Ain Shams Engineering Journal (2014) 5, 121–135

Ain Shams University

Ain Shams Engineering Journal

www.elsevier.com/locate/asej
www.sciencedirect.com

ELECTRICAL ENGINEERING

Fractional order PID controller design for LFC in electric power systems using imperialist competitive algorithm

Seyed Abbas Taher *, Masoud Hajiakbari Fini, Saber Falahati Aliabadi

Department of Electrical Engineering, University of Kashan, Kashan, Iran

Received 14 May 2013; revised 10 July 2013; accepted 26 July 2013
Available online 27 August 2013

KEYWORDS

Load frequency control;
Fractional order controller;
Imperialist competitive algorithm;
PID

Abstract In this paper, fractional order PID (FOPID) controller was proposed for load frequency control (LFC) in an interconnected power system. This controller had five parameters to be tuned; thus, it provided two more degrees of freedom in comparison with the conventional PID. For proper tuning of the controller parameters, imperialist competitive algorithm (ICA) was used. ICA is a new evolutionary algorithm with proved efficiency. In this study, simulation investigations were carried out on a three-area power system with different generating units. These results showed that FOPID controller was robust to the parameter changes in the power system. Also, the simulation results certified much better performance of FOPID controller for LFC in comparison with conventional PID controllers.

1. Introduction

Controlling large interconnected power systems is one of the most challenging problems for controller designers [1]. One of the most important control objectives in power systems is to control the output power of generating units. Controlling the output power of generating units in such a way that the transient deviations of the frequency of each area and the interchanged power between areas remain within the specified limits and their steady state error equals zero is known as load frequency control [2–4]. A number of control strategies for LFC have been proposed in the literature over past decades.

Using PI controller for LFC has been proposed by some authors. In [5], genetic algorithm was used for tuning the PI controller for LFC. An adaptive fuzzy gain scheduling was proposed in [6] for LFC of a two interconnected power system. In [7], LFC was carried out by a hybrid evolutionary fuzzy PI controller. Bacteria foraging optimization algorithm was used for tuning the PI controllers of a two-area power system in [8]. Alternatively, PID controller can be used for LFC of the power system. PID controller provides more damping for power system [9], but PI controller is usually preferred in noisy environments such as power systems. In [10], a new derivative structure was proposed which resulted in better noise reduction in

* Corresponding author. Address: Department of Electrical Engineering, University of Kashan, Kashan 87317-51167, Iran. Tel./fax: +98 3615559930.
E-mail address: sataher@Kashanu.ac.ir (S.A. Taher).

Peer review under responsibility of Ain Shams University.

Production and hosting by Elsevier

2090-4479 © 2013 Production and hosting by Elsevier B.V. on behalf of Ain Shams University.
http://dx.doi.org/10.1016/j.asej.2013.07.006

Nomenclature

f_i	frequency of area i (Hz)	T_R	reset time of hydraulic unit (s)
R_i	speed regulation constant (Hz/p.u.)	R_t	temporary droop (Hz/p.u.)
T_{Gi}	speed governor time constant (s)	B_i	frequency response characteristic for area i (p.u./Hz)
M	inertia constant of the generator (p.u. s)	ACE_i	area control error
D	load damping constant (p.u./Hz)	ΔP_{Li}	load demand change in area i
T_i	synchronizing torque coefficient of the tie-line which is connected to area i (p.u./rad.)	ΔP_{Ci}	the change in speed changer position in area i
T_{ch}	non-reheat turbine time constant (s)	ΔP_{Gi}	change in governor valve position of ith area generator
T_{rh}	low pressure reheat time constant (s)	ΔP_{tie}	change in tie-line power
F_{hp}	high pressure stage		
T_w	water starting time (s)		

comparison with the conventional differentiator. Afterward, PID controller has been widely proposed in the literature for LFC of power systems. In [11], an intelligent PID controller based on the principle of anthropomorphic intelligence was suggested. Designing PID controller using particle swarm optimization algorithm is presented in [12] for LFC in an interconnected power system. In [13], Artificial Bee Colony (ABC) algorithm has been used to tune the automatic generation controllers in an interconnected reheat thermal power system. The results of this paper show the better performance of ABC in comparison with PSO. Several novel heuristic stochastic search techniques are presented in [14] for optimizing PID gains used in Sugeno fuzzy logic based automatic generation control (AGC) of multi-area system with thermal generating plants. In [15], unified tuning of PID was proposed for LFC in power systems via internal model control. LFC has been carried out by a new decentralized robust optimal MISO PID controller based on matrix eigenvalues and Lyapunov method in [16].

Recently, increasing interest in enhancing the performance of conventional PID has led to considerable attention toward FO-PID controllers, in which the order of derivative and integral is not integer. FOPID controllers are applied by researchers in different fields of engineering. FOPID controller is used in [17] for designing aerospace control systems, in [18] for hypersonic flight vehicle, in [19] for stabilizing fractional order time delay systems, in [20] for weapon system, and in [21–23] for automatic voltage regulator system. A number of methods have been used in the literature for tuning FOPID [20–29]. In [20–25], evolutionary algorithms were implemented to tune the FOPID controller.

In this paper, FOPID was used for LFC in a three-area power system. The performance of FOPID was compared with that of conventional PID controller. In this article, it was illustrated that the FOPID controller had considerably better performance in this case. Imperialist competitive algorithm (ICA) is a new evolutionary algorithm, which has been widely used by researchers for solving different optimization problems. In this study, ICA was implemented for tuning the parameters of both FOPID and conventional PID controllers of a three-area power system.

2. Fractional calculus

Fractional order calculus is not a new concept, and as mentioned in [30], probably the earliest systematic studies have been done by Liouville, Riemann, and Holmgren in the 19th century. Since then, many definitions have been proposed in the literature for it, from which one is selected to be presented here. In the following definition of fractional calculus, the operator ${}_aD_t^q$, depending on the sign of q denotes fractional differentiation or integration. This operator is defined as follows:

$$ {}_aD_t^q = \begin{cases} \frac{d^q}{dt^q} & q > 0 \\ 1 & q = 0 \\ \int_a^t (d\tau)^{-q} & q < 0 \end{cases} \tag{1}$$

where a and t are operational limits and q is the fractional order. There are some definitions for fractional derivation in the literature. In this paper, Caputo definition, which is referred to as smooth fractional derivative in the literature [31], was chosen. Its formulation is as follows:

$$ {}_aD_t^q f(t) = \begin{cases} \frac{1}{\Gamma(m-q)} \int_0^t \frac{f^{(m)}(\tau)}{(t-\tau)^{q+1-m}} \quad d\tau & m-1 < q < m \\ \frac{d^m}{dt^m} f(t) & q = m \end{cases} \tag{2}$$

where m is the smallest integer which is larger than q and Γ represents the Gamma function given by:

$$\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt \tag{3}$$

The Laplace transform of Eq. (2) is given below:

$$L\{{}_0D_t^q f(t)\} = s^q F(s) - \sum_{k=0}^{n-1} s^{q-k-1} f^{(k)}(0) \quad n-1 < q < n, \quad n \in N \tag{4}$$

To implement the fractional order transfer functions in simulation or practical studies, one way is to approximate them with integer order transfer functions. For an exact approximation of a fractional order transfer function with an integer order one, the integer order transfer function has to include an infinite numbers of zeroes and poles.

Crone is one of the approximations [32], which can be used. It is a French acronym that means robust fractional order control. In this approximation method, a recursive distribution of N poles and N zeros is used. This can be formulated as follows:

$$s^v \approx \prod_{n=1}^{N} \frac{1 + \frac{s}{\omega_{zn}}}{1 + \frac{s}{\omega_{pn}}}, \quad v \in \mathbb{R} \tag{5}$$

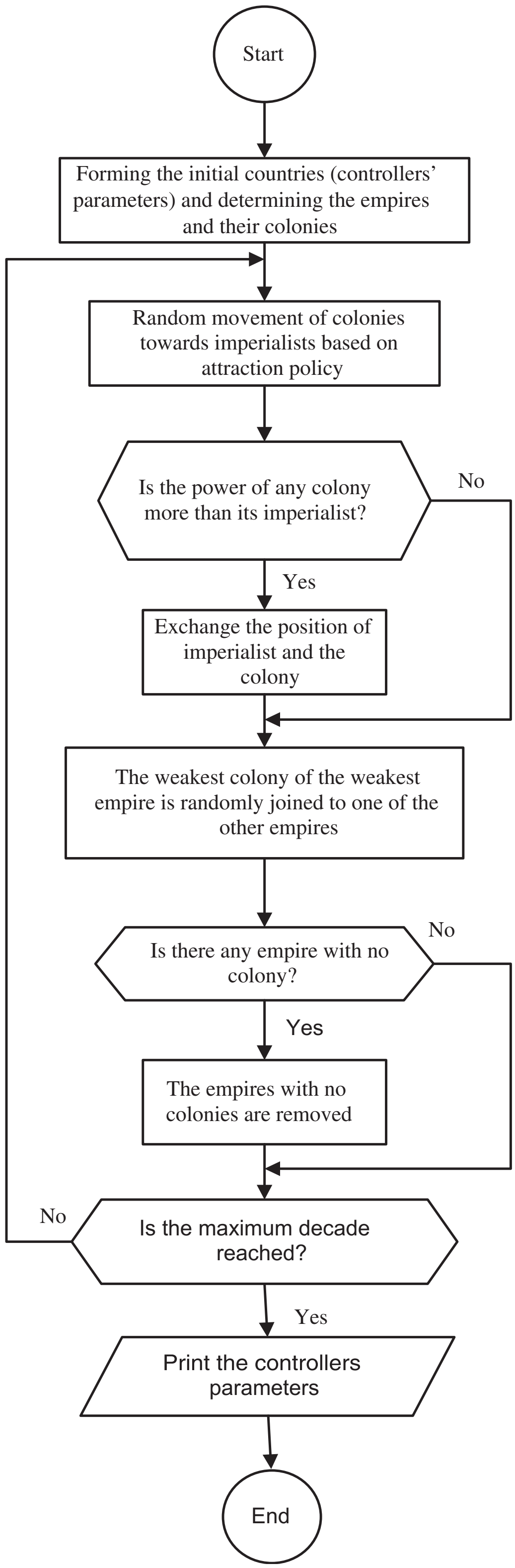


Figure 1 ICA flowchart for tuning the FOPID controller.

The zeroes and poles are to be assigned inside the frequency range $[\omega_\lambda\ \omega_\eta]$, within which the approximation is valid, and for a positive v, they are given by:

$$\alpha = \left(\frac{\omega_h}{\omega_l}\right)^{v/N} \quad (6)$$

$$\eta = \left(\frac{\omega_h}{\omega_l}\right)^{(1-v)/N} \quad (7)$$

$$\omega_{z,1} = \omega_l\sqrt{\eta} \quad (8)$$

$$\omega_{p,n} = \omega_{z,n-1}\alpha, \quad n = 1, \ldots, N \quad (9)$$

$$\omega_{z,n} = \omega_{p,n-1}\eta, \quad n = 2, \ldots, N \quad (10)$$

These equations can be written for the negative values of v in a similar way; the only difference is that role of zeroes and poles is exchanged (i.e. $\omega_{p,1} = \omega_l\sqrt{\eta}$ and so on). For $|v| > 1$, it is recommended that the fractional orders of s are separated as follows:

$$s^v = s^n s^\delta, \quad c = n + \delta, \quad n \in \mathbb{Z}, \quad \delta \in [0, 1] \quad (11)$$

and only s^δ is approximated. Also, it is required to mention that electric circuits which can serve as exact fractional integrators and differentiators are reported in [30,33].

3. Imperialist competitive algorithm

In recent years, ICA has gained popularity among researchers due to its high speed and accuracy in finding solutions of optimization problems [34–39]. Similar to other evolutionary algorithms, this algorithm starts with an initial random population. Each of the members of this population is called a country. Some of the best members are considered imperialists and others are colonies. Imperialists, regarding their power, attract colonies in a certain procedure as follows [40]:

3.1. Forming initial empires

In an optimization problem, the goal is to find the optimum solution in terms of problem variables. For this purpose, an array of variables which is to be optimized is formed. In an N_{var}-dimensional optimization problem, a country is an $N_{var} \times 1$ array, defined as follows:

$$Country = [p_1, p_2, \ldots, p_{N_{var}}] \quad (12)$$

The value of variables in every country is represented by a floating point number. From the historical–cultural point of view, social–political characteristics of the country such as culture, language, and political structure are considered the components of that country.

To start the optimization process, $N_{country}$ country is generated and N_{imp} most powerful members of this population are selected as imperialists (in this problem, the sets of controller coefficients with smaller cost function). The remaining N_{col} countries are the colonies (in this problem, the sets of controller coefficients with higher cost function), each of which is a part of one of the above mentioned empires.

Table 1 ICA parameters.

Parameters	Values
N_{pop}	1000
MaxDecades	127
Beta	2
$P_{\text{Revolution}}$	0.1
Zeta	0.1

Table 2 Controllers' parameters.

Controller parameters		K_p	K_I	K_D	λ	μ
Area1	PID	−0.4130	−0.8284	0.3298	1	1
	FOPID	0.6700	−0.4006	−0.9910	1	0.6543
Area2	PID	−0.0463	−0.2745	−0.1973	1	1
	FOPID	−0.3266	−0.2946	−1	1	0.8650
Area3	PID	−1	−1	0.9862	1	1
	FOPID	−1	−1	0.4888	0.6762	0.5686

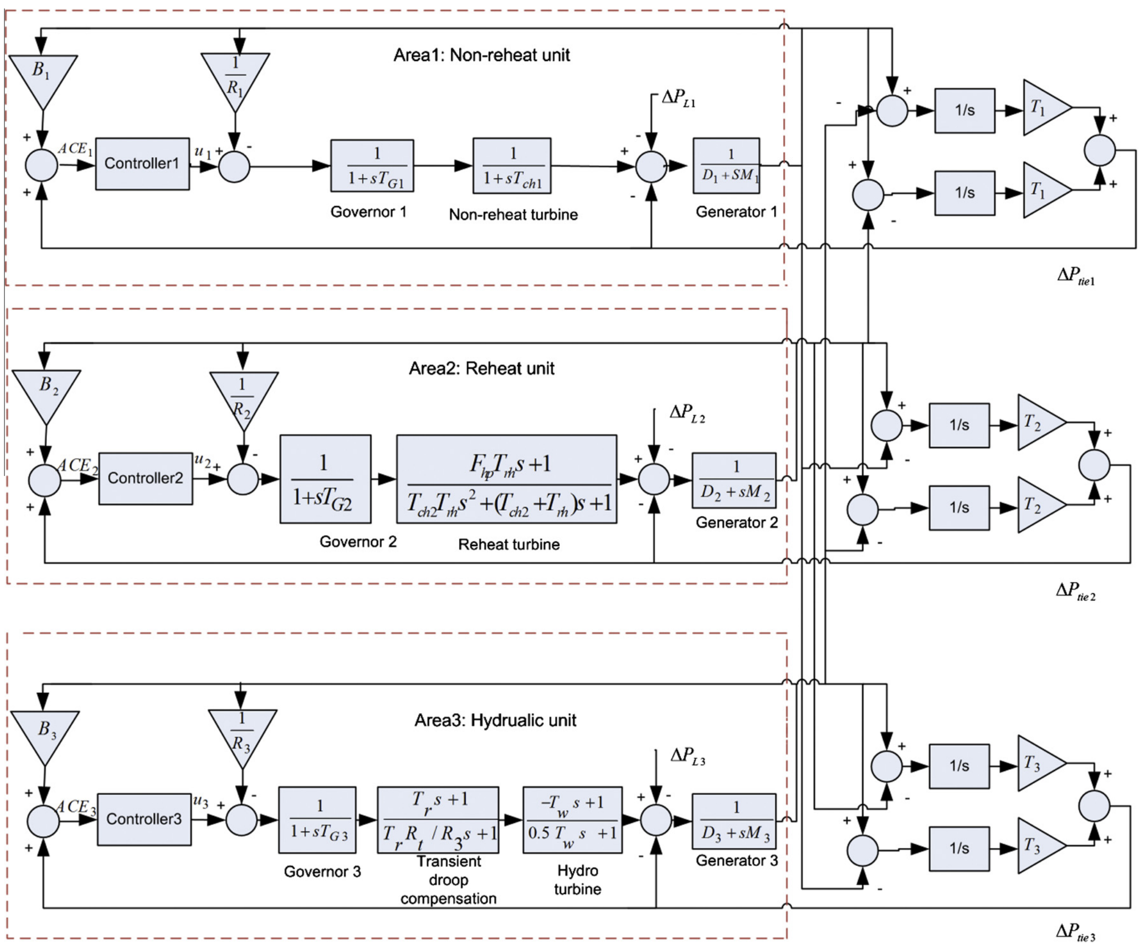


Figure 2 Three-area power system with different generating units.

3.2. The attraction policy

Along with this policy, the colonies move toward imperialists along x units and are situated in a new position. x is a random variable with uniform (or any other proper) distribution. Then, x can be expressed as follows:

$$x \sim U(0, \beta * d) \tag{13}$$

where β is a number with a value greater than 1 and close to 2.

3.3. Revolution

In this optimization algorithm, revolution prevents the algorithm from stopping in local valleys. In some cases, this

Table 3 Three-area power systems' parameters.

Non-reheat		Reheat		Hydraulic	
M_1(p.u. s)	10	M_2(p.u. s)	10	M_3(p.u. s)	6
D_1(p.u./Hz)	1	D_2(p.u./Hz)	1	D_3(p.u./Hz)	1
T_{ch1}(s)	0.3	T_{ch2} (s)	0.3	T_{G3}(s)	0.2
T_{G1}(s)	0.1	F_{hp}	0.3	T_r(s)	5
R_1(Hz/p.u)	0.05	T_{rh}(s)	7	R_t(Hz/p.u.)	0.38
B_1(p.u./Hz)	21	T_{G2}(s)	0.2	R_3(Hz/p.u)	0.05
T_1(p.u./rad)	22.6	R_2(Hz/p.u)	0.05	B_3(p.u./Hz)	21
		B_2(p.u./Hz)	21	T_w(s)	1
		T_2(p.u./rad)	22.6	T_3(p.u./rad)	22.6

improves the position of a country and moves it to a better optimization area.

3.4. Exchanging positions of imperialists and colonies

During the movement of colonies toward the imperialist country, some of these colonies may achieve a better position in comparison with the imperialist (and cause a lower cost function in comparison with the imperialist). This situation will result in exchanging the position of imperialist and colony, and after that, the algorithm will be continued with new imperialists.

3.5. Imperialistic competition

The power of an empire is defined as power of the imperialist country plus the percentage of power of its colonies. Each imperialist which is unable to increase its power or, in other words, loses its competitive power will collapse in the imperialistic competition. When an imperialist collapses, its colonies are divided among other imperialists.

4. Implementing FOPID for LFC

4.1. FOPID controller

The concept of FOPID controller was first proposed by Podlubny in [41,42]. The difference between FOPID and PID controller is that, in FOPID, the order of derivative and integral is not integer. This characteristic provides extra degrees of freedom in tuning the controller and can lead to better dynamic performance in comparison with conventional PID [43]. Due to increasing interest in improving the response of conventional PID, FOPID controller has received considerable attention in the last few years [17–22].

The formulation of FOPID controller is shown below:

$$K(S) = K_p + \frac{K_I}{S^{\lambda}} + K_d S^{\mu} \tag{14}$$

where K_p, K_I, and K_d are proportional, integral, and derivative gain, respectively. Also, λ and μ are orders of integral and derivative, respectively.

It is shown in Section 5 that implementing FOPID controller for LFC improves the power system response in terms of settling time, overshoots, and undershoots. Moreover, this controller is robust to changes in power system parameters.

4.2. Optimal tuning of FOPID controller using ICA

Each FOPID controller has five parameters to be tuned, and each area of power system has a FOPID controller; therefore, in the studied three-area power system, there were fifteen parameters to be optimally tuned. Fig. 1 shows the flowchart of tuning the parameters using ICA. The values of parameters of this algorithm are given in Table 1.

For optimal tuning of the controller parameters using evolutionary algorithms, it is necessary to use a proper objective function. By minimizing the objective function, the optimal values of parameters are obtained. In this paper, as shown below, integral of time multiply absolute error (ITAE) of deviation of frequency and tie-line power of all areas were defined as objective functions.

$$J = \int_0^{\infty} t(|\Delta f_1| + |\Delta f_2| + |\Delta f_3| + |\Delta P_{tie1}| + |\Delta P_{tie2}| + |\Delta P_{tie3}|)dt \tag{15}$$

The optimization problem can be stated as minimizing J considering the following constraints:

$$K_p^{\min} < K < K_p^{\max}, \quad K_I^{\min} < K < K_I^{\max}, \quad K_D^{\min} < K < K_D^{\max},$$
$$\lambda^{\min} < \lambda < \lambda^{\max}, \quad \mu^{\min} < \mu < \mu^{\max} \tag{16}$$

Table 4 Settling time and maximum deviation of system responses to different disturbances in the presence of: (a) PID controllers, (b) FOPID controllers.

Parameters	Max. deviation						Settling time					
	f_1	f_2	f_3	P_{tie1}	P_{tie2}	P_{tie3}	f_1	f_2	f_3	P_{tie1}	P_{tie2}	P_{tie3}
(a) PID												
Disturbance In area 1	0.0038	0.0041	0.0042	0.0810	0.0552	0.0506	26.15	20.93	25.33	27.34	25.50	32.17
Disturbance In area 2	0.0046	0.0045	0.0057	0.0815	0.1079	0.0625	25.96	25.52	21.91	25.82	37.67	41.40
Disturbance In area 3	0.0047	0.0058	0.0064	0.0856	0.0795	0.1639	25.37	18.62	21.60	26.76	39.71	37.46
Disturbance In all areas	0.0107	0.0124	0.0110	0.1401	0.0627	0.1154	21.03	16.79	20.31	22.58	33.70	20.82
(b) FOPID												
Disturbance In area 1	0.0027	0.0029	0.0029	0.0448	0.0349	0.0256	19.60	19.50	19.55	16.42	20.33	20.44
Disturbance In area 2	0.0027	0.0033	0.0039	0.0546	0.0965	0.0437	21.87	20.74	20.15	21.96	29.11	34.62
Disturbance In area 3	0.0047	0.0062	0.0068	0.0938	0.0855	0.1758	21.78	8.11	15.20	22.48	32.33	30.23
Disturbance In all areas	0.0095	0.0101	0.0108	0.1105	0.0525	0.1618	13.58	13.66	13.65	22.71	30.17	24.48

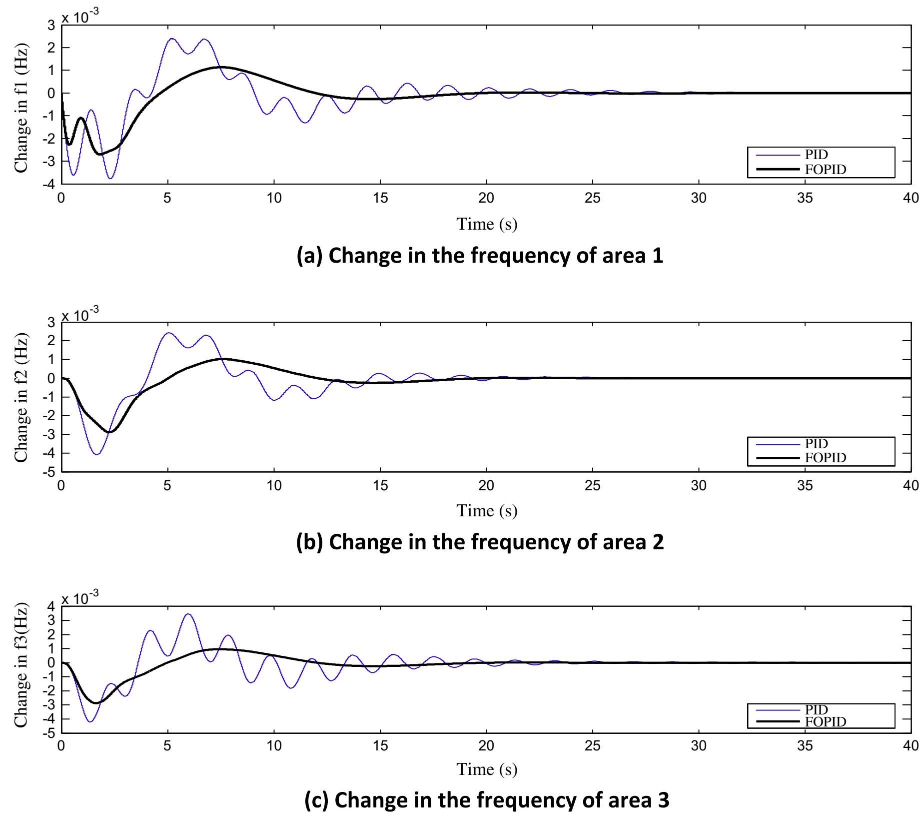


Figure 3 Change in the frequency of all areas for step increase in the demand of area 1. (a) Change in the frequency of area 1. (b) Change in the frequency of area 2. (c) Change in the frequency of area 3.

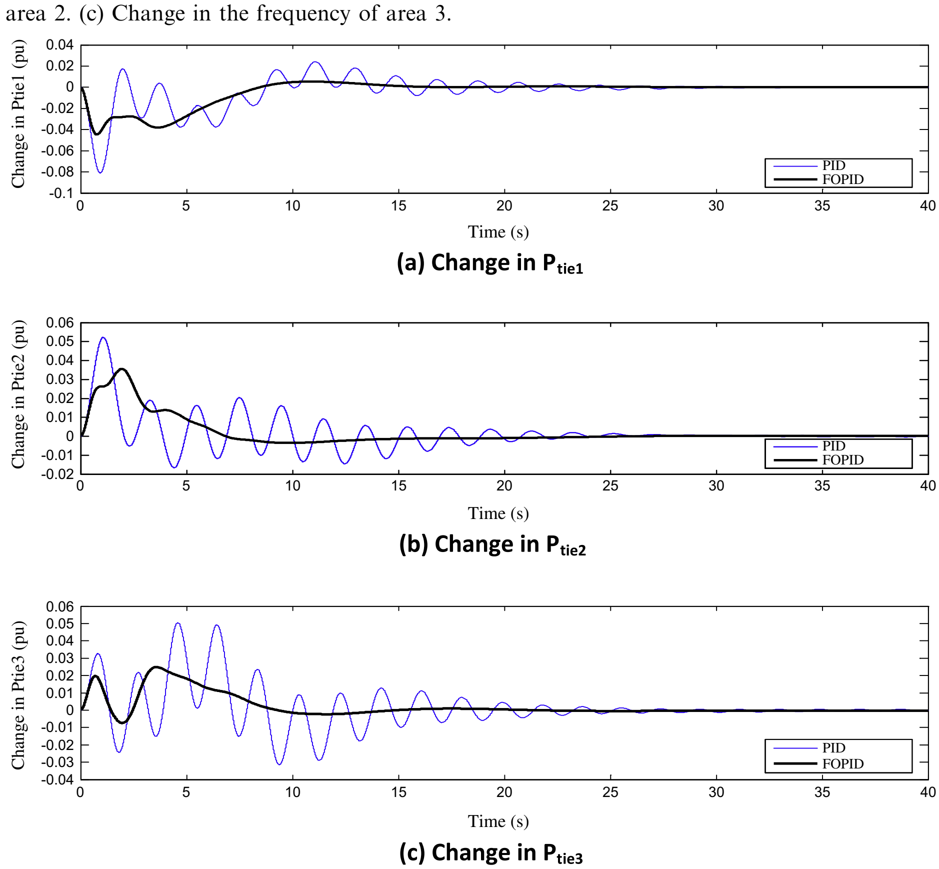


Figure 4 Change in Ptie of all areas for step increase in the demand of area 1. (a) Change in Ptie1. (b) Change in Ptie2. (c) Change in Ptie3.

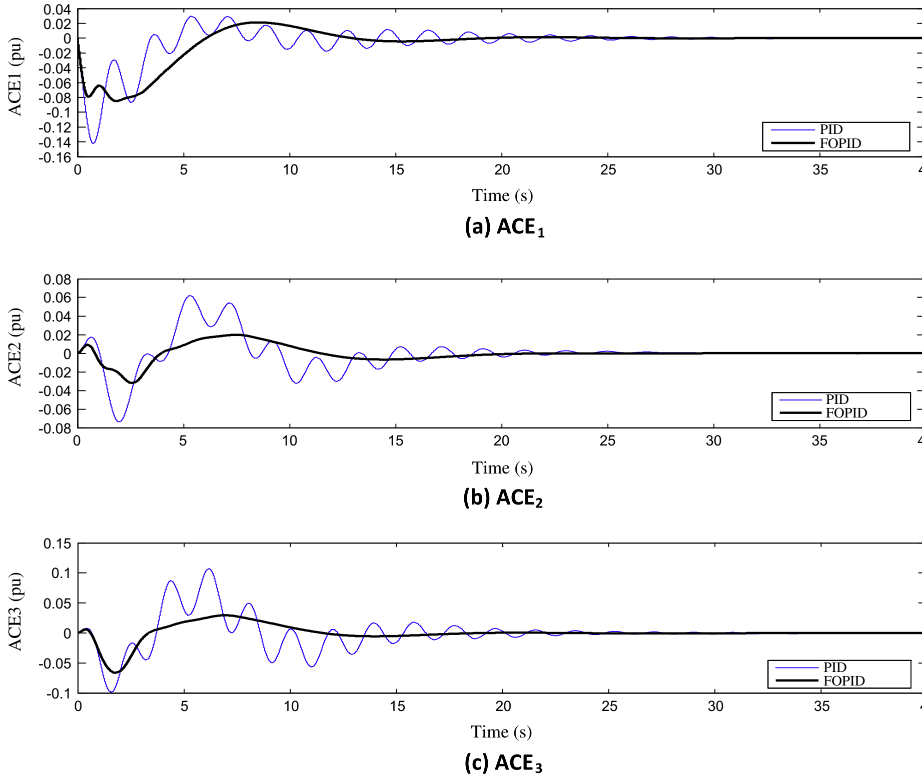


Figure 5 Change in ACE of all areas for step increase in the demand of area 1. (a) ACE1. (b) ACE2. (c) ACE3.

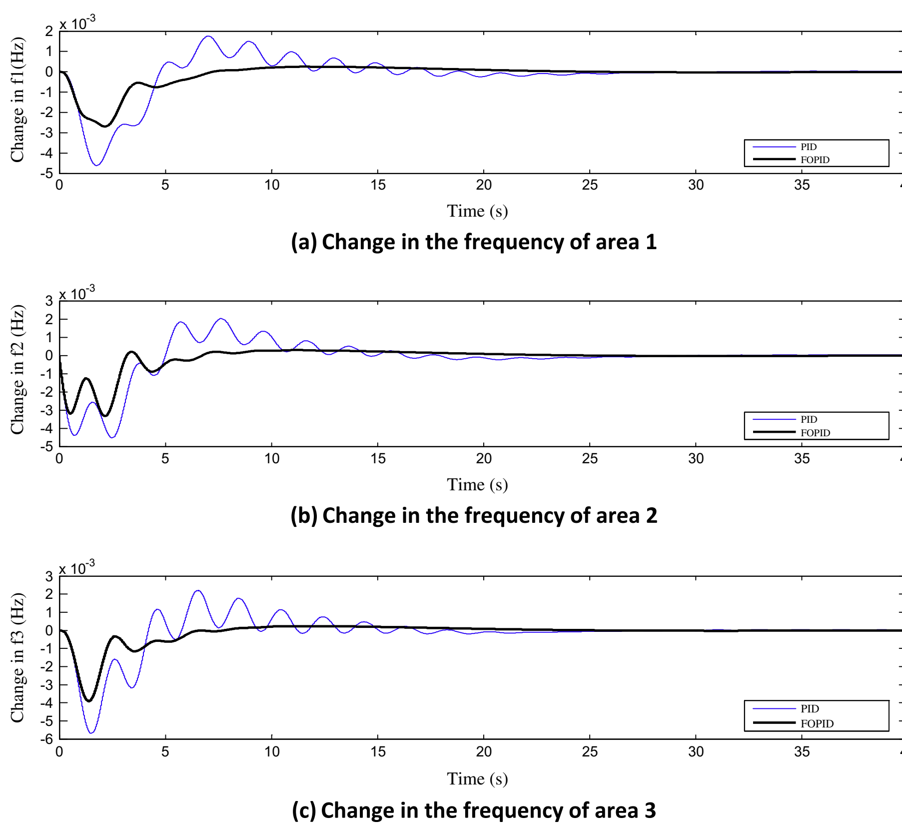
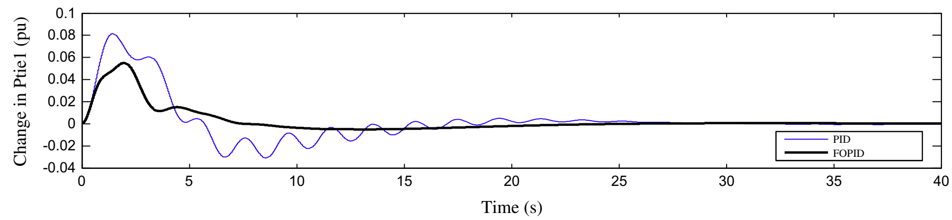
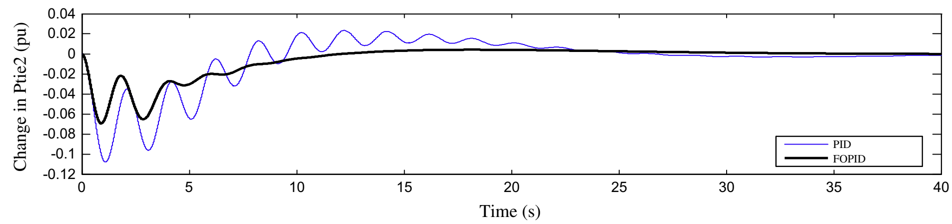


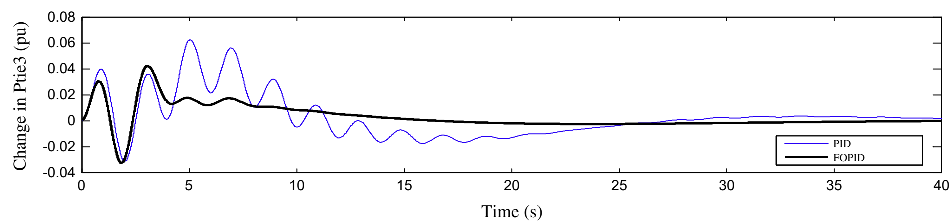
Figure 6 Change in the frequency of all area for step increase in the demand of area 2. (a) Change in the frequency of area 1. (b) Change in the frequency of area 2. (c) Change in the frequency of area 3.



(a) Change in P_{tie1}

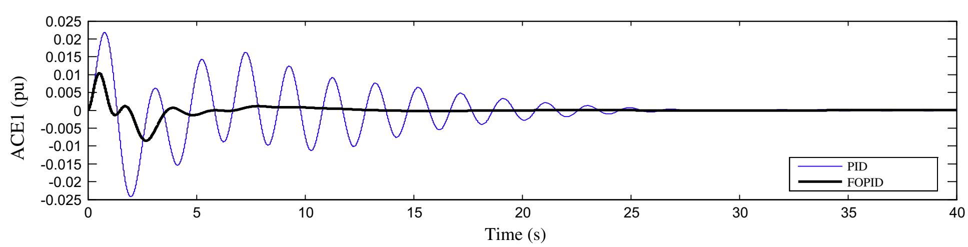


(b) Change in P_{tie2}

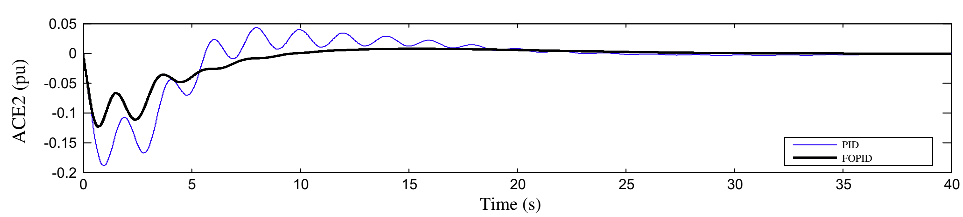


(c) Change in P_{tie3}

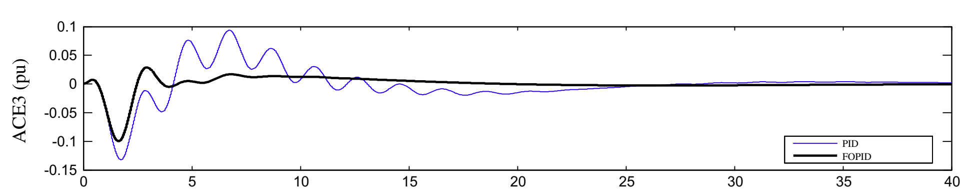
Figure 7 Change in Ptie of all areas for step increase in the demand of area 2. (a) Change in Ptie1. (b) Change in Ptie2. (c) Change in Ptie3.



(a) ACE_1



(b) ACE_2



(c) ACE_3

Figure 8 Change in ACE of all areas for step increase in the demand of area 2. (a) ACE1. (b) ACE2. (c) ACE3.

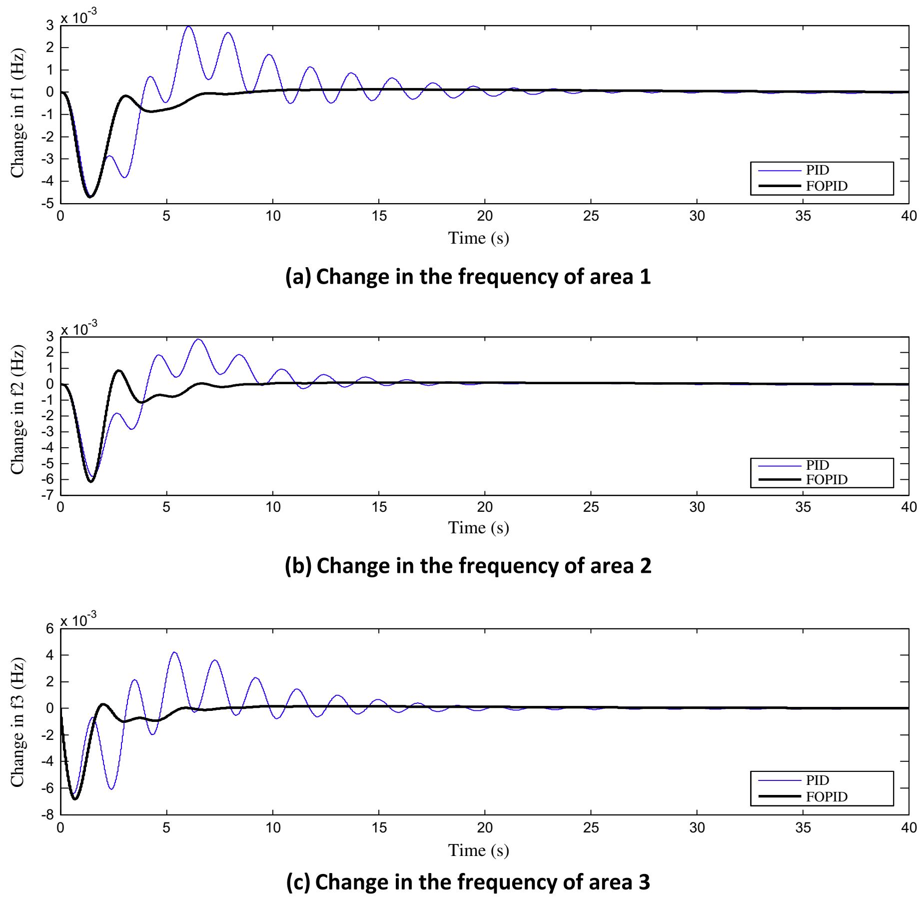


Figure 9 Change in the frequency of all areas for step increase in the demand of area 3. (a) Change in the frequency of area 1. (b) Change in the frequency of area 2. (c) Change in the frequency of area 3.

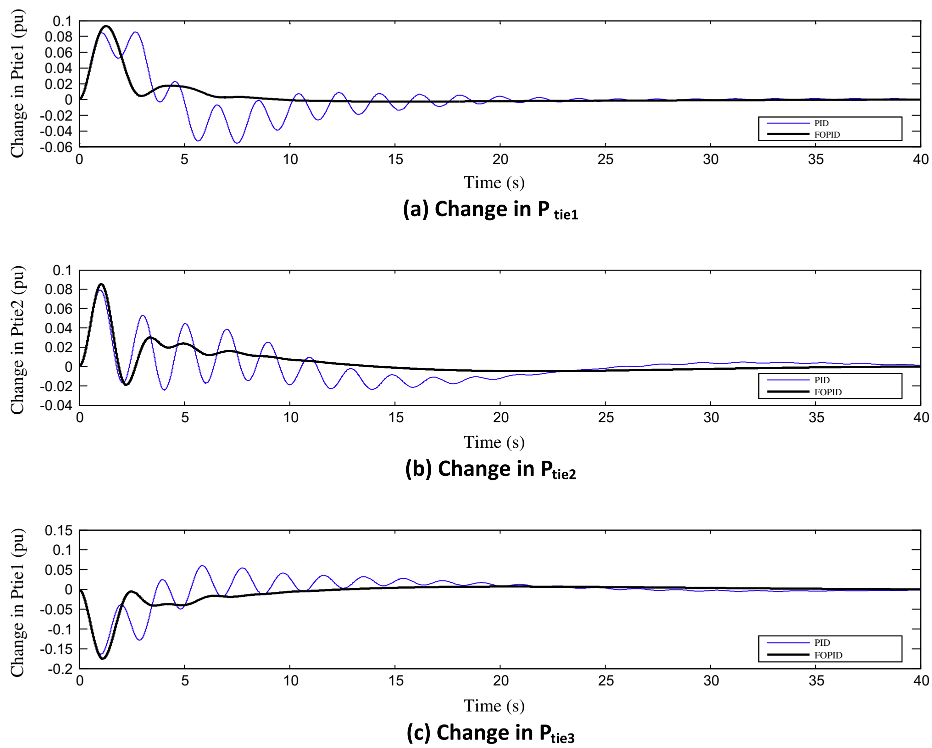


Figure 10 Change in Ptie of all areas for step increase in the demand of area 3. (a) Change in Ptie1. (b) Change in Ptie2. (c) Change in Ptie3.

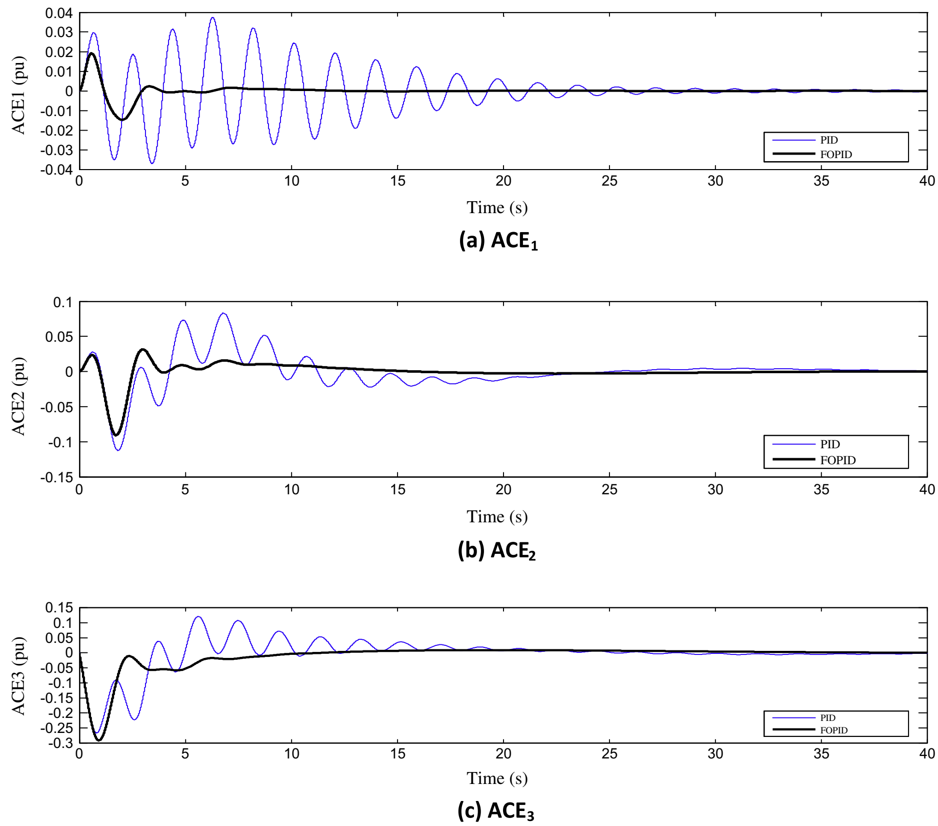


Figure 11 Change in ACE of all areas for step increase in the demand of area 3. (a) ACE1. (b) ACE2. (c) ACE3.

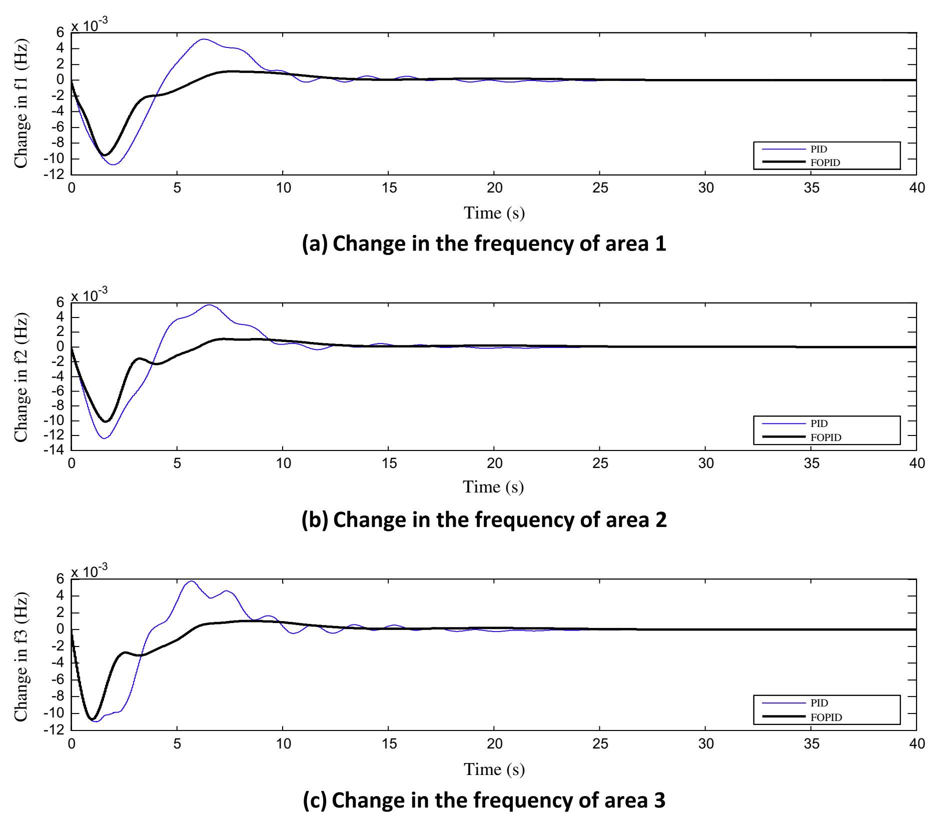
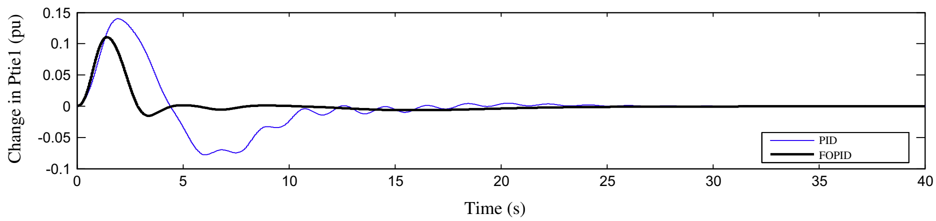
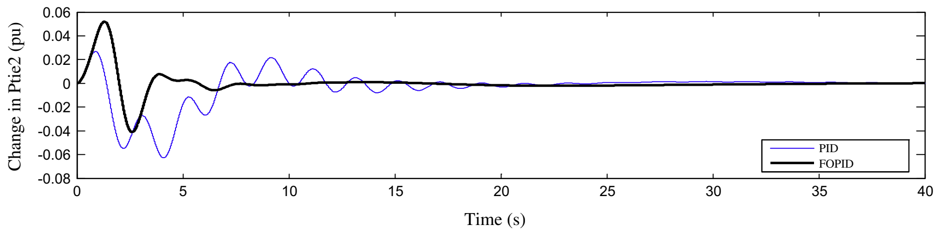


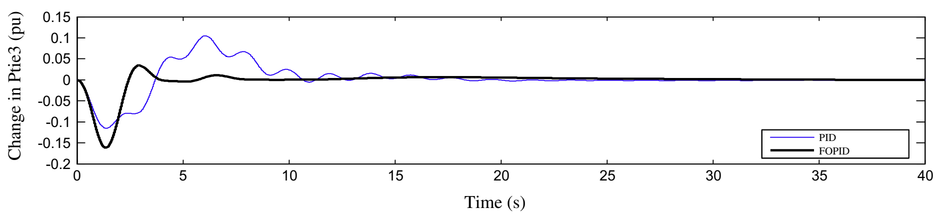
Figure 12 Change in the frequency of all areas for step increase in the demand of three area. (a) Change in the frequency of area 1. (b) Change in the frequency of area 2. (c) Change in the frequency of area 3.



(a) Change in P_{tie1}

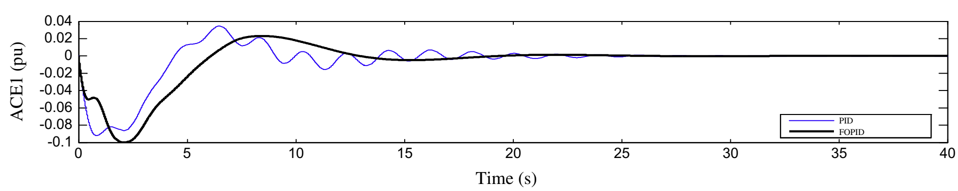


(b) Change in P_{tie2}

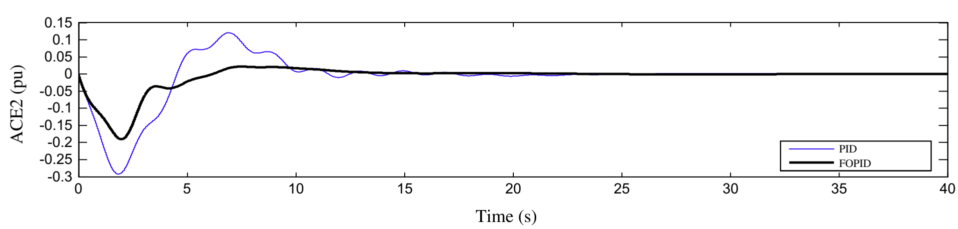


(c) Change in P_{tie3}

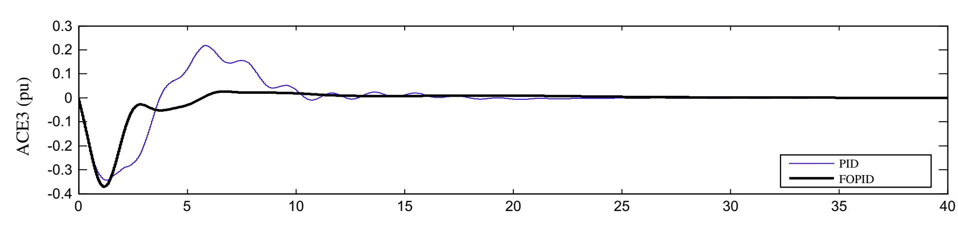
Figure 13 Change in Ptie of all areas for step increase in the demand of three area. (a) Change in Ptie1. (b) Change in Ptie2. (c) Change in Ptie3.



(a) ACE_1



(b) ACE_2



(c) ACE_3

Figure 14 Change in ACE of all areas for step increase in the demand of three area. (a) ACE1. (b) ACE2. (c) ACE3.

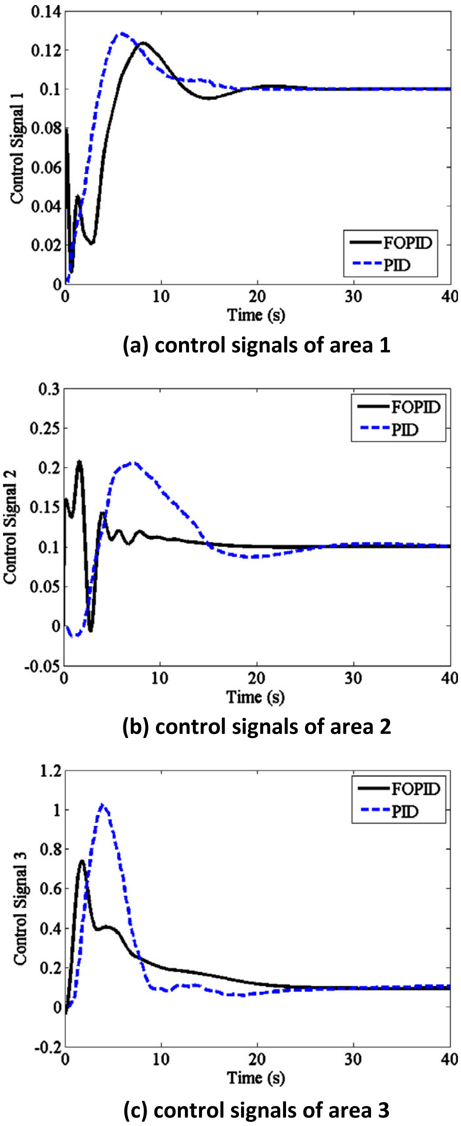


Figure 15 Control signals. (a) Control signals of area1. (b) Control signals of area2. (c) Control signals of area3.

The main goal of this optimization is to determine controller parameters in such a way that a high level of damping is provided for the oscillations which occur in the power system, and the settling times, undershoots, and overshoots of system responses are minimized. The values of the designed controllers' parameters are given in Table 2.

5. Simulation results

The investigated system, as shown in Fig. 2, was a three-area power system with different generating units, including reheat, non-reheat, and hydraulic units. This power system could be modeled as a multivariable system in the state space form:

$$\dot{x} = Ax + Bu + Ld \tag{17}$$

$$y = Cx \tag{18}$$

where $u = [u_1 u_2 u_3]^T$, $y = [y_1 y_2 y_3]^T = [ACE_1 ACE_2 ACE_3]^T$, $d = [d_1 d_2 d_3]^T = [P_{D1} P_{D2} P_{D3}]^T$, $x = [\Delta f_1 \Delta P_{T1} \Delta P_{G1}\ \Delta P_{c1} \Delta P_{tie1}$ $\Delta f_2 \Delta P_{T2} \Delta P_{G2} \Delta P_{c2} \Delta P_{tie2} \Delta f_3 \Delta P_{T3} \Delta P_{G3} \Delta P_{c3} \Delta P_{tie3}]^T$.

Parameters of the studied system are given in Table 3.

Simulation studies were performed on a three-area power system with different generating units. Several different com-

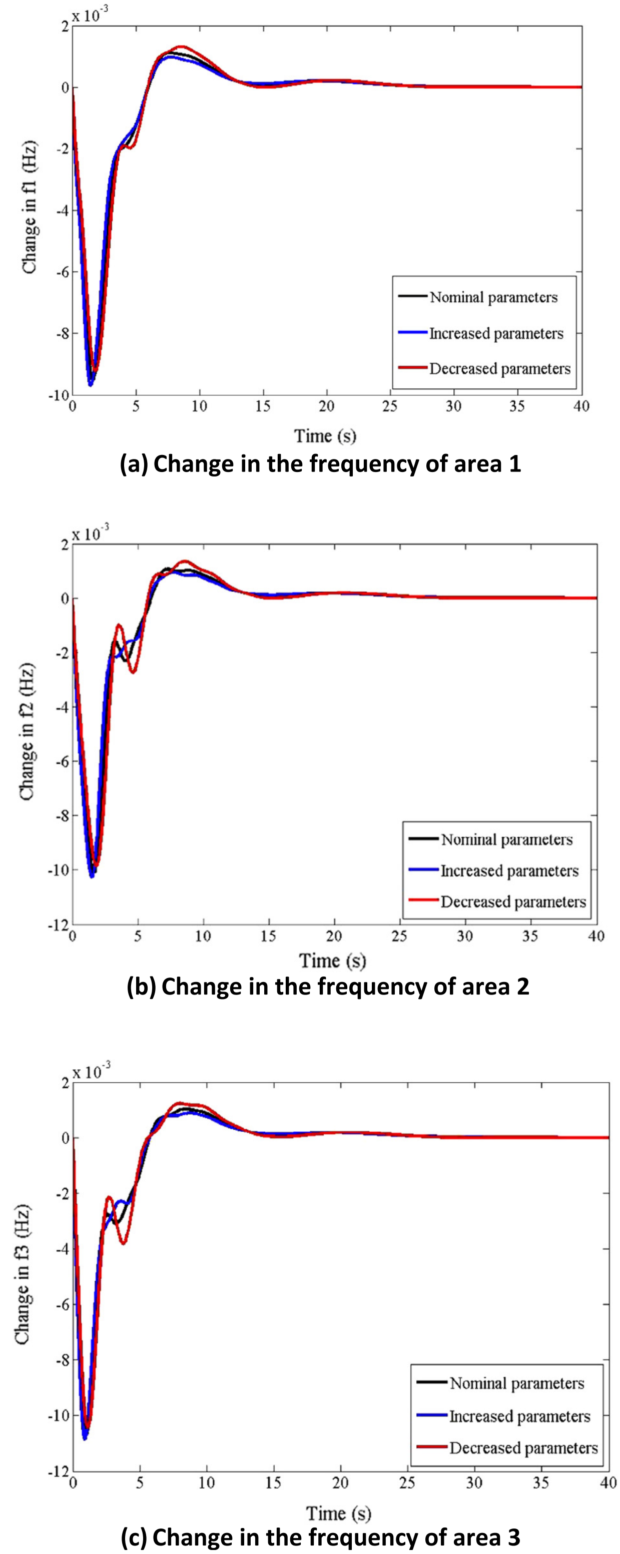


Figure 16 Change in the frequency of all areas following parameter variation. (a) Change in the frequency of area 1. (b) Change in the frequency of area 2. (c) Change in the frequency of area 3.

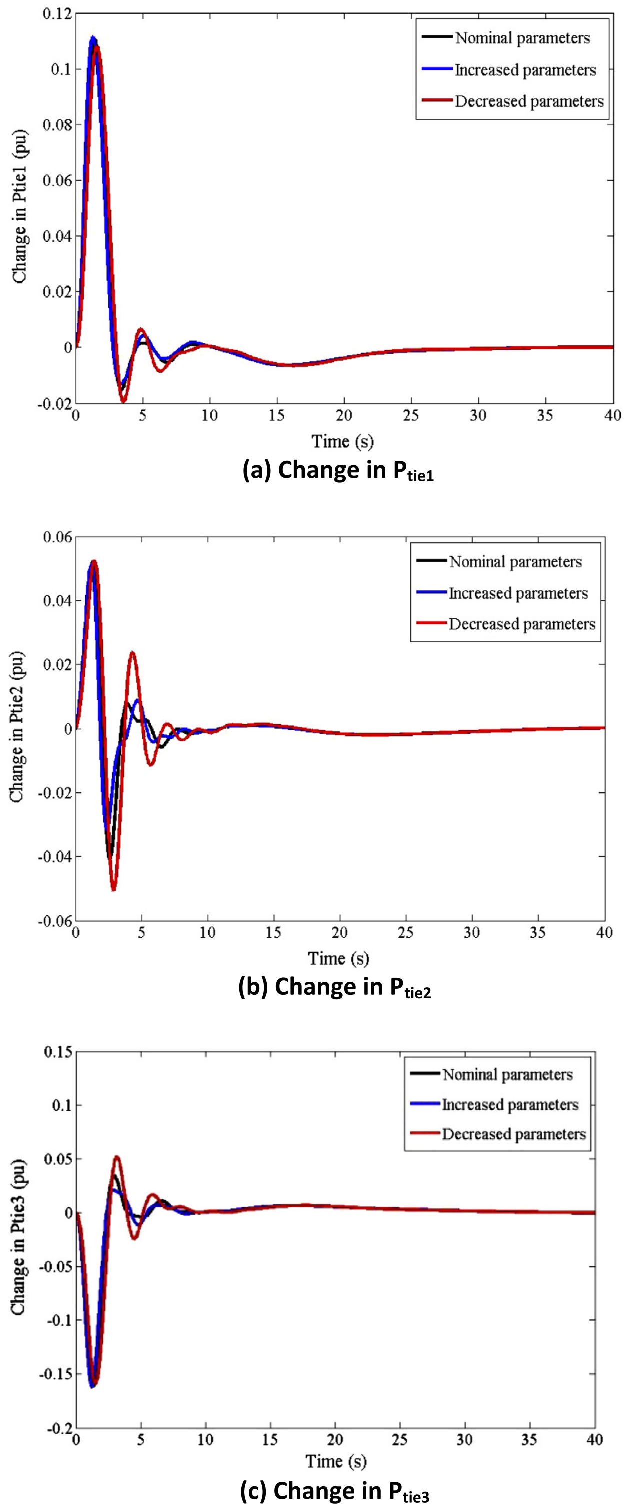


Figure 17 Change in Ptie of all areas following parameter variation. (a) Change in Ptie1. (b) Change in Ptie2. (c) Change in Ptie3.

parative cases were examined to show the effectiveness of FO-PID controller tuned by ICA for LFC in the power system. To evaluate the performance of FOPID controller, it was compared with the conventional PID controller designed by the same method. The settling time and maximum deviation of responses to disturbances in the presence of PID and FOPID controllers are given in Table 4a and b, respectively. It is worth mentioning that the optimized value of the objective function for the power system with PID and FOPID controllers was 10.6210 and 4.7642, respectively.

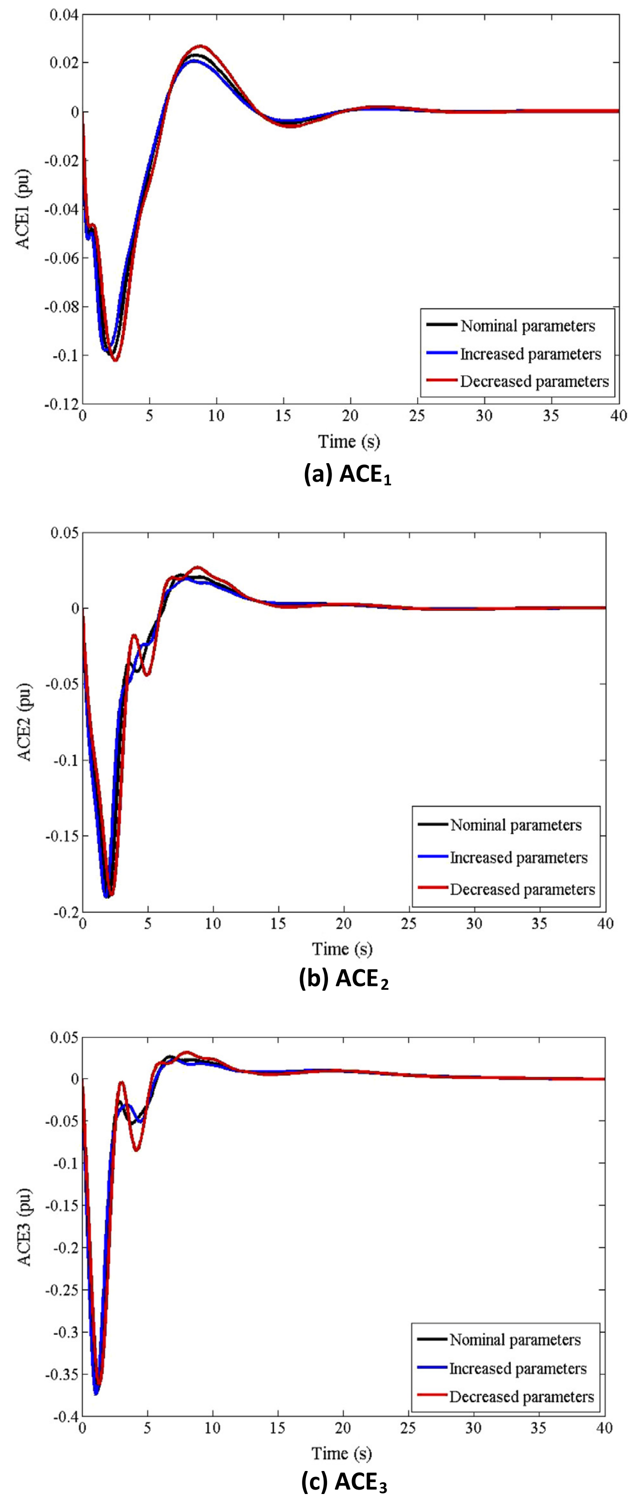


Figure 18 Change in ACE of all areas following parameter variation. (a) ACE1. (b) ACE2. (c) ACE3.

5.1. Step increase in the demand of area 1

In the first case, a 0.1pu step increase in the demand of area 1, with non-reheat generating unit, was applied at the nominal operating point. The frequency deviation of all the areas (Δf), the deviation in the power transmitted to areas (ΔP_{tie}), and the areas' control error (ACE) are shown in Figs. 3–5.

It is obvious from the simulation results that FOPID controller improved system responses in terms of overshoots and settling times when a disturbance occurred in area 1.

5.2. Step increase in the demand of area 2

Due to the importance of reheat generating units in power systems, in the second case study, a 0.1pu step increase in the demand of area 2 ($P_{d1} = P_{d3} = 0$, $P_{d2} = 0.1$pu) with reheat generating unit was applied at the nominal operating point. The results shown in Figs. 6–8 demonstrate higher ability of FOPID controller in compensating for the disturbance which occurred in area 2.

5.3. Step increase in the demand of area 3

Hydroelectric power generators produce 17.5% of the world's electricity [44], which indicates the importance of testing the effectiveness of FOPID controllers for hydraulic units.

In this section, a 0.1pu step increase in the demand of area 3 ($P_{d1} = P_{d2} = 0$, $P_{d3} = 0.1$pu) with hydraulic generating unit was applied at the nominal operating point. Figs. 9–11 confirm that FOPID controller led to smoother responses in this case study. It is clear from the data given in Table 4a and b that, although PID controllers had a little better performance in terms of maximum deviations, FOPID controllers improved system responses in terms of settling times.

5.4. Step increase in the demand of all areas

In order to test the performance of FOPID controllers when disturbances occur simultaneously in all the areas, in the forth case study, a 0.1pu step increase in the demand of all areas ($P_{d1} = P_{d2} = P_{d3} = 0.1$pu) was applied at the nominal operating point, and the responses of the system were observed. The frequency deviation (Δf), area control error (ACE), and tie-line power deviation (ΔP_{tie}) for all the three areas are shown in Figs. 12–14. These simulation results confirmed that FOPID had better performance in reducing settling times and maximum deviations of frequency of all the three areas of the power system. For further investigation on performance of controllers, control signals are shown in Fig. 15. It is clear from this figure that the amplitude of FOPID control signals is less than that of PID control signals. So, in case of FOPID controller, governor valves are subjected to less change.

5.5. Parameter variation

In modeling a complex interconnected power system, parameter approximation cannot be avoided [45]. Therefore, robustness of the proposed controllers to the parameters' change should be verified.

In this case study, inertia constant, damping constant, and synchronizing coefficient were changed as follows:

1/M: $\pm 15\%$
D: $\pm 15\%$
T_i: $\pm 10\%$

In Figs. 16–18, the performance of FOPID controller with the change in system parameters is compared with that of nominal ones. From these results, robustness of the proposed controller to changes in system parameters can be concluded.

6. Conclusion

In this paper, an FOPID controller was proposed for LFC in a three-area power system. The parameters of controllers were tuned using ICA. Simulation of comparative cases confirmed that the proposed controller had better performance in LFC of the interconnected power system.

Responses of the power system to disturbances were much smoother and less oscillatory using the proposed controllers. In most cases, the settling time and maximum deviation of power system responses diminished when FOPID controllers were implemented. In some cases, PID controllers led to lower maximum deviations and settling time; however, the responses of FOPID controllers were still much smoother and less oscillatory. Moreover, robustness of the proposed controller to changes in power system parameters was verified.

References

[1] Wood AJ, Wollenberg BF. Power generation operation and control. 2nd ed. John Wiley and Sons, INC.; 1996.
[2] Kundur P. Power system stability and control. McGraw-Hill; 1994.
[3] Kassem AM. Neural predictive controller of a two-area load frequency control for interconnected power system. Ain Shams Eng J 2010;1(1):49–58.
[4] Rout UK, Sahu RK, Panda S. Design and analysis of differential evolution algorithm based automatic generation control for interconnected power system. Ain Shams Eng J 2013;4(3):409–421.
[5] Rerkpreedapong D, Hasanovic A, Feliachi A. Robust load frequency control using genetic algorithms and linear matrix inequalities. IEEE Trans Power Syst 2003;18(2):855–61.
[6] Talaq J, Al-Basri F. Adaptive fuzzy gain scheduling for load frequency control. IEEE Trans Power Syst 1999;14(1):145–50.
[7] Juang CF, Lu C-F. Load–frequency control by hybrid evolutional PI controller. IEE Proc Generat Transm Distrib 2006;153(2):196–204.
[8] Ali ES, Abd-Elazim SM. Bacteria foraging optimization algorithm based load frequency controller for interconnected power system. Int J Electr Power Energy Syst 2011;33(3):633–8.
[9] Moon YH. Modified PID load–frequency control with the consideration of valve position limits. Proceedings of the IEEE PES 1999 Winter Meeting; 1999.
[10] Moon YH, Ryu HS, Lee JG, Kim S. Power system load frequency control using noise-tolerable PID feedback. Proc IEEE Int Symp Ind Electron (ISIE) 2001;3:1714–8.
[11] Cheng Y, Ye L. Anthropomorphic intelligent PID control and its application in the hydro-turbine governor. In: Proceedings of the first international conference on machine learning and cybernetics. Beijing; 2002; p. 391–5.
[12] Sabahi K, Sharifi A, Aliyari M, Teshnehlab M, Aliasghary M. Load frequency controller in interconnected power system using multi-objective PID controller. J Appl Sci 2008;8(20):3676–82.
[13] Gozde H, Ce Taplamacioglu M, Kocaarslan İ. Comparative performance analysis of artificial bee colony algorithm in automatic generation control for interconnected reheat thermal power system. Int J Electr Power Energy Syst 2012;42(1):167–78.

[14] Roy R, Bhatt P, Ghoshal SP. Evolutionary computation based three-area automatic generation control. Int J Electr Power Energy Syst 2010;37(8):5913–24.
[15] Tan W. Unified tuning of PID load frequency controller for power systems via IMC. IEEE Trans Power Syst 2010;25(1):341–50.
[16] Yazdizadeh A, Ramezani MH, Hamedrahmat E. Decentralized load frequency control using a new robust optimal MISO PID controller. Int J Electr Power Energy Syst 2012;35(1):57–65.
[17] Aboelela MAS, Ahmed MF, Dorrah HT. Design of aerospace control systems using fractional PID controller. Adv Res 2012;3(3):225–32.
[18] Changmao Q, Naiming Q, Zhiguo S. Fractional PID controller design of hypersonic flight vehicle, computer, mechatronics. In: International conference on control and electronic engineering (CMCE), vol. 3. Digital Object Identifier; 2010. p. 466–9.
[19] Hamamci SE. An algorithm for stabilization of fractional-order time delay systems using fractional-order PID controllers. IEEE Trans Automatic Control 2007;52(10):1964–9.
[20] Jia L, Xiuyuna M, Zaozhena L. Freestyle fractional order controller design with PSO for Weapon system. ESEP 2011, Singapore; 2011.
[21] Zamani M, Karimi-Ghartemani M, Sadati N, Parniani M. Design of fractional order PID controller for an AVR using particle swarm optimization. Control Eng Practice 2009;17(12):1380–7.
[22] Tang Y, Cui M, Hua Ch, Li L, Yang Y. Optimum design of fractional order $PI^{\lambda}D^{\mu}$ controller for AVR system using chaotic ant swarm. Expert Syst Appl 2012;39(8):6887–96.
[23] Pan I, Das S. Chaotic multi-objective optimization based design of fractional order $PI^{\lambda}D^{\mu}$ controller in AVR system. Int J Electr Power Energy Syst 2012;43(1):393–407.
[24] Maiti D, Acharya A, Chakraborty M, Konar A, Janarthanan R. Tuning PID and $PI^{\lambda}D^{\mu}$ controllers using the integral time absolute error criterion. In: Proceedings IEEE international conference on information and automation for sustainability. Colombo (CL); 2008.
[25] Biswas A, Das S, Abraham A, Dasgupta S. Design of fractional-order $PI^{\lambda}D^{\mu}$ controllers with an improved differential evolution. Eng Appl Artif Intell 2009;22(2):343–50.
[26] Vinagre B. Modelado y control de sistemas dina´micos caracterizados por ecuaciones ı´ntegrodiferenciales de orden fraccional. PhD Thesis, Universidad Nacional de Educacio´n a Distancia. Madrid; 2001.
[27] Monje CA, Vinagre BM, Chen YQ, Feliu V, Lanusse P, Sabatier J. Proposals for fractional $PI^{\lambda}D^{\mu}$ tuning. In: Fractional differentiation and its applications. Bordeaux; 2004.
[28] Vale´rio D, da Costa JS. Tuning of fractional PID controllers with Ziegler–Nichols type rules. Signal Process 2006;86(10):2771–84.
[29] Zhao Ch, Dingÿ UX, Chen Y. A fractional order PID tuning algorithm for a class of fractional order plants. IEEE Int Conf Mech Automat 2005;1:216–21.
[30] Oldham KB, Spanier J. The fractional calculus. New York and London: Academic Press; 1974.
[31] Podlubny I. Fractional differential equations. San Diego: Academic Press; 1999.
[32] Oustaloup A. La dérivation non entière: Théorie, synthèse et applications. Paris: Hermes; 1995.
[33] Oldham B, Zoski CG. Analogue instrumentation for processing polarographic data. J Electroanal Chem 1983;157(1):27–51.
[34] Karami A, Rezaei E, Shahhosseni M, Aghakhani M. Optimization of heat transfer in an air cooler equipped with classic twisted tape inserts using imperialist competitive algorithm. Exp Thermal Fluid Sci 2012;38:195–200.
[35] Kaveh A, Talatahari S. Optimum design of skeletal structures using imperialist competitive algorithm. Comput Struct 2010;88(21–22):1220–9.
[36] Nazari-Shirkouhi S, Eivazy H, Ghodsi R, Rezaei K, Atashpaz-Gargari E. Solving the integrated product mix-outsourcing problem using the imperialist competitive algorithm. Expert Syst Appl 2010;37(12):7615–26.
[37] Khorani V, Disfani VR. A mathematical model for urban traffic and traffic optimization using a developed ICA technique. IEEE Trans Intell Transport Syst 2011;12(4):1024–36.
[38] Hadji MM, Vahidi B. A solution to the unit commitment problem using imperialistic competition algorithm. IEEE Trans Power Syst 2012;27(1):117–24.
[39] Shabani H, Vahidi B, Ebrahimpour M. A robust PID controller based on imperialist competitive algorithm for load–frequency control of power systems. ISA Trans 2013;52:88–95.
[40] Atashpaz-Gargari E, Lucas C. Imperialist competitive algorithm: an algorithm for optimization inspired by imperialistic competition. IEEE Cong Evol Comput 2007:4661–7.
[41] Podlubny I. Fractional-order systems and $PI^{\lambda}D^{\mu}$ controllers. IEEE Trans Automatic Control 1999;44(1):208–14.
[42] Podlubny I, Dorcak L, Kostial I. On fractional derivatives, fractional-order dynamic systems and $PI^{\lambda}D^{\mu}$ controllers. In: Proceedings of the 36th conference on decision and control. San Diego, California, USA; 1997.
[43] Akbari Moornani K, Haeri M. Robustness in fractional proportional–integral–derivative-based closed-loop systems". IET Control Theory Appl 2010;4(10):1933–44.
[44] <http://www.mpoweruk.com/hydro_power.htm>.
[45] Ohba S, Ohnishi H, Iwamoto S. An advanced LFC design considering parameter uncertainties in power systems. Proc IEEE Conf Power Sympos 2007:630–5.

Seyed Abbas Taher was born in Kashan, Iran, in 1964. He received his B.Sc. degree in electrical engineering from the university of Amirkabir-Tehran, in 1988, and his MSc and PhD degrees in electrical engineering from the university of Tarbiat Modares-Tehran, 1991 and 1997, respectively. In 1996, he joined the faculty of engineering, University of Kashan, where he has been an Associate Professor since 2009. His current research interests include power system optimization and control design, analysis of electrical machines, power quality and renewable energy.

Masoud Hajiakbari Fini was born in Kashan, Iran in 1986. He received the B.Sc. degree in electrical engineering from Isfahan University of Technology, Isfahan, Iran in 2010. He is currently a M.Sc. student in Kashan University, Kashan, Iran. His research interests include power system frequency control, load shedding and active power filters.

Saber Falahati Aliabadi was born in Kashan, Iran in 1987. He received the BSc. and MSc degrees in electrical engineering from University of Kashan, Iran in 2010 and 2012, respectively. He is currently a PhD student in University of Kashan, Kashan, Iran. His research interests include power system frequency control, load sharing and renewable energies.