ISA Transactions ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at SciVerse ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research Article

A robust PID controller based on imperialist competitive algorithm for load-frequency control of power systems

Hamed Shabani, Behrooz Vahidi *, Majid Ebrahimpour

Department of Electrical Engineering, Amirkabir University of Technology, Hafez Ave., No 424, Tehran 159165-34311, Iran

ARTICLE INFO

Article history:
Received 10 October 2011
Received in revised form
23 September 2012
Accepted 29 September 2012
This paper was recommended for publication by Dr. A.B. Rad.

Keywords:
Imperialist competitive algorithm (ICA)
Automatic generation control (AGC)
Generation rate constraint (GRC)
Load frequency control (LFC)
PID controller

ABSTRACT

A new PID controller for resistant differential control against load disturbance is introduced that can be used for load frequency control (LFC) application. Parameters of the controller have been specified by using imperialist competitive algorithm (ICA). Load disturbance, which is due to continuous and rapid changes of small loads, is always a problem for load frequency control of power systems. This paper introduces a new method to overcome this problem that is based on filtering technique which eliminates the effect of this kind of disturbance. The object is frequency regulation in each area of the power system and decreasing of power transfer between control areas, so the parameters of the proposed controller have been specified in a wide range of load changes by means of ICA to achieve the best dynamic response of frequency. To evaluate the effectiveness of the proposed controller, a three-area power system is simulated in MATLAB/SIMULINK. Each area has different generation units, so utilizes controllers with different parameters. Finally a comparison between the proposed controller and two other prevalent PI controllers, optimized by GA and Neural Networks, has been done which represents advantages of this controller over others.

1. Introduction

Modern power systems are interconnected units which the electrical power is transferred between them. Automatic generation control (AGC) play a great role in power system because of its duty to preserve frequency and transferred power in their scheduled value, in normal condition and in case of a very slight deviation of the load. Generally AGC is a control system with three main objects as mentioned below:

- Preserving system frequency in its nominal value or a value close to it.
- Preserving correct value of power transfer between areas.
- Preserving each unit generation in an economically suitable value [1,2].

The initial aim of AGC is frequency regulation to nominal value and preserving power transfer between the control areas by changing output of selected generators. This is called load frequency control. The second aim is to distribute the needed change between generations of the units, so the operation cost will decrease [2,3].

When the load increases, the turbine's velocity will decrease until the governor could coordinate the incoming steam with the new load. The less changes of the velocity will result in less error. One way to restore nominal values of the velocity or the frequency is to add a PI controller to the system. The PI controller will detect the average value of error and overcome the deviation. Since the power system load change is continuous, generation control is set to automatic state to restore nominal values of frequency [4,5].

It is obvious that frequency is related to active power (P) and any change of power is influenced by system frequency. An optimal power system should tolerate sudden changes of load and preserve voltage and frequency in an acceptable range. Lots of investigations have been done on the load-frequency control of power system in the latest decades that represent its important effect on power system generation, operation, and reliability and power quality. Also deregulation in power systems has attracted lots of attention on the LFCs since numerous on/off switching in the load side have made it difficult to precisely preserve the frequency nominal value. All conventional LFC schemes have two substantial problems; first increasing the gain of frequency feedback will result in LFC loop instability, i.e., frequency drop control range will be limited; Second they will be unstable if there is any load disturbance in the power system. Substitution of the conventional PI controller with a new PID controller can improve the operation of LFC.

* Corresponding author. Tel.: +98 21 64543330; fax: +98 21 66406469.
E-mail addresses: h_shabani@aut.ac.ir (H. Shabani), vahidi@aut.ac.ir (B. Vahidi), m.ebrahimpour@aut.ac.ir (M. Ebrahimpour).

0019-0578/$ - see front matter © 2012 ISA. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.isatra.2012.09.008

It is well known that in actual power system, LFC is exposed to load disturbance. The disturbance mentioned here is due to continuous and rapid changes of very small loads in each area of power system. In this paper the load disturbance represents very small changes of the load in rate of 1 Hz and amplitude range of [−0.001, 0.001] p.u.

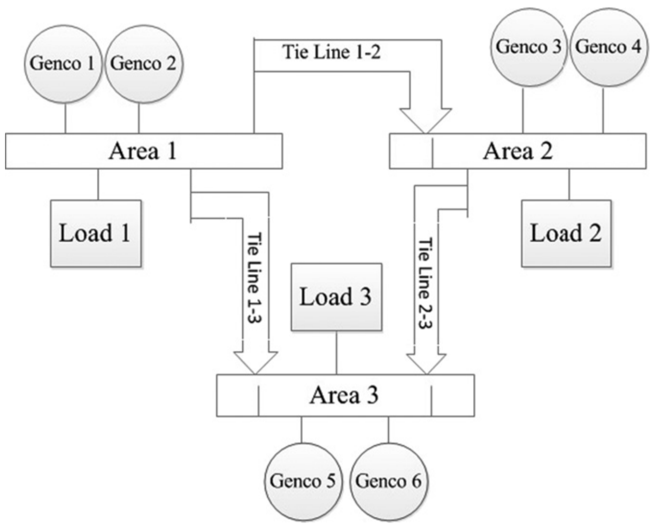

Fig. 1. Block diagram of the three-area power system.

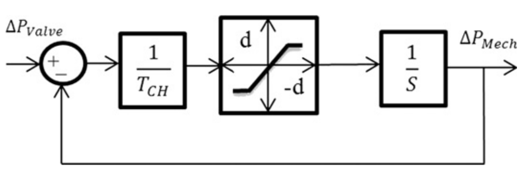

Fig. 2. Block diagram of nonlinear turbine (GRC).

Using *derivative operator*(s) in the controller will boost disturbances drastically which causes system instability. If the disturbance problem could be solved in some manner, the PID control can provide better performance in comparison to the PI control. Lots of efforts have been made to utilize the filtering techniques in order to solve this problem. For this purpose, a low-pass filter can be added to the differential feedback loop but this method has the following drawbacks [6]:

1) The feedback effects of the differential signal will be reduced if the filtering function is reinforced.
2) An increase in the gain of the filter block may change system behaviour. The change could be system instability.

To overcome the mentioned drawbacks, a 1st order low-pass filter with an appropriate time constant has been added to the differential feedback loop serially to eliminate load disturbance. Parameters of the PID controllers including K_I, K_D and K_P have been determined by using ICA, so that in a wide range of load changes the dynamic response of frequency has better performance with respect to PI controllers optimized by GA and Neural Networks [7]. More over by optimization of the K_D parameter of the controller, the suitable gain of the filter can be set to avoid subsequent problems.

2. Three-area load frequency control model

As mentioned in the previous section, the investigated power system is a three-area system that is given in Fig. 1.

Directions of power transfer between areas are:

- Area 1 to area 2.
- Area 2 to area 3.
- Area 1 to area 3.

There are two generation units with non-identical capacity in each area, so we have six generation units that each one has a

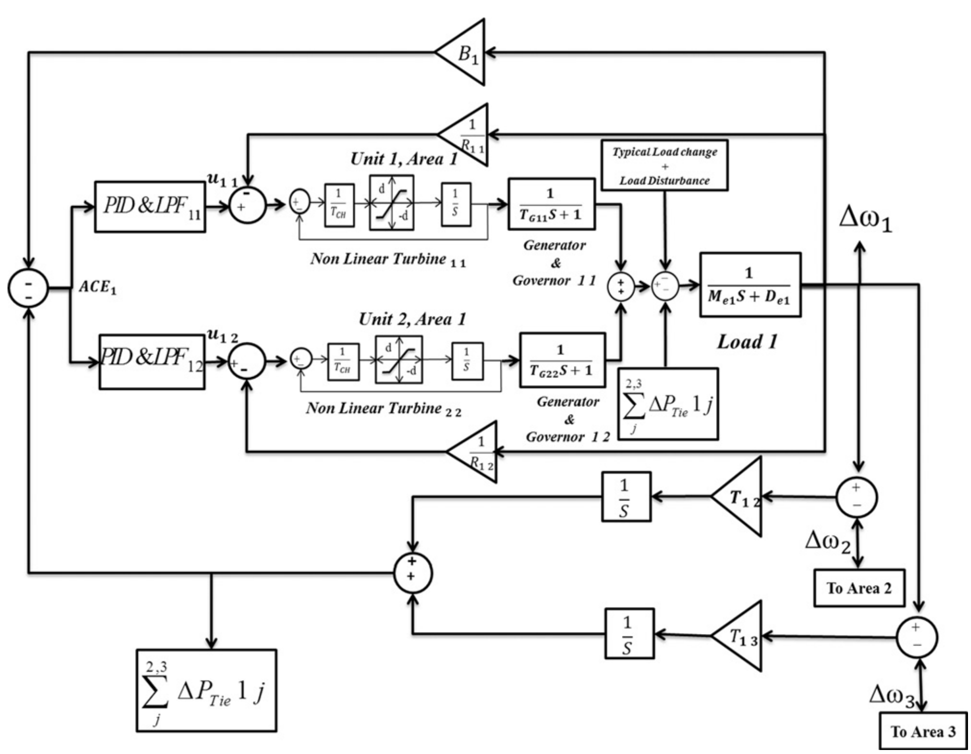

Fig. 3. Block diagram of area 1, unit 1 and 2.

turbine with a different capacity. It is needed to utilize a unique controller for each generation unit, so six controllers must be considered totally. Each turbine has a maximum generation rate. The constraints of the nonlinear characteristics of the turbine control should be considered in the load frequency controller design. The power system may face large momentary disturbance if these constraints are not considered in the controller design. So in this paper we have used the nonlinear model of the turbine to take into account the effect of non-linear elements such as GRC that emulates the practical limit on the response of the turbine [8].

Block diagram of the turbine is illustrated in Fig. 2 in which T_{CH} is charging time.

As long as each area is transferring power to two other ones, the transferred power, by considering the directions of power transfer between areas, is considered contributing to Area Control Error (ACE). ACE is a linear combination of tie line power variation and local frequency variation in a same area. Fig. 3 shows block diagram of area-1 of the three-area power system. The load disturbance will cause malfunction of the PID controller in a LFC system, thus its effect should be eliminated in some manner. Using the proposed filter is a simple and suitable method to achieve this object. A 1st order low-pass filter is used in order to minimize the changes of the system behaviour due to adding the differential block. Eq. (1) gives the transfer function of the filter.

$$H_D(s) = \frac{1}{1+\tau s} \qquad \|\tau\| < < 1 \tag{1}$$

Effects of the filter can be minimized by selecting a small amount of time constant, evolved in the equation. However insufficient filtering can occur by selecting a too small amount of τ. The value of τ is usually selected several times less than the period of the lowest frequency disturbance [4]. The value of the lowest frequency disturbance is 1 Hz, so an amount of 0.1 s is selected for τ here. Block diagram of the proposed PID controller of each unit is shown in Fig. 4. Output of the PID controller is u_{ik} which $i=\{1,2,3\}$ refers to the areas, and $k=\{1,2\}$ refers to the generation units. The input of the controller is area control error of area "i" (ACE_i) which is given by Eq. (2). $\Delta\omega_i$ is the frequency deviation (Δf) of area ith due to load change in area ith which and parameter B_i is calculated by Eq. (3).

$$\mathrm{ACE}_i = \sum_j \Delta P_{Tie_{i-j}} + B_i \Delta\omega_i \tag{2}$$

$$B_i = D_{e_i} + \sum_{k=1,2} \frac{1}{R_{ik}} \tag{3}$$

$\Delta P_{Tie_{i-j}}$ is the active power flow between areas i and j which can be calculated by Eq. (4). Also the block diagram of the tie line between areas i and j is presented in Fig. 5.

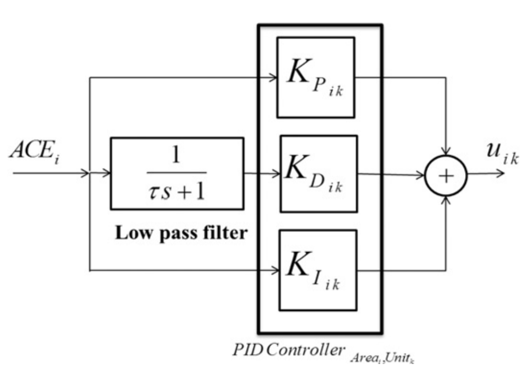

Fig. 4. Block diagram of PID controller and low pass filter, area-i, unit-k ($i=1,2,3$ and $k=1,2$).

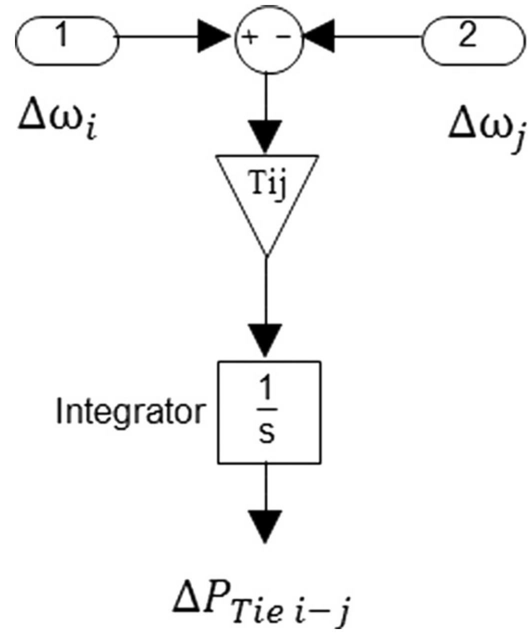

Fig. 5. Block diagram of the tie line between areas i and j.

$$\Delta P_{Tie_{i-j}} = \frac{T_{ij}}{s}(\Delta\omega_i - \Delta\omega_j) \tag{4}$$

Power systems parameters are given in Table 1 [1,2].

3. Objective function

Saturation effects of power system components have been considered in the design of the proposed controllers. The designed controllers can profit from the utmost permissible capabilities of the system components to decrease the amount of frequency deviation.

For designing purposes, the cost criterion function can be based on minimizing the following criteria [9]:

- IAE: Integral of absolute error.
- ISE: Integral of square error.
- ITAE: Integral of time multiplied absolute error.

Equations of Table 2 are used to calculate the mentioned criteria. IAE and ISE decrease the maximum of overshoot more than ITAE, however ITAE has the advantage of decreasing settling time more than IAE and ISE [9].

The new cost function not only should have the advantages of conventional cost functions but also should prevent saturation of system components. In this paper the objective function is developed in comparison to the conventional objective functions introduced in other related papers like [9]. The new and hybrid objective function includes ITAE, changes and overshoot of ACE signal, frequency and its overshoot in each area and the transferred power of the tie lines. This objective function is given by Eq. (5).

$$\mathrm{Cost}(K_P,K_I,K_D) = \sum_{i=1}^{3}\left\{\frac{1}{T}\int_0^{\infty} t \times |\mathrm{ACE}_i|(t)dt + \sum_{\substack{j=1\\ j\neq i}}^{3}\frac{1}{T}\int_0^{\infty} t \times |\Delta\omega_i|(t)dt + \frac{1}{T}\sum_{\substack{j=1\\ j\neq i}}^{3}\int_0^{\infty} t \times |\Delta P_{Tie_{i-j}}|(t)dt\right\} + \mathrm{Overshoot}(|\mathrm{ACE}_i|)$$

Please cite this article as: Shabani H, et al. A robust PID controller based on imperialist competitive algorithm for load-frequency control of power systems. ISA Transactions (2012), http://dx.doi.org/10.1016/j.isatra.2012.09.008

$$+\text{Overshoot}(|Dw_i|)$$

$$+\text{Overshoot}\left(\left|DP_{Tie\ i-j}\right|\right) \quad (5)$$

Considering the properties of the three criteria discussed above, this new objective function utilizes ITAE as long as it decreases settling time more than IAE and ISE, but unfortunately it cannot decrease the maximum overshoot of error signal as same as the two other criteria; so the three last terms have been added to the objective function to decrease the overshoot of error signal as long as they would be decreased autonomously by the optimization process of the objective function.

It should be noted that in the first term, ACE_i contains $\Delta\omega_i$ according to Eq. (2); so to prevent any interference, the second term introduces only when $j \neq i$. Parameter T is the optimization duration in second. MATLAB code is used to calculate the overshoot of the each signal in the optimization period, so that the value of maximum overshoot would be chosen to be added to the cost function. All of the signals in Eq. (5) are finite and a big number (1000 s) has been applied instead of ∞ in this simulation, so that the signal will be integrated completely.

For the purpose of considering saturation effects and non-linearity of turbines, the total load change has been considered. The total load change is the sum of load disturbances and a wide range of considerable load changes shown in Fig. 6. Parameters of the controllers shall be optimum for this total range in each area, so the AGC can have the best response. Other optimization methods optimize the objective function only for a specific value of load change without considering the disturbance effects, which cannot be practically used in an actual power system.

Table 1
Parameters of the power system [1,2].

Parameters	Generation unit					
(QUOTE $MVA_{base}=1000$ MVA) $f=60$ Hz	**Area 1**		**Area 2**		**Area 3**	
	Unit **no. of 1**	Unit **no. of 2**	Unit **no. of 3**	Unit **no. of 4**	Unit **no. of 5**	Unit **no. of 6**
M_e (s)	8	10	8	10	8	10
R (Hz/p.u)	0.0625	0.05	0.0625	0.05	0.0625	0.05
T_G (s)	0.3	0.2	0.3	0.2	0.3	0.2
T_{CH} (s)	0.6	0.5	0.6	0.5	0.6	0.5
D_e	0.9		0.6		0.5	
T_{ij} (p.u/rad)	$T12=2$		$T13=2$		$T23=2$	

Table 2
Equation criteria.

$IAE = \int_0^\infty \lvert e(t)\rvert dt$
$ISE = \int_0^\infty e^2(t)dt$
$ITAE = \int_0^\infty t\lvert e(t)\rvert dt$

4. Imperialist competitive algorithm

In an optimization problem, having an objective function cost (p), the object is to find an argument "p", whose relevant cost is optimum. A variety of algorithms have been proposed for this purpose, including GA, PSO and Fuzzy logic. These algorithms are mostly based on computer simulation of the natural processes, but the imperialist competitive algorithm is inspired by imperialistic competition. ICA is an evolutionary algorithm which starts with some initial populations, each one called a country [8].

If the optimization problem is N-dimensional, a country is a $1 \times N$ array, defined by:

$$\text{country} = [p_1, p_2, p_3, \ldots, p_{N_{var}}] \quad (6)$$

Our optimization problem is designing a robust PID controller for the load-frequency control of the power system, so we generate the initial country that is defined by:

$$\text{country}_{i\,k} = [K_{P_{i\,k}}, K_{I_{i\,k}}, K_{D_{i\,k}}] \quad (7)$$

The initial matrix of the countries is defined by:

$$\text{COUNTRY} = \begin{bmatrix} \text{country}_{11} \\ \text{country}_{12} \\ \text{country}_{21} \\ . \\ \text{country}_{ik} \\ . \\ \text{country}_{\text{Area}\,\sharp\,\text{Unit}\,\sharp} \end{bmatrix}$$

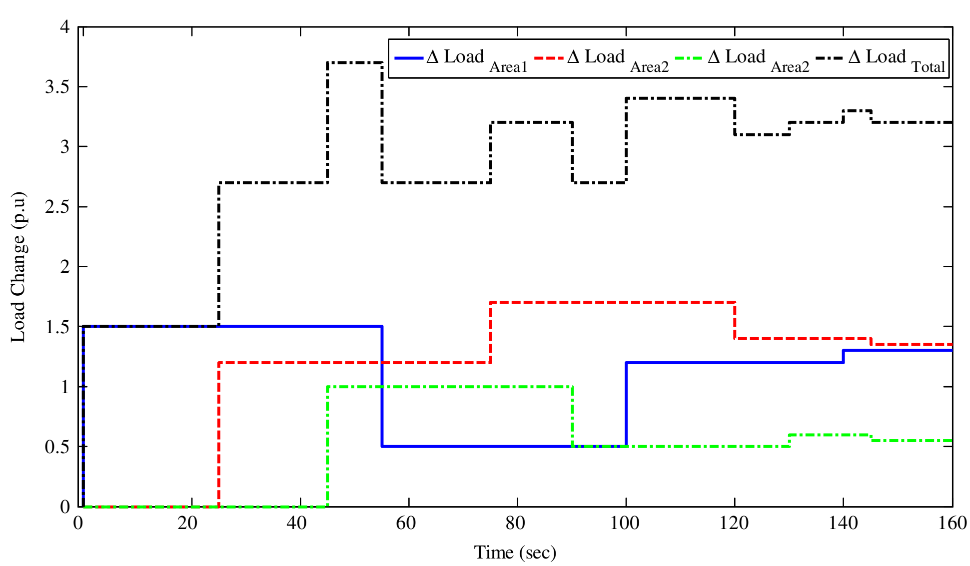

Fig. 6. Typical load changes.

$$= \begin{bmatrix} K_{P_{11}} & K_{I_{11}} & K_{D_{11}} \\ K_{P_{12}} & K_{I_{12}} & K_{D_{12}} \\ K_{P_{21}} & K_{I_{21}} & K_{D_{21}} \\ . & . & . \\ K_{P_{ik}} & K_{I_{ik}} & K_{D_{ik}} \\ . & . & . \\ K_{P_{\text{Area Num Unit Num}}} & K_{I_{\text{Area Num Unit Num}}} & K_{D_{\text{Area Num Unit Num}}} \end{bmatrix} \quad (8)$$

The cost function which is according to Eq. (5), is extracted as the output of figure (III), implemented by Simulink. In order to calculate the cost functions, the initial matrixes of the countries are transferred to the Simulink. According to Table 3, there are 500 countries which will result in 500 initial cost functions. These cost functions are transferred to the ICA algorithm subsequently. A country with a less cost is deduced as a powerful one, so N_{imp} of the most powerful ones will be selected to form empires. Rest of them will be the colonies; each of them belongs to an empire. The power of weaker empires will decrease and the power of more powerful ones will increase gradually during imperialistic competition. This competition is modelled by picking some of the weakest empires to initiate a competition among all empires to possess these weak colonies. The most powerful empires have more chance to possess these colonies. In the competition process, weak empires will lose their colonies and ultimately all the empires except the most powerful one will collapse, so just this unique empire will govern all the colonies in a country which the power and position of its colonies and the empire is identical. In this process whenever it is needed to calculate a new cost function, the algorithm transfers new parameters to the Simulink and extract the cost function. The first iteration will end after this process. This procedure ends when the stop condition 100 iterations according to Table 3 is satisfied. The minimum value between all the cost functions will be selected as the optimum one. This cost function results the optimum parameters of the controllers. γ, ζ, β are the ICA parameters [10] and are given in Table 3. Flow chart of ICA algorithm is presented in Fig. 7.

Table 3
Parameters of ica algorithm.

Number of iterations	100	β	1.5
Number of countries	500	γ	0.5
Number of initial empires	40	ζ	0.05
Number of initial colonies		$500-40=460$	

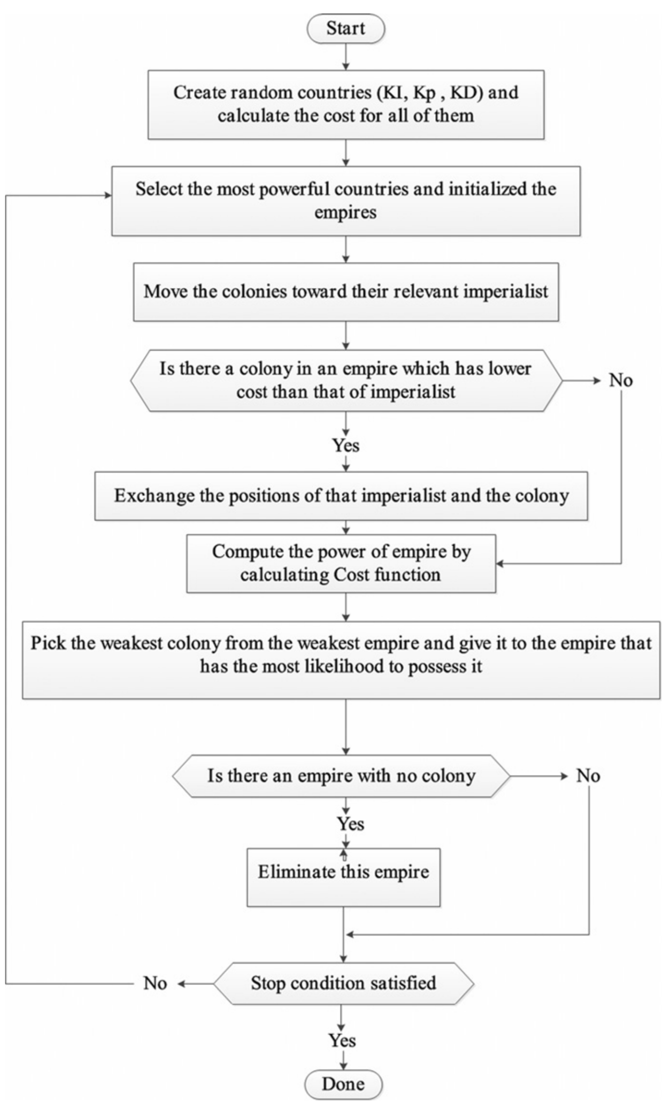

Fig. 7. Flow chart diagram of ICA algorithm.

In this paper two other prevalent PI controllers, optimized by GA [7,9,11] and Neural Networks [7] has been simulated in MATLAB/SIMULINK to make a comparison with the results of ICA. The type of neural network controller is NARMA-L2. NARMA model is an exact representation of input/output behaviour of a finite-dimensional and nonlinear discrete time dynamic plant in neighbourhood of the equilibrium state [7]. Its implementation for real time control systems is difficult as long as it has non-linearity property. Two classes of NARMA are introduced in [7], NARMA-L1 and NARMA-L2, to overcome computational complexity related to use of this type of ANN. Using multi-layer neural networks, the NARMA-L2 is more convenient to be practically implemented.

Also a kind of discontinuous GA is used in this paper which its objective function is the same as ICA, i.e., its objective function is Eq. (5). Also the parameters of K_I is obtained by GA optimization and presented in Table 4.

Table 4
Obtained optimal coefficients of the controllers.

Areas\units			Optimal values of the coefficients		
╳	**No. of area**	**No. of unit**	K_P	K_I	K_D
PID controller -ICA	**Area 1**	**1**	1.08716	1.85041	1.111767
		2	1.81119	1.99962	1.048346
	Area 2	**3**	1.02830	1.99986	0.465220
		4	0.01277	1.78810	1.964379
	Area 3	**5**	0.00014	0.01286	1.999039
		6	0.04649	1.83836	0.000477
PI controller-GA	**Area 1**	**1**	=	0.17070	=
		2	=	0.19060	=
	Area 2	**3**	=	0.22832	=
		4	=	0.12830	=
	Area 3	**5**	=	0.31433	=
		6	=	0.21510	=

It should be noted that the power system used in this paper is identical for all the three methods but the load disturbances has not been considered for the NN and GA as long as they will be unstable. This clearly shows their defect to be practically implemented in the actual power system.

5. Simulation results

MATLAB/SIMULINK was used for simulation studies on the explained three-area power system. By considering the power system parameters, the proposed new objective function, the total load changes (sum of the load disturbance and the load changes shown in Fig. 6), the coefficients of the PID controllers were obtained by applying ICA. Table 5 depicts the obtained coefficients.

Table 5
Nomenclature.

$\Delta\omega_i$	Incremental frequency deviation of area I in (Hz)
$\Delta P_{Tie_{i-j}}$	Power deviation of the tie-line between the areas i and j
M	Angular momentum of load
R_i	Droop characteristic in (Hz/p.u)
$T_{G\ i\ k}$	time constant of area i, unit k, in (s)
T_{CH}	Turbine charging time
D_e	Area load governing characteristic;
T_{ij}	Tie-line synchronizing coefficient between area i and j
β, γ, ζ	Parameters of ICA algorithm

By using the proposed controllers and all the values of the load changes shown in Fig. 6 and the load disturbances, the simulation of the three area power system has been done. Frequency deviation of the three areas due to a wide range of load changes is shown in Fig. 8. Also a comparison between the power system responses is evaluated using the proposed PID controllers, the GA and Neural Network optimized PI controllers which have been applied in a same system in [7].

Figs. 9 and 10 display frequency deviation of the three areas due to a wide range of load changes, using the mentioned controllers.

Power deviation responses of the tie-lines due to a wide range of load changes, are illustrated in Figs.11–13.

Figs. 8–13 clearly illustrate the effectiveness of the proposed PID controllers. The frequency deviation response based on these controllers is better than both the GA and the Neural Network optimized PI controllers in terms of fast response and small maximum overshoot. Furthermore the tie-lines power values

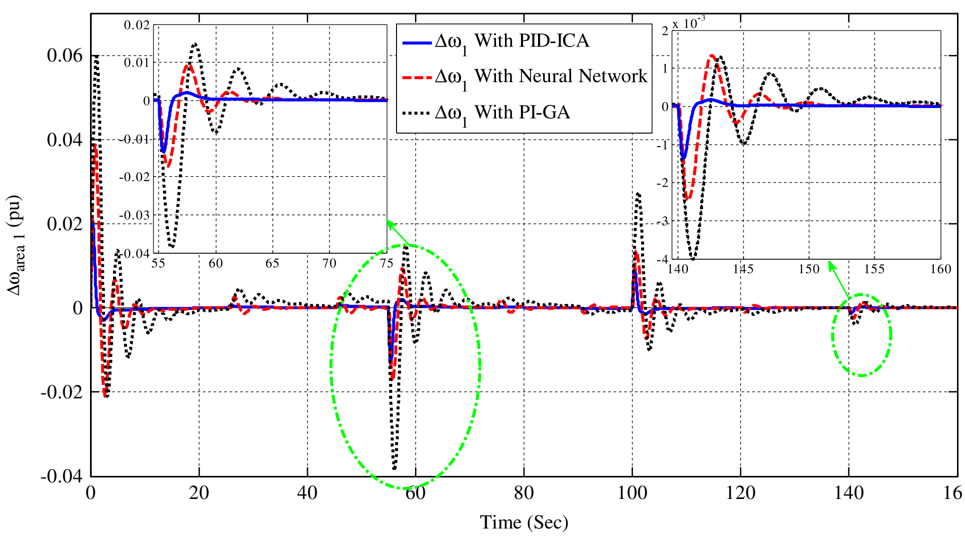

Fig. 8. Frequency deviation of area 1 due to load changes of Fig. 6 and load disturbance.

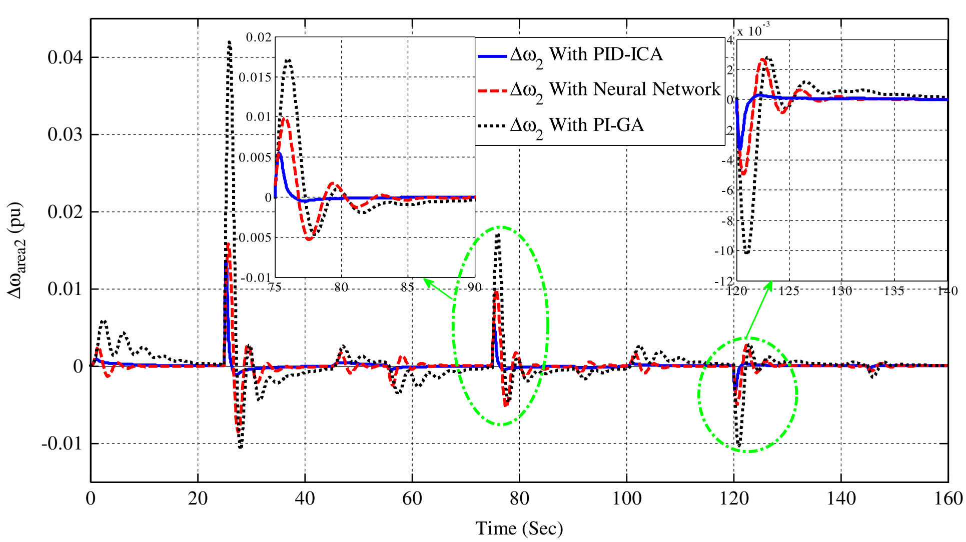

Fig. 9. Frequency deviation of area 2 due to load changes of Fig. 6 and load disturbance.

Please cite this article as: Shabani H, et al. A robust PID controller based on imperialist competitive algorithm for load-frequency control of power systems. ISA Transactions (2012), http://dx.doi.org/10.1016/j.isatra.2012.09.008

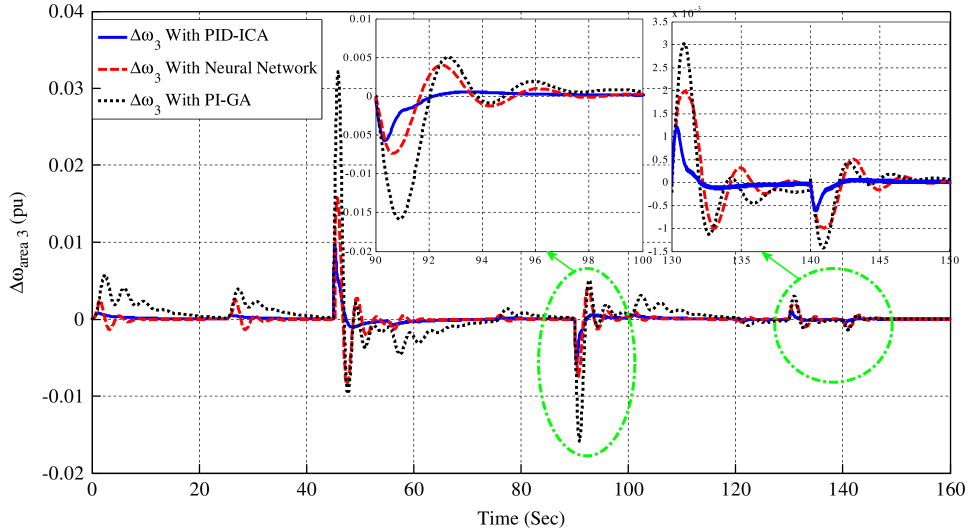

Fig. 10. Frequency deviation of area 3 due to load changes of Fig. 6 and load disturbance.

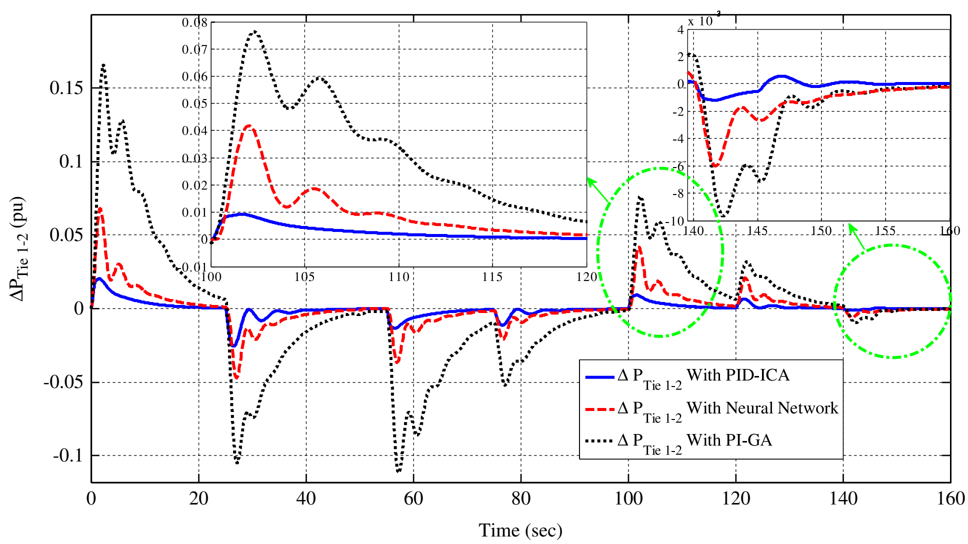

Fig. 11. Power deviation response of the tie-line between the areas 1 and 2 due to load changes of Fig. 6 and load disturbance.

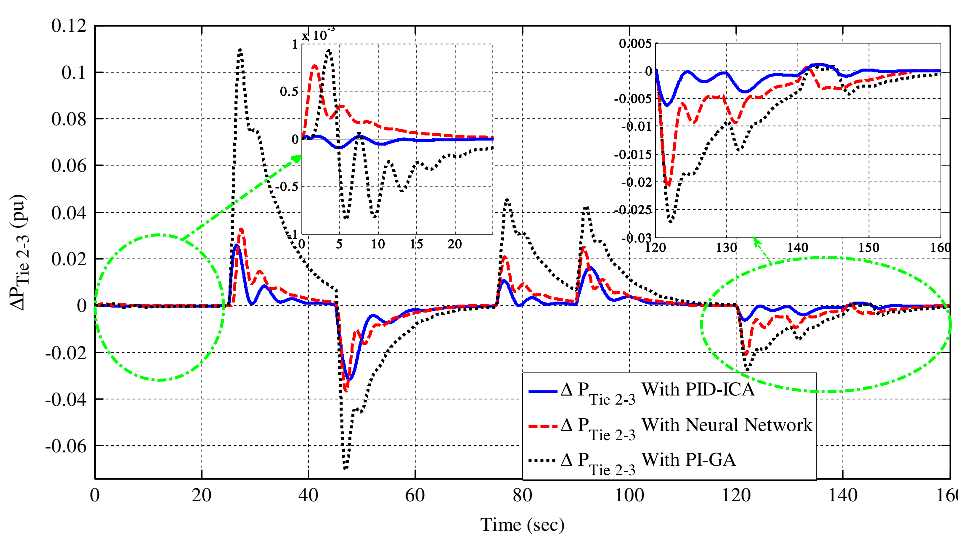

Fig. 12. Power deviation response of the tie-line between the areas 2 and 3 due to load changes of Fig. 6 and load disturbance.

Please cite this article as: Shabani H, et al. A robust PID controller based on imperialist competitive algorithm for load-frequency control of power systems. ISA Transactions (2012), http://dx.doi.org/10.1016/j.isatra.2012.09.008

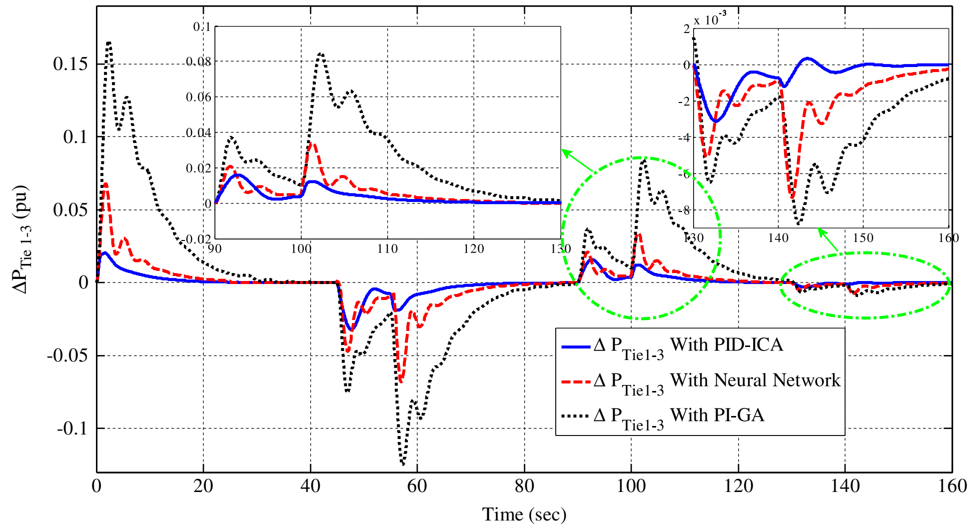

Fig. 13. Power deviation response of the tie-line between the areas 1 and 3 due to load changes of Fig. 6 and load disturbance.

have less oscillation and faster damping by applying the proposed PID controllers. Investigation on the other related papers and comparing the results, show better performance of the ICA optimization, specially optimized PID controllers [10,12–15].

6. Conclusion

A kind of load disturbance robust PID controller for load-frequency control of power system is presented in this paper. Three of these controllers have been considered for LFC of a three-area power system and parameters of them was obtained based on imperialist competitive algorithm. A simple and suitable filtering technique has been used to decrease the effects of disturbance which is always a major problem for the LFC purpose of power systems. Unlike other works which represent optimization of the objective function only for a specific value of load change, in this paper a wide range of load changes – which the disturbance has been added to it – is applied to consider saturation effects and non-linearity of turbines, so that LFC should be optimum for this wide range. Simulation results show a better performance of ICA optimized PID controllers with respect to the GA and Neural Network Optimized PI controllers. Dynamic response of the simulated power system has improved significantly by applying the proposed ICA optimized PID controllers.

References

[1] Wood AJ, Wollenberg BF. Power generation, operation and control. New York: John Wiley & Sons; 1996 pp. 328-362.
[2] Kundur P. Power system stability and control. New York: McGraw-Hill; 1994.
[3] Bevrani H, et al. Robust decentralized AGC in a restructured power system. Energy Conversion and Management 2004;45:2297–312.
[4] Saikia L Chandra, et al. Performance comparison of several classical controllers in AGC for multi-area interconnected thermal system. International Journal of Electrical Power & Energy Systems 2011;33:394–401.
[5] Dong L, et al. A robust decentralized load frequency controller for interconnected power systems. ISA Transactions 2012;51:410–9.
[6] Moon YH, et al., Power system load frequency control using noise-tolerable PID feedback, presented at the industrial electronics (ISIE), Pusan, 2001.
[7] Adaryani MR, Afrakhte H. NARMA-L2 controller for three-area load frequency control, in Electrical engineering (ICEE), 2011 19th Iranian conference on, 2011, pp. 1–6.
[8] Heon-Su R, et al., Extended integral control for load frequency control with the consideration of generation-rate constraints, In: Power engineering society summer meeting, IEEE, 2000; vol. 3, pp. 1877–1882.
[9] Abdel-Magid YL, Dawoud MM. Genetic algorithms applications in load frequency control genetic algorithms in engineering systems: innovations and applications, presented at the first international conference on (Conf. Publ. No. 414), GALESIA, 1995.
[10] Atashpaz-Gargari E, Lucas C. Imperialist competitive algorithm: an algorithm for optimization inspired by imperialistic competition, In: Evolutionary computation CEC, IEEE congress on, 2007, pp. 4661–4667.
[11] Herreros A, et al. Design of PID-type controllers using multiobjective genetic algorithms. ISA Transactions 2002;41:457–72.
[12] Rajabioun R, et al. Colonial competitive algorithm: a novel approach for PID controller design in MIMO distillation column. Process International Journal of Intelligent Computing and Cybernetics 2008;1:337–55.
[13] Oskouyi A Biabangard, et al. Application of imperialist competitive algorithm for material properties characterization from sharp indentation test. International Journal of Engineering Simulation (IJES) 2010;43:495–506.
[14] Moghimi Hadji M, Vahidi B. A solution to the unit commitment problem using imperialistic competition algorithm. Power Systems, IEEE Transactions on 2012;27:117–24.
[15] Ebrahimzadeh A, et al. Control chart pattern recognition using K-MICA clustering and neural networks. ISA Transactions 2012;51:111–9.