areas 1, 2 and 3 with GRC. The poolco based contracts between DISCOs and available GENCOs is simulated based on the following AGPM. The variations in tie line power flows and frequency is shown in Figures 5 and 6 and the values are depicted in Tables 4 and 5.

Scenario 2 combination of poolco and bilateral based transactions

In this case, DISCOs have the freedom to contract with any of the GENCOs within or with other areas. All the GENCOS are participating in the AGC task as per the following AGPM. The discrepancies based on this

Table 2. Power system plant and control parameters.

Area 1			Area 2		Area 3	
Thermal-Hydro-GAs			Hydro-Thermal		Thermal-Hydro	
GENCO-1	GENCO-2	GENCO-3	GENCO-1	GENCO-2	GENCO-1	GENCO-2
Thermal	Hydro	Gas	Thermal	Hydro	Thermal	Gas
Tg=0.06s	Tg=0.2s	Tg=0.049s	T1=0.06s	Tg=0.2s	Tg=0.06s	T1=0.049s
Tt=0.3s	Tt=0.55s	Tt=0.2s	T3=10.2s	Tt=28.149s	Tt=10.2s	T3=1.1s
R=0.3333Hz/p.u.MW	Kr =0.3113	Kr =0.5	T2=0.3s	R=.29633Hz/p.u.MW	Kr =0.33	T2=0.2s
Tr=10.2s	Tr=10.6 s	Tr=1.1s	Tw =1s	Kg=1	Tr=10s	Tw =1.5s
	R=0.32Hz/p.u.MW	R=.33Hz/p.u.MW	R=0.32Hz/p.u.MW	Kt=1	R=0.2899Hz/p.u. MW	R=0.3077Hz/p.u .MW
Kg=1	Kg=1	Kg=1	Kg=1		Kg=1	Kg=1
Kt=1	Kt=1	Kt=1	Kt=1		Kt=1	Kt=1
Kp=20 Hz/ p.u. MW Tp=120s B=0.532p.u. MW/Hz Prated=2000 MW (Nominal Load) P^{o}= 1000 MW f=60Hz			Kp=20 Hz/ p.u. MW Tp=120s B=0.495p.u. MW/Hz Prated=2000 MW (NominalLoad) Po= 1000 MW f=60Hz		Kp=20 Hz/ p.u. MW Tp=120s B=0.542 p.u.MW/Hz Prated=2000 MW (Nominal Load) Po= 1000 MW f=60Hz	
T12=T13=T23= 0.543 p.u/Hz						

Table 3. Controller parameter.

Parameter	RCGA	HCPSO	ANN
Number of population	20	20	Number of hidden layers 10
Number of Generation	200	200	1000
	Probability crossover -0.8	W_{max}-0.6	Sampling interval-0.05s
	Mutation function taken as Gaussian	W_{min}0.1	Number of delayed inputs-2
	Fitness scaling function is Rank	C_1=C_2=1.5	Number of delayed output-1

transaction are shown in Figures 7 and 8 prevailing to frequency and tie line power deviations.

Scenario 3 contract violation

In this scenario, the DISCOs may violate the contracts by demanding more power than that specified in the contract. This excessive power is reflected as a located load of that area (un contracted demand).The AGPM of this case follows the scenario 2 and the un contracted loads for DISCO 1 in area1 is 0.018 p.u, DISCO 2 in area1 is 0.0230 p.u, DISCO1 in area is 0.3800 p.u, DISCO 1 in area 3 is 0.0125 p.u, DISCO 2 in area3 0.0125 p.u. The purpose of this scenario is to test the effectiveness of the proposed controller against the uncertainties and sudden large load disturbances in the presence of GRC (Figures 9 and 10).

The Table 6 demonstrates the comparison of GENCO power deviation for the three scenarios with theoretical and the simulated values by Equation (10). The deviation in tie line power flows for these possible contracts are presented in appendix. The results thus obtained through simulation depicts that the proposed HCPSO-PID controller holds good performance as compared to RCGA-PID and ANN controller for all possible contracts and for wide range of load disturbances.

Conclusions

Multi source generation is universal for any real time grid in function. It is incredibly hard to synchronize the various areas in a deregulated environment by means of frequency and tie line power flows. However, the conventional PID controller can be able to coordinate but with large overshoots and settling time. Hence soft computing techniques proposed for this AGC problem. The HCPSO-PID controller is proposed here for multi source generation system for a deregulated environment. This controller accomplishes consistency over tracking frequency and tie line power deviations for a wide range of load disturbances and system uncertainties. To prove its robustness the performance has been compared with RCGA-PID and ANN controller. The simulated result shows that the proposed controller is

$$
\text{AGPM=}\begin{pmatrix}
0.3 & 0.25 & 0 & 0 & 0 \\
0.4 & 0.35 & 0 & 0 & 0 \\
0.3 & 0.4 & 0 & 0 & 0 \\
0 & 0 & 0.5 & 0 & 0 \\
0 & 0 & 0.5 & 0 & 0 \\
0 & 0 & 0 & 0.45 & 0.6 \\
0 & 0 & 0 & 0.55 & 0.4
\end{pmatrix}
$$

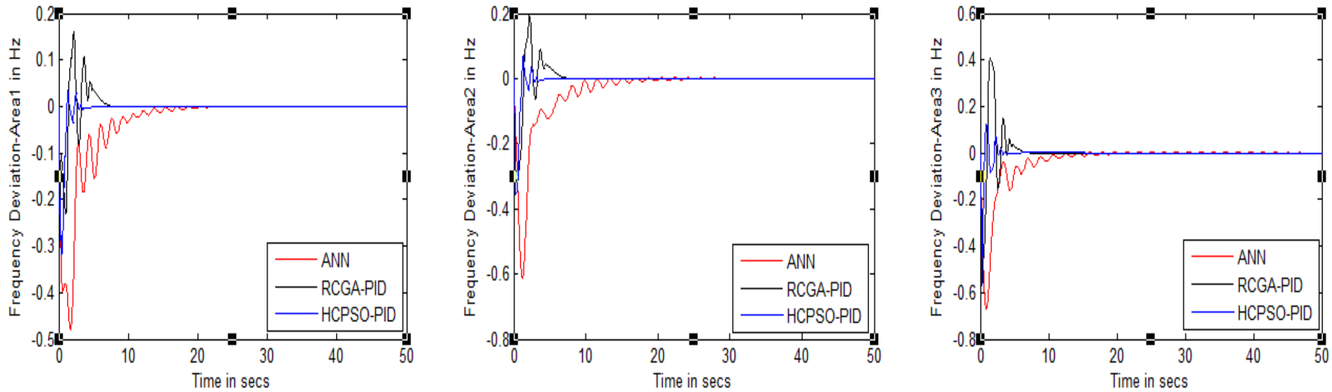

Figure 5. Frequency deviation for scenario 1.

$$
\text{AGPM=}\begin{matrix}
0.2 & 0.15 & 0.1 & 0 & 0.2 \\
0.25 & 0.2 & 0 & 0.1 & 0.15 \\
0.1 & 0 & 0.3 & 0.25 & 0.15 \\
0.3 & 0.15 & 0.3 & 0.25 & 0.2 \\
0 & 0.2 & 0 & 0.15 & 0.2 \\
0.15 & 0.2 & 0.15 & 0.15 & 0 \\
0 & 0.1 & 0.15 & 0.1 & 0.1
\end{matrix}
$$

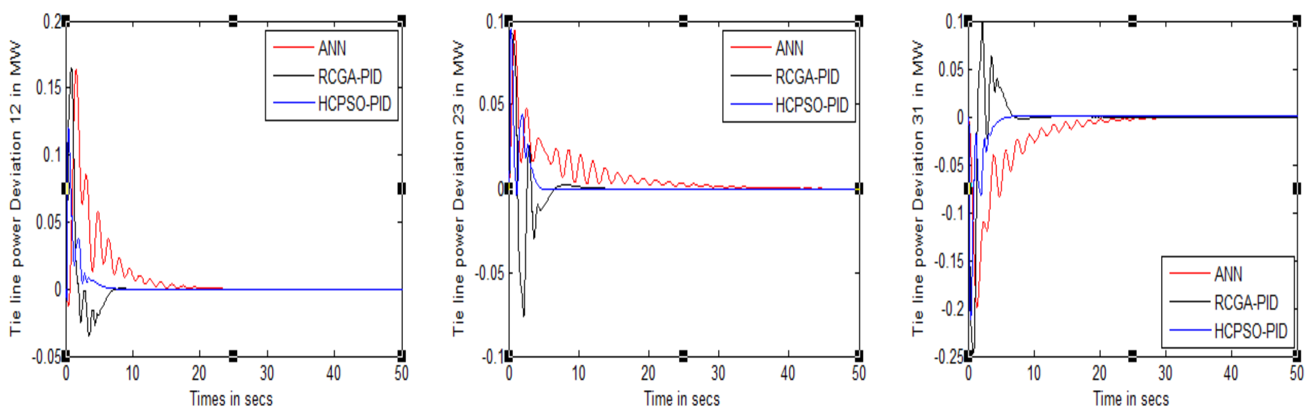

Figure 6. Tie line power deviation for scenario 1.

Table 4. Tie line power deviations.

Controller	Area	Peak overshoots (MW)			Peak Undershoot(MW)			Settling time(secs)			Computational time (secs)
		Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	
	1	0.120428	0.118588	0.141012	-0.00813	-0.05842	-0.10009	7	6	4	
HCPSO-PID	2	0.094645	0.139323	0.19326	-0.00436	-0.00656	-0.02693	8	6	5	0.45
	2	0.000912	0.03702	0.052313	-0.21249	-0.25369	-0.30557	4	8	6	
	1	0.165357	0.126169	0.160866	-0.03485	-0.00822	-0.00821	14	20	18	
RCGA-PID	2	0.093712	0.111066	0.11627	-0.07594	0	0	15	21	18	0.85
	3	0.098728	0	0	-0.24801	-0.23711	-0.27666	11	19	19	
	1	0.164209	0.172452	0.208209	-0.01273	-0.01034	-0.01637	34	38	19	
ANN	2	0.093889	0.093077	0.090079	-0.0001	0	0	36	41	20	0.23
	3	0.000762	0	0	-0.19951	-0.22226	-0.24809	36	28	25	

Table 5. Frequency deviations.

Controller	Area	Peak overshoots (Hz)			Peak Undershoot (Hz)			Settling time (secs)			Computational time (secs)
		Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	
	1	0.03352	0.083241	0.128561	-0.31716	-0.286	-0.34254	7	6	4	
HCPSO-PID	2	0.06948	0.148039	0.221594	-0.35658	-0.28115	-0.37978	8	6	5	0.45
	2	0.12463	0.168112	0.228224	-0.57114	-0.56928	-0.70162	4	8	6	
	1	0.16183	0.193253	0.365623	-0.28816	-0.30916	-0.39173	14	20	18	
RCGA-PID	2	0.19515	0.296932	0.480645	-0.30682	-0.23067	-0.36772	15	21	18	0.85
	3	0.40514	0.341415	0.572651	-0.56879	-0.56651	-0.71862	11	19	19	
	1	0.16420	0.000799	0.017762	-0.01273	-0.47493	-0.63228	34	38	19	
ANN	2	0.09388	0.00333	0.018313	-0.00023	-0.58227	-0.75234	36	41	20	0.23
	3	0.00091	0.002363	0.028305	-0.19951	-0.67788	-0.85948	36	28	25	

most excellent for real time application. In future, all techniques like ANFIS can be incorporated to get online coordination for the deregulated environment.

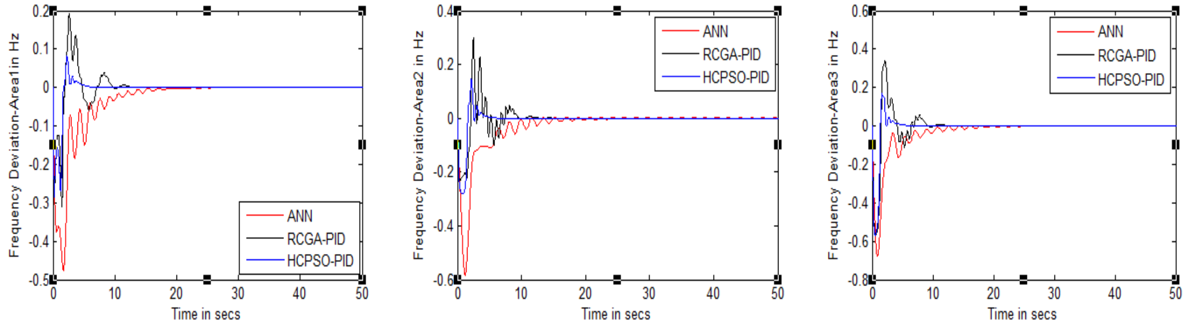

Figure 7. Frequency deviation for scenario 2.

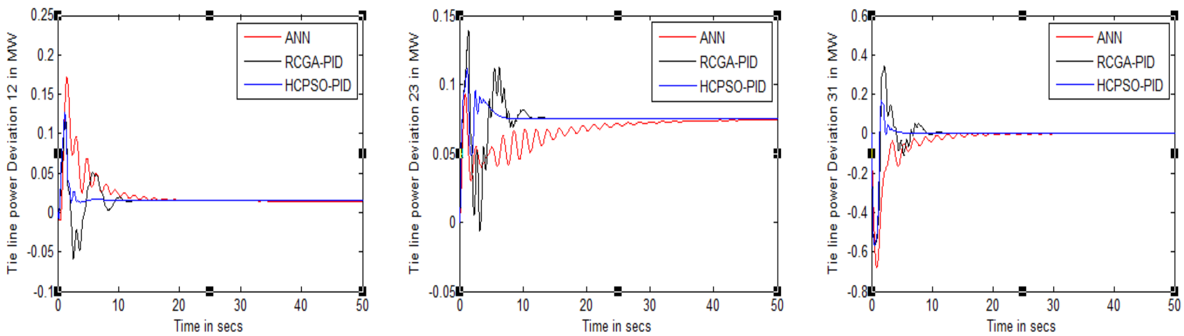

Figure 8. Tie line power deviation for scenario 2.

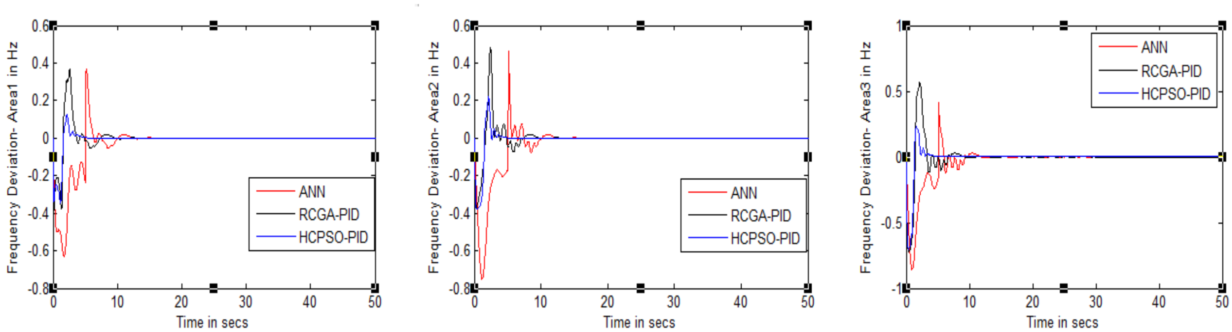

Figure 9. Frequency deviation for scenario 3.

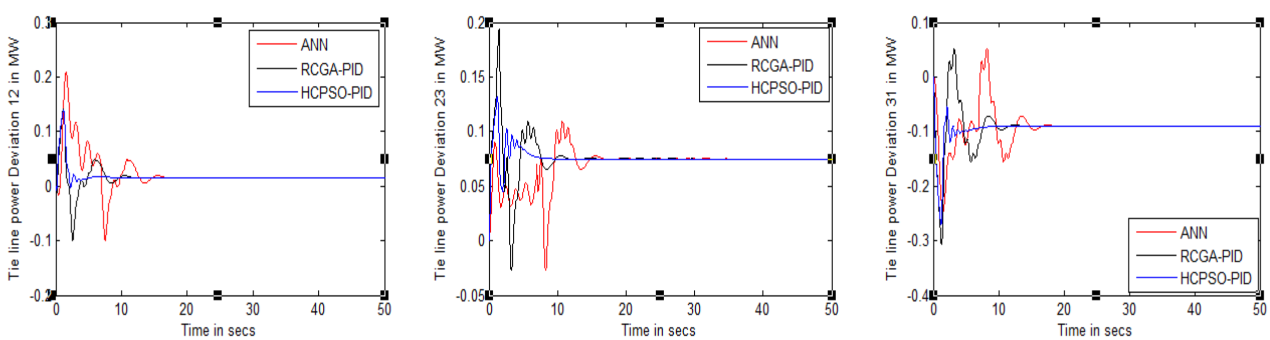

Figure 10. Tie line power deviation for scenario 3.

Table 6. Genco power deviations for 0.1 p.u. load disturbance.

Genco power deviation	Scenario	Theoretical value	Value obtained through Simulation			Error Value		
			RCGA	HCPSO	ANN	RCGA	HCPSO	ANN
Area 1								
GENCO 1 – Thermal	1	0.055	0.055006	0.055005	0.055006	$-6\text{x}10^{-6}$	$-5\ \text{x}10^{-6}$	$-6\text{x}10^{-6}$
	2	0.065	0.065005	0.065005	0.065005	$-4.9\ \text{x}10^{-6}$	$-4.6\ \text{x}10^{-6}$	$-4.9\ \text{x}10^{-6}$
	3	0.085	0.085025	0.085008	0.085025	$-2.5\ \text{x}10^{-5}$	$-8\ \text{x}10^{-5}$	$-2.5\ \text{x}10^{-5}$
GENCO 2 Hydro	1	0.075	0.074982	0.074983	0.074982	$0.18\ \text{x}10^{-6}$	$0.17\ \text{x}10^{-6}$	$0.18\ \text{x}10^{-6}$
	2	0.07	0.079996	0.079999	0.079996	$-4.3\ \text{x}10^{-6}$	$-1\ \text{x}10^{-6}$	$-4.3\ \text{x}10^{-6}$
	3	0.085	0.084994	0.084992	0.084994	$6.1\ \text{x}10^{-6}$	$7.8\ \text{x}10^{-6}$	$6.1\ \text{x}10^{-6}$
GENCO 3 Gas	1	0.07	0.070013	0.070014	0.070013	$-1.3\ \text{x}10^{-5}$	$-1.4\ \text{x}10^{-5}$	$-1.3\ \text{x}10^{-5}$
	2	0.08	0.079996	0.079999	0.079996	$-4.3\ \text{x}10^{-6}$	$-1\ \text{x}10^{-6}$	$-4.3\ \text{x}10^{-6}$
	3	0.095	0.095008	0.095001	0.095008	$0.49\ \text{x}10^{-4}$	$-1.3\ \text{x}10^{-6}$	$0.49\ \text{x}10^{-4}$
Area 2								
GENCO 1 Thermal	1	0.055	0.049999	0.049999	0.049999	$0.1\ \text{x}10^{-6}$	$0.1\ \text{x}10^{-6}$	$0.1\ \text{x}10^{-6}$
	2	0.12	0.119999	0.119998	0.119999	$1.1\ \text{x}10^{-6}$	$2.3\ \text{x}10^{-6}$	$1.1\ \text{x}10^{-6}$
	3	0.144	0.143862	0.143998	0.143862	$0.138\ \text{x}10^{-6}$	$2.3\ \text{x}10^{-6}$	$0.13\text{x}10^{-6}$
GENCO 2 Hydro	1	0.05	0.050001	0.049994	0.050001	$-1\ \text{x}10^{-6}$	$0.6\ \text{x}10^{-6}$	$-1\ \text{x}10^{-6}$
	2	0.055	0.054998	0.055	0.054998	$1.7\ \text{x}10^{-6}$	$2.5\ \text{x}10^{-6}$	$1.7\ \text{x}10^{-6}$
	3	0.071	0.071028	0.071006	0.071028	$-2.8\ \text{x}10^{-5}$	$-6.2\ \text{x}10^{-6}$	$-2.8\ \text{x}10^{-5}$
Area 3								
GENCO 1 Thermal	1	0.105	0.104981	0.105	0.104981	$0.19\ \text{x}10^{-6}$	$-1\ \text{x}10^{-7}$	$0.19\ \text{x}10^{-6}$
	2	0.065	0.064978	0.06497	0.064978	$2.19\ \text{x}10^{-5}$	$0.3\ \text{x}10^{-5}$	$2.19\ \text{x}10^{-5}$
	3	0.144	0.079403	0.079976	0.079403	$0.597\ \text{x}10^{-6}$	$2.42\ \text{x}10^{-5}$	$0.59\text{x}10^{-6}$
GENCO 2 Gas	1	0.095	0.095012	0.095002	0.095012	$0.12\ \text{x}10^{-6}$	$0.2\ \text{x}10^{-6}$	$0.12\ \text{x}10^{-6}$
	2	0.045	0.045028	0.045039	0.045028	$-2.8\ \text{x}10^{-5}$	$-3.8\ \text{x}10^{-5}$	$-2.8\ \text{x}10^{-5}$
	3	0.06	0.061845	0.06002	0.061845	$-0.184\ \text{x}10^{-5}$	$-2\ \text{x}10^{-5}$	$-0.18\ \text{x}10^{-5}$

Conflict of Interest

The authors have not declared any conflict of interest.

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Appendix

Nomenclature

i: Subscript referred to area,
F: Area frequency,
P_{tie}: Tie line power flow,
P_T: Turbine power,
P_V: Governor valve position,
P_C: Governor set point,
ACE: Area control error,
AGC: Automatic generation control,
GRC: Generator rate constraint,
DPM: DISCO participation matrix,
AGPM: Augmented generation participation matrix,
cpf: Contract participation factor,
gpf: Generation participation factor,
K_P: Subsystem equivalent gain constant,
T_P: Subsystem equivalent time constant,
T_T: Turbine time constant,
T_G: Governor time constant,
R: Droop characteristic,
B: Frequency bias,
FD: Frequency Deviation,
ITAE: Integral time multiplied absolute error,
Tij: Tie line synchronizing coefficient between areas i and j,
Pd: Area load disturbance,
P_{Lji}: Contracted demand of DISCO j in area I,
P_{ULji}: Un-contracted demand of DISCO j in area I,
$P_{M,ji}$: Power generation of GENCO j in area I,
P_{Loc}: Total local demand,
η**:** Area interface,
ξ **:** Scheduled power tie line power flow deviation.