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Multi area AGC scheme using imperialist competition algorithm in restructured power system

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ABSTRACT

This paper is focused on optimization based design methodology and application of PID controller in restructured, competitive electricity market environment, for AGC problem. The paper compares two search algorithms for designing of PID controller used for AGC in multiarea power system. The optimal parameters of PID controller have been determined with the use of Imperialist Competitive Algorithm (ICA). A deregulated scenario has been considered to develop the model of the multiarea AGC scheme. This paper presents that the ICA tuned PID (ICA-PID) controller can optimally regulate the generators output and can provide the best dynamic response of frequency and tie-line power on a load perturbation. The performance of proposed controller has been checked on 2-area thermal power system and 3-area thermal-hydro power system with the consideration of generation rate constraint (GRC). The results obtained by ICA-PID controller and genetic algorithm tuned (GA-PID) controller have been compared on the basis of performance parameters (settling time and oscillations). It is seen that ICA-PID controller shows the better performance as compared to GA-PID controller.

1. Introduction

AGC is used to maintain zero steady state errors in deviation of system frequency and tie-line power exchange to other areas. The conventional AGC scheme for isolated and interconnected power system has been discussed in [1–3]. For the improvement in the efficiency of the operation of power system, it has been restructured according to open market system, which consists Gencos (generation companies), Transcos (transmission companies), Discos (distribution companies), and ISO (independent system operator). ISO is an independent agent which procures various ancillary services for stable and secure operation of a power system [4,5]. AGC is one of the most important ancillary services among all. The main goal of this ancillary service is to provide a balance between generation and load demand of each area and maintain the frequency and tie-line power flow within the specified limit. In deregulated power system, poolco-based transactions, bilateral transactions, and a combination of poolco and bilateral i.e. mixed transactions are used for various contracts between Discos and Gencos [6–8]. Various load frequency control issues related to deregulation is reported in [9]. Q4

The increasing complexities in power system encouraged researchers to explore appropriate control algorithms for AGC. Various control strategies, such as optimal control [10,11], variable structure control [12,13], adaptive and self-tuning control [14,15], robust control [16–18] etc. have been discussed in the literature for AGC scheme. PID controller has a simple structure and widely used in AGC scheme to control the frequency and the tie-line power. The literature reveals that the different methods have been proposed to determine the parameters of a PID controller. A variety of optimization algorithm have been reported to find the optimal parameters of PID controller such as Fuzzy logic (FL) [19–24], genetic algorithm (GA) [25,26], bacterial foraging [27,28], particle swarm optimization (PSO) [29,30] etc. In addition to these, ICA may be used as an alternate tuning method due to its global search and stable convergence characteristics. ICA is inspired by the socio political idea [31]. In recent years, ICA has been successfully applied to the different control processes or optimization problems, some of them are the economic dispatch problem [32], power system stabilizer [33], oil flow rate [34], reactive power dispatch [35] and tuning of PID controller [36–39].

According to the recent literature available, the controller designed using ICA has capability of handling parameter

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uncertainty, possess robustness and eliminate steady state errors efficiently. It also gives better stability [33–39]. The versatility and efficient performance of this technique in different areas motivated us to investigate its implementation to the problem of AGC under deregulated environment. It is seen that ICA-PID controller works well, provides stability and ensured good dynamic performance of AGC in restructured environment.

In present study, ICA algorithm is used to determine the optimal parameters of a PID controller for multiarea AGC scheme in deregulated environment. Poolco and bilateral transactions have been considered between the areas. Disco participation matrix (DPM) is used for implementation of various contracts. Mean square error (MSE) of area control error (ACE) is considered as a performance index (objective function) for this optimization problem. The proposed controller is tested on 2-area thermal power system [6], and 3-area thermal-hydro power system considering GRC [40]. The performance of ICA-PID controller has been compared with GA-PID controller. The convergence characteristic of ICA shows the higher convergence rate than GA. Results show that ICA-PID controllers have reduced settling time and oscillations in dynamic response of frequency, tie-line power and change in generation as compared to PID controllers optimized by GA.

2. System modeling

Any mismatch between real power generation and load demand, give rise to area control error (ACE) [7]. Coefficients that distribute ACE to several Gencos are known as ACE participation factors (αpf). Power system satisfactory operation requires the removal or minimization of ACE. In a deregulated electricity market different transactions can take place such as poolco based transaction, bilateral transaction and the combination of these two transactions [8]. Poolco based transaction does not change the scheduled tie-line exchange, but the bilateral transaction can change the tie-line exchange which can modify the ACE.

The net tie-line power flow from an area-i can be represented as given below,

$$\Delta Ptie_{i-schd} = \Delta Ptie_i + \sum_{\substack{j=1 \\ i\neq j}}^{n} D_{ij} - \sum_{\substack{j=1 \\ i\neq j}}^{n} D_{ji} \quad (1)$$

where, D_{ij} and D_{ji} represent the demand of the Disco of area-j and area-i from the Genco of area-i and area-j respectively, $\Delta Ptie_i$ shows the change in tie-line power when no bilateral transaction is considered. n represents the number of areas. The error in the tie-line power flow can be represented as,

$$\Delta Ptie_{i\_error} = \Delta Ptie_{i\_actual} - \Delta Ptie_{i\_schd} \quad (2)$$

Therefore, the modified ACE signal can be represented as,

$$ACE_i = B_i \Delta f_i + \Delta Ptie_{i\_error} \quad (3)$$

where, B_i is the frequency bias factor and Δf_i is the frequency deviation in area-i. Fig. 1 represents the block diagram of the k^{th} Genco in area-i. The pf is the Genco participation factor, R_i is the droop,

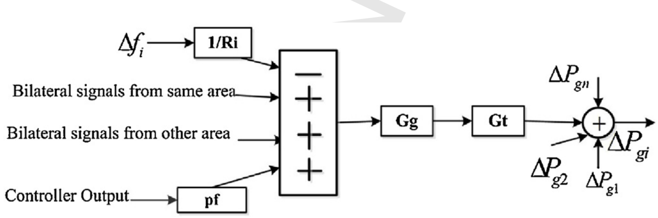

Fig. 1. Block diagram of Genco-k of area-i.

and G_g and G_t represents the transfer function model of governor and turbine respectively. $\Delta P_{g1}, \Delta P_{g2}, \ldots\ldots \Delta P_{gk}, \ldots\ldots \Delta P_{gn}$ represents the change in the output of Gencos in area-i. Fig. 2 shows the overall block diagram representation for the AGC scheme of area-i

3. PID controller design using ICA

3.1. PID controller

PID controllers are the most widely used industrial controllers because of simple and easy implementation. The structure of a PID controller can be expressed as the sum of three terms, proportional, integral, and derivative control. The transfer function of such a PID controller can be expressed as:

$$G_{PID}(s) = K_P + \frac{K_I}{s} + K_D s \quad (4)$$

where, K_P, K_I, K_D are the proportional, integral and derivative gains of the controller. For the good performance of the system, these gains should be determined optimally. In this study, ICA is utilized to determine the optimal parameters of PID controller for each area. It is necessary to use a proper objective function for optimal tuning of controller parameters using evolutionary algorithms. The optimal values of gains of controller are obtained by minimizing the considered objective function. In this paper mean square error of ACE is taken as the optimization function which can be formulated in the following manner,

Minimize mean square of area control error

$$f = \frac{1}{n}\sum_{i=1}^{n}[(ACE_i)^2] = J = \frac{1}{n}\sum_{i=1}^{n}[(B_i \Delta F_i + \Delta Ptie_{i\_error})^2] \quad (5)$$

Here, f is used to determine the optimum gains of the PID controller for step load disturbance in different areas with the consideration of the following constraints

$$\begin{aligned} &K_{P,i}^{\min} \le K_{P,i} \le K_{P,i}^{\max} \\ &K_{I,i}^{\min} \le K_{I,i} \le K_{I,i}^{\max} \\ &K_{D,i}^{\min} \le K_{D,i} \le K_{D,i}^{\max} \end{aligned} \quad (6)$$

where, $K_{P,i}^{\min}$, $K_{I,i}^{\min}$, $K_{D,i}^{\min}$ and $K_{P,i}^{\max}$, $K_{I,i}^{\max}$, $K_{D,i}^{\max}$ are the lower bounds and upper bounds of the PID controller for area-i. The ACE minimization problem has been solved using the ICA which is explained in the following section.

3.2. Imperialist competitive algorithm (ICA)

ICA was proposed by Esmail Atasphaz- Gargari for optimization [31]. It starts with an initial population known as country, which is further divided in colony and states to make empires. After forming empires, imperialistic competition takes place among all the empires. During this competition weak empires will lose their power and collapse and at the end of competition only one empire will exists. The details of ICA are well explained in the references [31–39].

The major steps involved to determine the optimal PID parameters using ICA are given below.

3.2.1. Initialize the empires

In this step, first an array of variables (country) which is to be optimized is determined as,

$$\text{Country} = [p_1, p_2, p_3, \ldots\ldots p_N] \quad (7)$$

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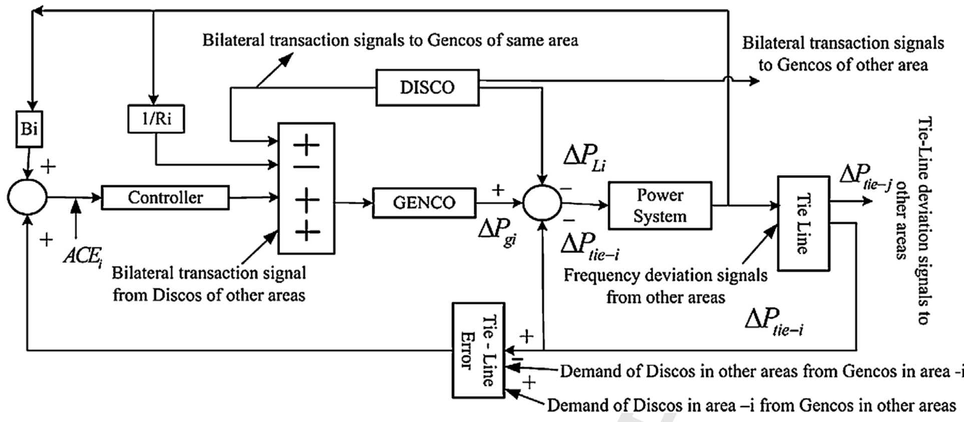

Fig. 2. AGC block diagram for area-i.

where, p_i is the set of variables to be optimized. Now the cost of a country by evaluating the cost function at the variables $[p_1, p_2, p_3, ...p_N]$is determined as,

$$\cos t = f(country) = f(p_1, p_2, p_3, ...p_N) \quad (8)$$

To form the initial empires, colonies are divided among imperialist uniformly using the normalized cost of an imperialist, which can be defined as

$$C_n = c_n - \max_i(c_i) \quad (9)$$

where, c_n is the cost of the n^{th} imperialist and C_n is its normalized cost. Now the normalized power (portion of colonies that should be possessed by that imperialist) of each imperialist is determined as,

$$P_n = \left| \frac{C_n}{\sum_{i=1}^{N_{imp}} C_i} \right| \quad (10)$$

where, N_{imp} is the most powerful countries to form empires. Finally the initial number of colonies of the n^{th} empire can be determined as,

$$N \times C_n = \mathrm{round}(P_n \times N_{col}) \quad (11)$$

where, $N \times C_n$ is the initial number of colonies of the n^{th} empire and N_{col} is the number of initial colonies.

3.2.2. Move the colonies towards their relevant imperialist

Each imperialist's colonies are assimilated to their respective imperialist given as,

$$x_{col}^{new} = x_{col}^{old} + \beta \times x \otimes (x_{imp} - x_{col}^{old}) \quad (12)$$

where, x_{col}^{old} represents the old position of colony, β represents the assimilation factor, x is a random variable with uniformly distribution. x_{imp}, x_{col}^{new} represent the position of imperialist and new position of colony respectively. Fig. 3 shows the movement of colonies toward their relevant imperialist. In Fig. 3, d is the distance between colony and imperialist, γ is a parameter that adjusts the deviation from the original direction and θ is a random number added to the direction of movement.

3.2.3. Imperialist competition

The imperialistic competition decreases the power of weaker empires and increases the power of more powerful empires. Powerless empires will collapse in imperialistic competition and their colonies will be divided among other empires.

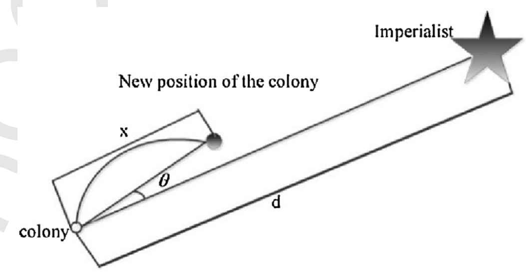

Fig. 3. Movement of colonies toward their relevant imperialist in a randomly deviated direction.

3.2.4. Convergence

At conversion point all empires collapse expect the most powerful one. At this point all colonies have same positions and same costs. At this condition imperialistic competition ends and the algorithm stop. The steps of ICA are shown in Fig. 4.

4. Results and discussion

The performance of the proposed ICA–PID controller has been checked on 2-area [6] and 3-area [40] power systems. The simulation for all the cases has been performed in MATLAB/Simulink R2011b environment.

4.1. Two area system

To check the performance of the ICA-PID controller, two area AGC scheme based on Fig. 2 is considered. Both the areas have two Gencos and two Discos respectively. ($Genco_{11}$, $Genco_{12}$, $Disco_{11}$ and $Disco_{12}$ (area-1), and $Genco_{21}$, $Genco_{22}$, $Disco_{21}$ and $Disco_{22}$ (area-2)). The parameters considered in AGC scheme is given in Table 1. The optimal parameters of the controller have been determined using the ICA and GA. The parameters of GA and ICA are given in Tables 2 and 3 respectively. The optimal values of parameters of PID controller determined Fig. 5 compare the convergence rate of ICA and GA for 2-area system. It is clear from this figure that the

Table 1
Two area power system parameters. Q6

Tg_i = 0.08 s Governor time constant	Tp_i = 24 s Power system time constant
Kp_i = 120 Hz/pu MW Power system gain constant	Tt_i = 0.3 s Turbine time constant
R_i = 2.4 Speed regulation	B_i =0.425 Frequency bias constant
Ti_j =0.0707, Synchronizing constant	

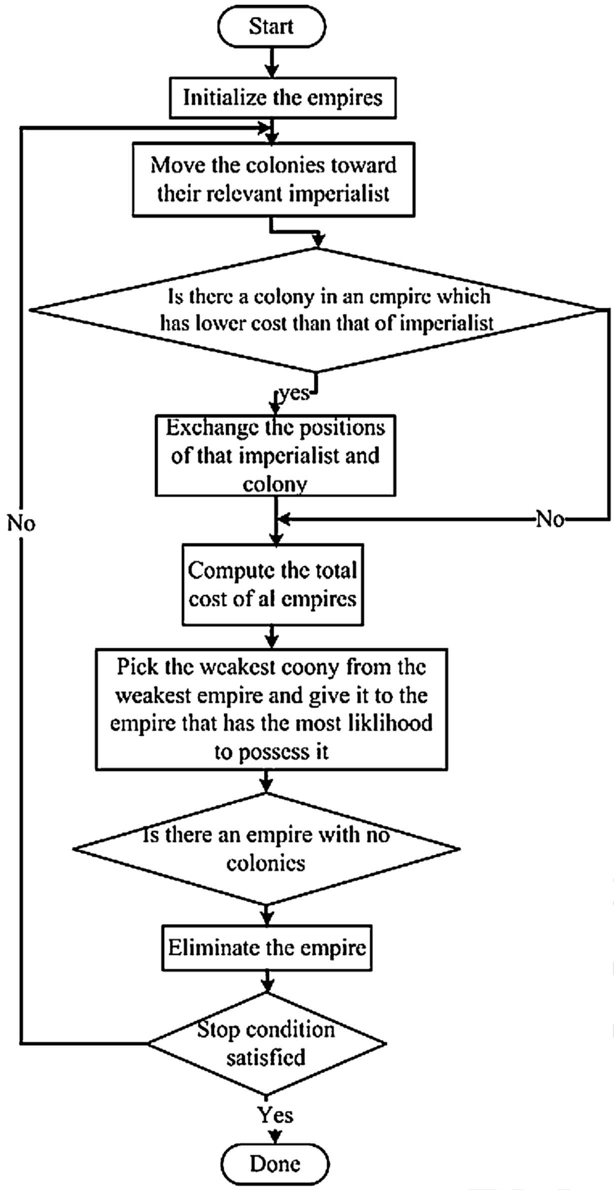

Fig. 4. Flowchart of the ICA algorithm.

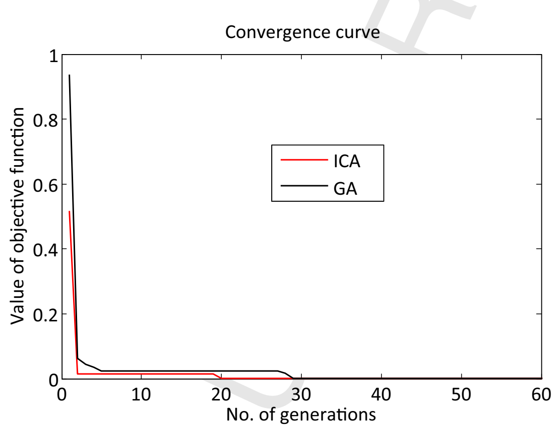

Fig. 5. Comparison of convergence characteristics of ICA with GA.

Table 2
GA Parameters.

	Value
Population size	20
Fitness scaling	rank
Elite count	2
Crossover	scattered
Selection	Stochastic uniform

Table 3
ICA parameters.

Parameters	Value
Number of countries	30
Number of Decades	100
Number of initial imperialist	2
Assimilation Coefficient (β)	2
Assimilation Angle Coefficient (γ)	0.5

convergence of ICA is faster than GA. ICA algorithm converges in 20 generations while GA converges after 30 generations .

4.1.1. Case study

In this case, 0.2 pu increase load demand has been considered in area-1 (0.1 pu in $Disco_{11}$ and 0.1 pu in $Disco_{12}$). To meet this demand $Disco_{11}$ and $Disco_{12}$ have contract with $Genco_{11}$ and $Genco_{12}$. Each Genco has ACE participation factors, given as, $\alpha pf_{11} = 0.5, \alpha pf_{12} = 0.5, \alpha pf_{21} = 0.5$, and $\alpha pf_{22} = 0.5$. The contract of Discos with Gencos is represented by following DPM .

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

A step increase in the demand of each Discos of area-1 has been considered at t = 0. The frequency deviation in area-1 and area-2 are given in Fig. 6(a). Fig. 6(b) shows deviation in the tie-line power. The results given in Fig. 6(a) show that frequency deviation in each area goes to zero at steady state. Since $Disco_{11}$ and $Disco_{12}$ in area-1, have increase in load demand, the transient dip in frequency of area-1 is larger than that of area-2. The actual power through tie-line goes to zero as shown in Fig. 6(b). At steady state, change in generation of all Gencos must match the demand of Discos. This desired generation of a Genco can be expressed in terms of contract participation factors and the total demand of Discos as given below,

$$\Delta P_{gi} = \sum_j cpf_{i_j} \Delta P_{Lj} \quad (13)$$

where, ΔP_{Lj} is the total load demand of Disco j and cpf_{ij} are elements of DPM.

$$\Delta P_{gi} = cpf_{i1}\Delta P_{L1} + cpf_{i2}\Delta P_{L2} + cpf_{i3}\Delta P_{L3} + cpf_{i4}\Delta P_{L4} \quad (14)$$

For the case under consideration,

$$\Delta P_{g11} = 0.5 \times \Delta P_{L1} + 0.5 \times \Delta P_{L2} = 0.1 \text{ pu} \quad (15)$$

Table 4
Optimum values for PID controllers.

	ICA-PID		
Two area	K_P	K_I	K_D
	−2	−0.0092	−2
Case-1	GA-PID		
	K_P	K_I	K_D
	−1.968	−0.014	−1.999

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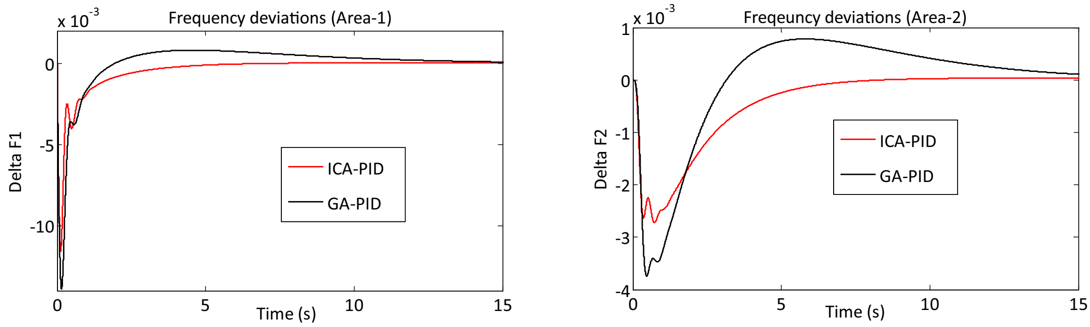
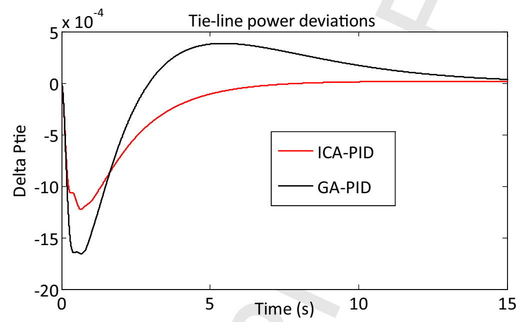
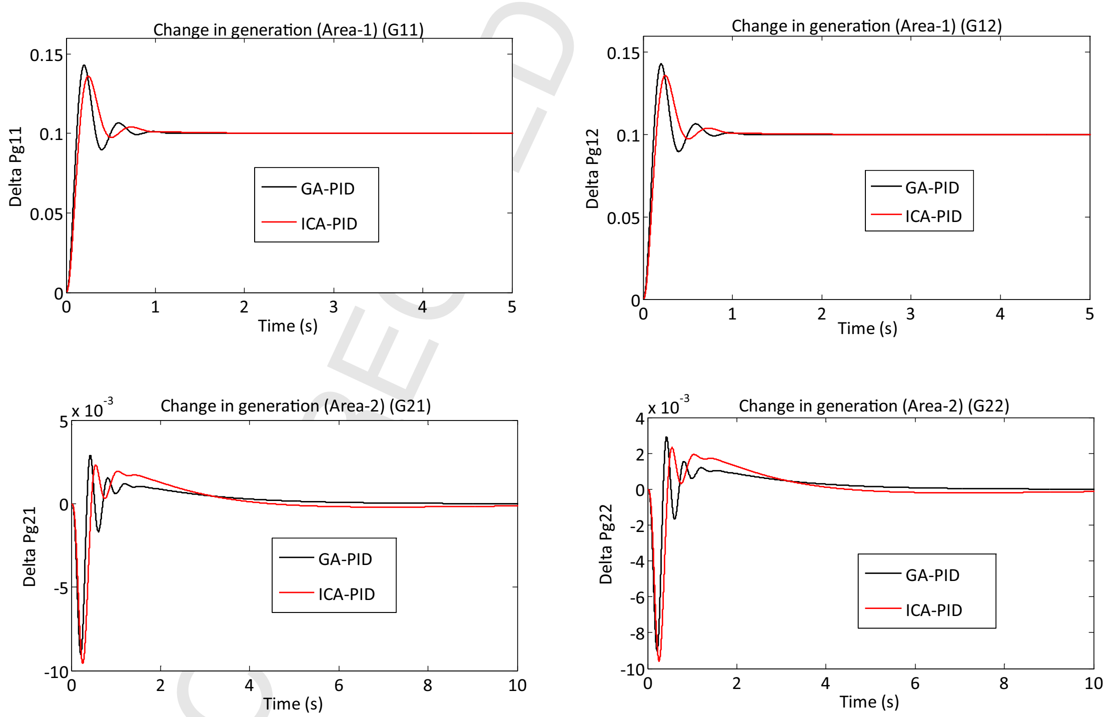


(a). Frequency deviations (rad/s).



(b). Tie line power (pu).



(c). Generated power (pu).

Fig. 6. (a) Frequency deviations (rad/s). (b) Tie line power (pu). (c) Generated power (pu).

Similarly, $\Delta P_{g12} = 0.1$ pu, $\Delta P_{g21} = \Delta P_{g22} = 0$ pu. Fig. 6(c) shows that real power output of each Genco in area-1 settled to 0.1 pu value at steady state. Since $Genco_{21}$ and $Genco_{22}$ of area-2 are not contracted by any Disco for power transaction, their real power output settled at zero at steady state, as shown in Fig. 6(c). It is observed that the tie-line power, frequency deviations, and change in generations are stabilized at steady state with lesser settling time and reduced oscillation using ICA-PID than GA-PID controller. It is seen from the Tables 5 and 6, that ICA-PID controller is less oscillatory and faster than GA-PID controller.

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Table 5
Comparative Study of Settling Time (Two area power system).

	Settling Time (second)		
Controller	Δf_1	Δf_2	ΔP_{tie}
ICA-PID	10	12	12
GA-PID	13	14	15

Table 6
Comparative Study of Peak Overshoot (Two area power system).

Case 1	Peak Overshoot (pu)		
Controller	Δf_1	Δf_2	ΔP_{tie}
ICA-PID	−0.0115	−0.00275	−0.001225
GA-PID	−0.0139	−0.00374	−0.001655

Table 7
Three area power system parameters.

Tg_i = 0.08 s governor time constant	Tp_i = 20 s power system time constant
Kp_i = 120 Hz/pu MW power system gain constant	Tt_i = 0.3 s turbine time constant
R_i = 2.4 speed regulation	B_i = 0.425 frequency bias constant
Ti_j = 0.545 synchronizing constant	Tr_i = 10 s Reheat turbine time constant

4.2. *Three area system*

To check the performance of the ICA-PID controller, a 3-area power system with reheat turbine and generation rate constraint (GRC) of 3% per minute has also been considered [40]. The system has two Discos and two Gencos in area-1 ($Genco_{11}$, $Genco_{12}$, $Disco_{11}$, and $Disco_{12}$), one Disco and one Genco (G_2, D_2, and G_3, D_3) in area-2 and area-3 respectively. The parameters of GA and ICA are same as given in Tables 2 and 3 respectively. The nominal parameters for 3-area system are given in Table 7.

Two cases are considered in the 3-area power system. In the first case, load changes occur in each area whereas, in the second case a contract violation occurs where Disco of area-1 violates the contract by demanding additional power than the contract. The optimal values of parameters of PID controller determined using ICA and GA are given in Table 8.

Fig. 7 compare the convergence of ICA with GA, applied to determine PID parameters for 3-area power system for the both cases. It is clear from Fig. 7 that for 3-area system the convergence of ICA is faster than GA. ICA converges in 45 generations while GA converges in 65 generations.

Table 8
Optimum Values for PID Controllers (Three area power system).

	ICA-PID		
	K_P	K_I	K_D
case 1	2	0.4181	2
case 2	1.5932	0.3042	0.1804
	GA-PID		
	K_P	K_I	K_D
case 1	1.115	0.289	0.03
case 2	2	0.359	0.447

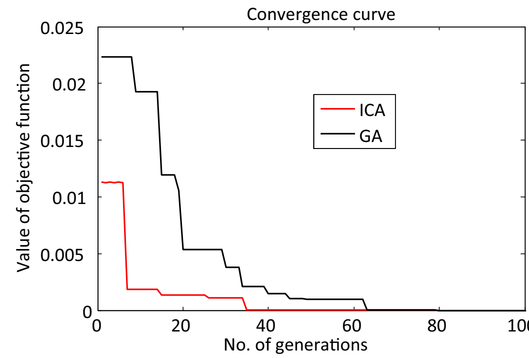

Fig. 7. Comparison of convergence characteristics of ICA with GA.

4.2.1. *Case 1*

Let us consider a case where each Disco has a demand of 0.01 pu. Each Disco has a contract of power transaction with each Genco of the system as per the given DPM.

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

$\alpha pf_{11} = \alpha pf_{12} = 0.5$, are the ACE participation factors considered for this case. At steady state each Genco must generate real power as given in (14). Therefore, the net change in the real power generation of Gencos of area-1 can be determine as,$\Delta P_{g_{11}} = (0.1 + 0.2 + 0.3 + 0.4) \times 0.01 = 0.01$ pu value.Dynamic response comparison for ICA-PID and GA-PID is shown in Fig. 8. Fig. 8(a) shows the frequency deviations of area-1 to area-3, which settle to zero value at steady state. The enlarged portion of frequency deviation figure of area-1 show the difference between the responses obtained with ICA-PID and GA-PID controller. Fig. 8(b) shows that tie-line power deviation between different areas settled down to their desired values with lesser settling time and reduced oscillation using ICA-PID than GA-PID controller. From Fig. 8(c), it is clearly seen that Gencos of area-1 to area-3 settled their real power output to their desired values smoothly using ICA-PID in comparison to GA-PID controller.

4.2.2. *Case 2: contract violation*

A Disco may violates a contract, by demanding additional power than the contract. This additional power may force the frequency to deviate from the nominal value. To keep the power system operational at nominal values, Gencos of the same area must supply this additional demand. On consider a case where $Disco_{11}$ of area-1 demands additional power of 0.01 pu. Therefore the total load demand in area-1 will be the contracted load of $Disco_{11}$ + additional load of $Disco_{11}$ + load of $Disco_{12}$ = (0.01 + 0.01) + 0.01 = 0.03 pu. This additional load of area-1 is reflected in the generation of $Genco_{11}$ and $Genco_{12}$ of area-1. Since Discos of area-2 and area-3 demanding the same load given in the contract, the power generation in area-2 and area-3 remains the same as the case 1, given in Section 4.2.1. The dynamic response obtained for frequency deviations, tie-line power flow and change in generation are shown in Fig. 9.

Fig. 9(a) and Fig. 9(b) show that ICA-PID gives better tracking of frequency deviations and tie-line power in comparison with GA-PID controller. Fig. 9(c) shows that Gencos of area-1 respond to the additional demand of area-1 and settled to a new generation level while Gencos of area-2 and area-3 settled to the same values as given in case 1. It is also seen that the deviation in change in real power generation is quite less with ICA-PID, compared to GA-PID controller. It is observed that the tie-line powers, frequency deviations, and change in generations are stabilized and settle to their desired values at steady state. The responses (transient and

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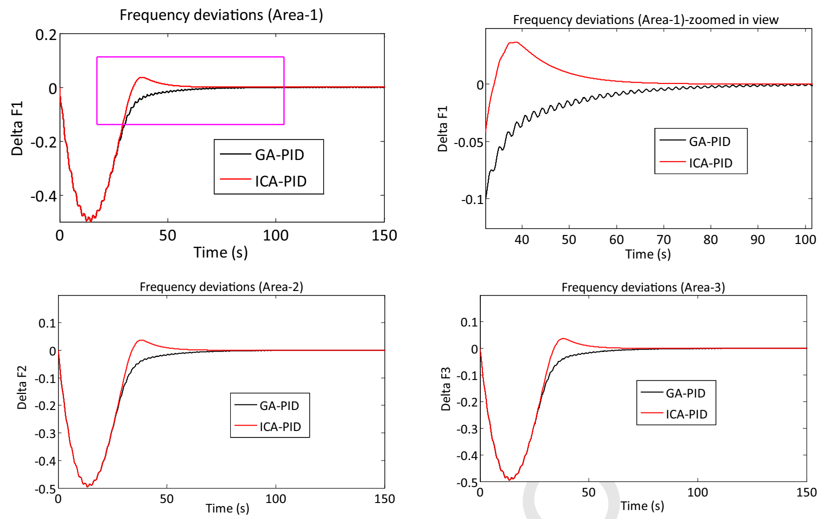
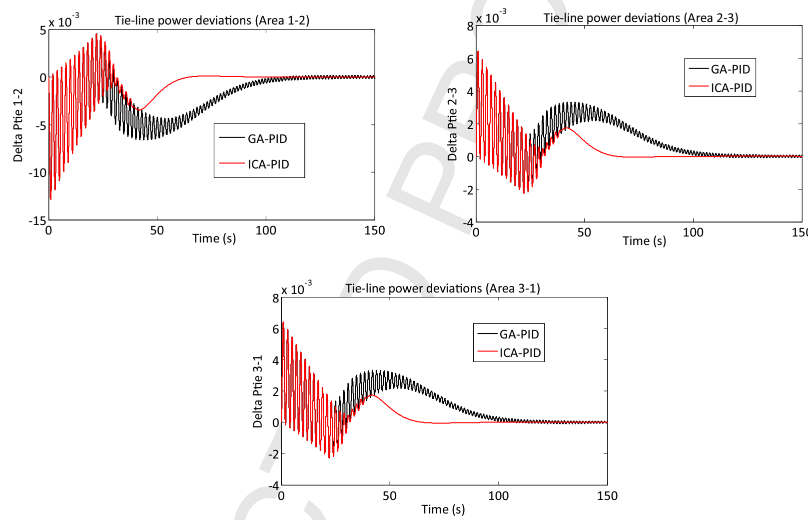
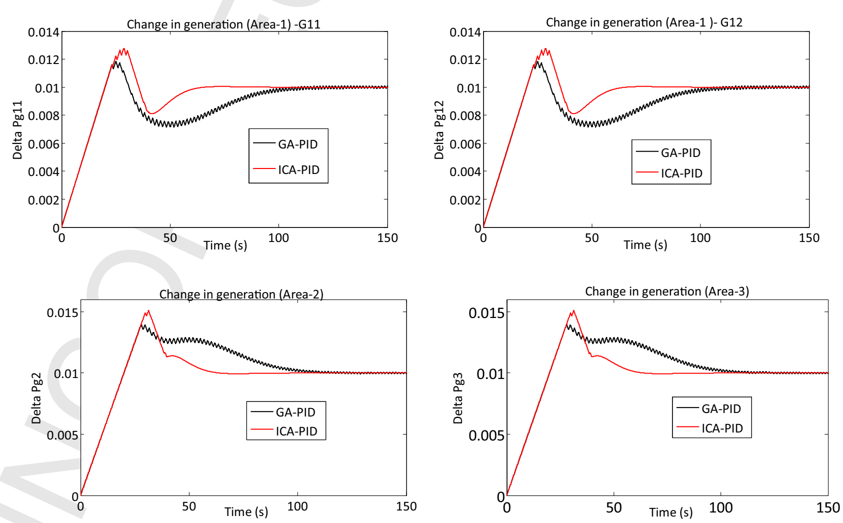


(a). Frequency deviations (rad/s).

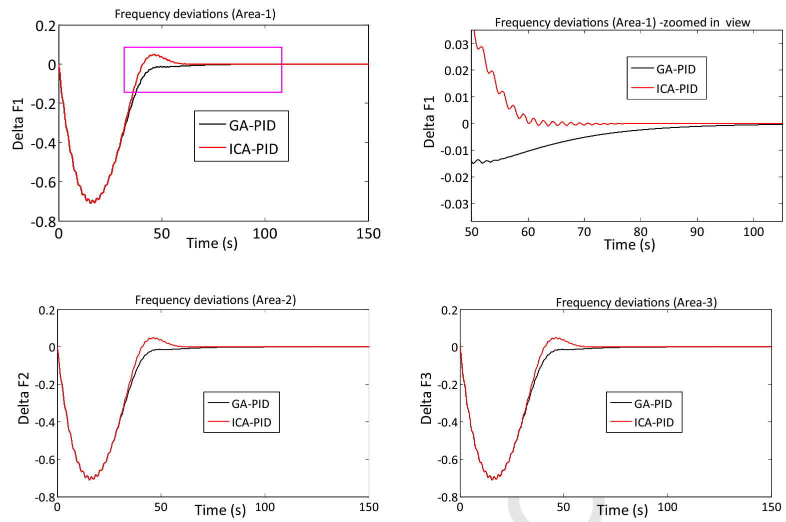


(b). Tie line power (pu).

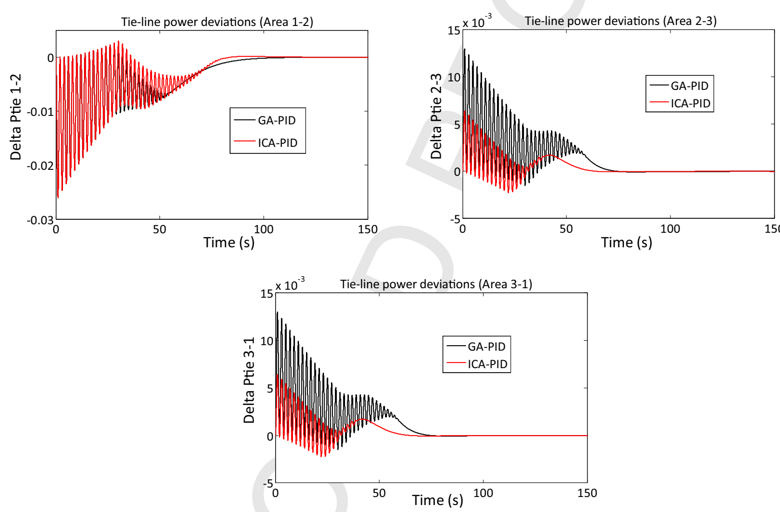


(c). Generated power (pu).

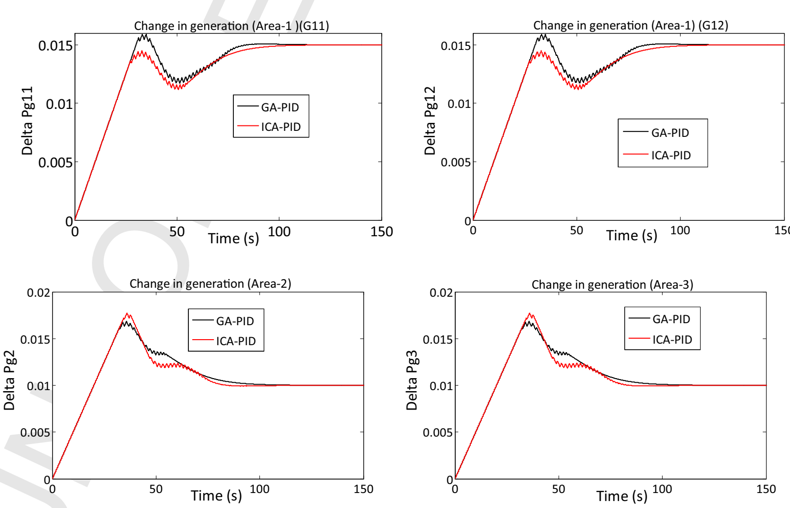
Fig. 8. (a) Frequency deviations (rad/s). (b) Tie line power (pu). (c) Generated power (pu).



(a). Frequency deviations (rad/s).



(b). Tie line power (pu).



(c). Generated power (pu).

Fig. 9. (a). Frequency deviations (rad/s). (b) Tie line power (pu). (c) Generated power (pu).

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Table 9
Comparative Study of Settling Time (Three area power system).

Controllers	Settling Time (second)			
	Case 1			
	Δf_1	Δf_2	Δf_3	$\Delta P_{tie1\text{-}2}$
ICA-PID	90	85	90	80
GA-PID	95	95	95	130
	Case 2			
	Δf_1	Δf_2	Δf_3	$\Delta P_{tie1\text{-}2}$
ICA-PID	90	90	90	90
GA-PID	95	95	95	105

steady state) show the superior performance of ICA-PID than GA-PID controller, in view of reduced settling time, and oscillations. Table 9 reveals that ICA-PID controller provides better settling performance than GA-PID.

5. Conclusion

In this paper, a PID controller is designed and applied to a multiarea power system in restructured environment. 2-area thermal power system and 3-area thermal-hydro power system with GRC have been used to check the performance of the controller. ICA is used to determine the optimal parameters of PID controller. The convergence of the ICA is faster compared to other search algorithm like GA. The PID controller is designed in such a way that it minimizes the ACE. Different market transactions and load change scenarios have been considered to show the effectiveness of the controller. Results show that the frequency error got eliminated in steady state and Gencos shared the load demand according to market transactions. ICA-PID controller has also been compared with GA-PID controller. The comparative results show that ICA-PID controller has better performance and improves system responses more effectively compared to GA-PID controller in terms of settling time and oscillations.

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