



Fuzzy PID Tuned by a Multi-Objective Algorithm to Solve Load Frequency Control Problem

Ehsan Tehrani¹, Mohsen Farahani², A.R. Zare Bidaki³

¹Department of electrical engineering, BuinZahra Branch, Islamic Azad University, BuinZahra, Iran. hsntrhani@gmail.com

²Young Researchers and Elite Club, East Tehran Branch, Islamic Azad University, Tehran, Iran. Email: m.farahani@basu.ac.ir

³Young Researchers and Elite Club, Buinzahra Branch, Islamic Azad University, Buinzahra, Iran. Email: azare@buinbau.ac.ir

Abstract

In this paper, a fuzzy PID with new structure is proposed to solve the load frequency control in interconnected power systems. In the structure of fuzzy PID, four gains are adjusted by a multi-objective algorithm. The genetic algorithm (GA) is used to generate the Pareto front. The best compromise solution from the obtained Pareto set is then chosen by a Fuzzy-based approach. In addition, we suggest a new control strategy based on the fuzzy PID for the LFC problem. The simulation results show that the frequency and tie-line power flow deviations are effectively damped and settling time in responses is considerably reduced.

Keywords: Load frequency control, AGC, Superconducting magnetic storage energy, Multi-objective optimization algorithm.

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1. Introduction

For large scale electric power systems with interconnected areas, the LFC is important to maintain the system frequency and the inter-area tie power as close to the scheduled values as possible. The input mechanical power to the generators is used to control the frequency of output electrical power and to maintain the power exchange between the areas as scheduled. A well designed and operated power system must cope with changes in the load and with system disturbances, and it should provide acceptable high level of power quality while maintaining both voltage and frequency within tolerable limits. Many control strategies for Load Frequency Control in electric power systems have been proposed by researchers over the past decades.

This extensive research is due to fact that LFC constitutes an important function of power system operation where the main objective is to regulate the output power of each generator at prescribed levels while keeping the frequency deviations within pre-specified limits. A unified tuning of PID load frequency controller for power systems via internal mode control has been proposed [1]. In this paper the tuning method is based on the two-degree-of-freedom (TDF) internal model control (IMC) design method

and a PID approximation procedure. A new discrete-time sliding mode controller for load frequency control in areas control of a power system has been presented by Vrdoljak et al. [2]. In this paper full-state feedback is applied for LFC not only in control areas with thermal power plants but also in control areas with hydro power plants, in spite of their non-minimum phase behaviors. To enable full-state feedback, a state estimation method based on fast sampling of measured output variables has been applied. The applications of artificial neural network, genetic algorithms and optimal control to LFC have been reported in [3-5]. An adaptive decentralized load frequency control of multi-area power systems has been presented by Zribi et al. [6]. Also the application of robust control methods for load frequency control problem has been presented by in [7,8]. Literature review confirms that in most works suggested to solve the LFC problem [1-14], though the area control errors converge to zero finally, however, the power frequency and the tie-line power deviations take a relatively long time period. This means that there is a long settling time in the step response of these signals. In this case, the governor system may never more be able to control the frequency deviations, because it has

a slow dynamical response [10]. So, an active power source with fast response can be used to overcome unexpected load changes. Several papers have been proposed the different types of devices such as SMES, phase shifter and FACTS devices. The use of an SMES unit has been suggested in each area of a two-area system for the LFC [10]. As expected, this method can damp the frequency deviations of both areas effectively. However, from economic point of view, it is not possible to locate an SMES in each area of a multi-area interconnected power system. Therefore, Ngamaroo et. al. proposed an SMES with a large capacity located in one of the areas where is available for the control of other interconnected areas [15]. Because the frequency deviations damping was not in line with expectations, the simultaneous use of flexible AC transmission system (FACTS) devices such as solid-state phase shifters [15] and SSSC [16] and the SMES was studied. Notwithstanding the satisfactory results, the economic feasibility is still a challenging problem for this method. Among various methods proposed for the LFC problem, optimization algorithms are well-liked methods to tune parameters of LFC. In this regard, different types of algorithms such as particle swarm optimization (PSO) [11], genetic algorithm [17, 18], bacteria foraging [19] and chaotic [13] have been proposed for this purpose thus far. In all of these methods, parameters are optimized by the classical weighted-sum method where the general objective function is formulated as a weighted-sum of the sub-objectives. But the problem lies in the correct selection of the weights to characterize the decision-makers preferences. In recent years, the multi-objective problems are used to find non-inferior (Pareto-optimal, non-dominated) solutions. The most widely used methods for generating such non-inferior solutions are the weighting method, ε -constraint method and weighed min-max method. The decision maker should pick out the best compromise solution from a solution set. This paper suggests a multi-objective algorithm to tune the LFC of fuzzy PID type. This study utilizes a new structure fuzzy PID to enhance the convergence speed of frequency and tie-line power flow deviations to zero. The fuzzy PID is then used in a new control strategy to overcome the LFC problem. The problem of obtaining optimal gains of PIDs is formulated into a constrained optimization algorithm. Three separate objective functions are then minimized by a multi-objective genetic optimization algorithm. The main inducement of employing GA is for the reason that it deals simultaneously with a set of possible solutions (the so-called population) which enables the user to find several members of the population. Moreover,

GAs are less susceptible to the shape or continuity of the Pareto front as they can easily deal with discontinuous and concave Pareto fronts, whereas these two issues are known problems with mathematical programming [20]. To choose the best compromise solution from the obtained Pareto set, a fuzzy-based method is used [20]. Simulation results are presented and compared with a conventional GA-PID controller and the results obtained from the tuning method of LFC proposed in [21]. The simulation results on an interconnected power system show that LFC of fuzzy PID type can increase the damping speed of the frequency and tie-line power flow oscillations following a load disturbance considerably so that lower settling time can be observed in the dynamical response of the power system.

2. Two-area Load Frequency Control

A standard and conventional block diagram of a linearized system model of a two area interconnected power system is given in Fig. 1 [22]. This model consists of a classical integral controller (so-called conventional PI controller) that sets the turbine reference power of each area. The tie-line Power ΔP_{tie} flows throughout the tie-line between existing areas. The supplementary frequency control (or secondary loop control) for a successful control of frequency and active power generation should control and balance the power flow at the tie-line and also damp oscillations at the tie line. For this purpose, the easiest way is that the local frequency variation in each area and the tie-line power variations are combined together. This signal is called the area control error (ACE). Generally, to achieve a satisfactory operation of generating units, the frequency and tie-line power should be fixed on their scheduled values even if a load disturbance occurs and, therefore, the area control error should be removed ($ACE=0$). In Fig. 1, each block has the following transfer function.

- Steam turbine = $1/(T_{Ts}+1)$
- Load and machine = $1/(2Hs+D)$
- governor = $1/(T_g s+1)$
- Droop characteristics of governor = $1/R$

In the above transfer functions, T_T and T_g are the turbine and governor time constants, respectively; H and D are the inertia coefficient of generator and ratio of load changes percentage to frequency changes percentage, respectively. In the model given in Fig. 1, ΔP_m and ΔP_{GV} are the incremental changes in the output mechanical power of turbine and governor valve position, respectively.

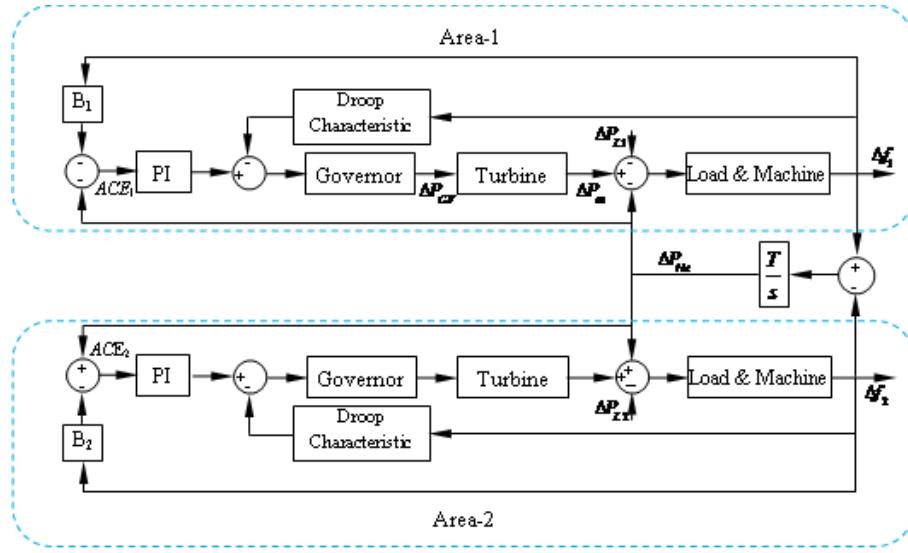


Fig. 1. Block diagram of a standard two-area interconnected power system

3. Fuzzy PID Controller

A fuzzy inference system (FIS) maps given inputs to outputs using fuzzy logic. The fuzzy PID controller uses a parallel structure [23] as shown in Fig. 2. It is a combination of fuzzy PI control and fuzzy PD control. We use the change of measurement $-(y(k)-y(k-1))$, instead of change of error $e(k)-e(k-1)$, as the second input signal to FIS to prevent the step change in reference signal from directly triggering the derivative action.

We adjust FIS settings such as its style, membership functions and rule base to obtain a desired nonlinear control surface. We choose to design a steep control surface using Sugeno style of FIS. Each input set has two terms (Positive and Negative). The following rules are defined:

- If E is Negative and CE is Negative then u is -20.
- If E is Negative and CE is Positive then u is 0.0 = -0 = -
- If E is Positive and CE is Negative then u is 0.

- If E is Positive and CE is Positive then u is 20.

The 3-D nonlinear control surface is plotted in Fig. 3. It has higher gain near the centre of the E and CE plane than the linear surface has, which helps reduce the error more quickly when the error is small. When the error is large, controller becomes less aggressive so that control action is limited to avoid possible saturation.

4. The Proposed Approach

A) Control strategy

The new control architecture for the LFC problem by using the fuzzy PID is displayed in Fig. 4. As seen in Fig. 4, the frequency deviation of each area (i.e. Δf_1 and Δf_2) and tie-line power flow deviations ΔP_{tie} are selected as the input signals to the fuzzy PID. In the structure presented in Fig. 4, to achieve the control inputs u_1 and u_2 , the Fuzzy PID controllers are used together with area control errors.

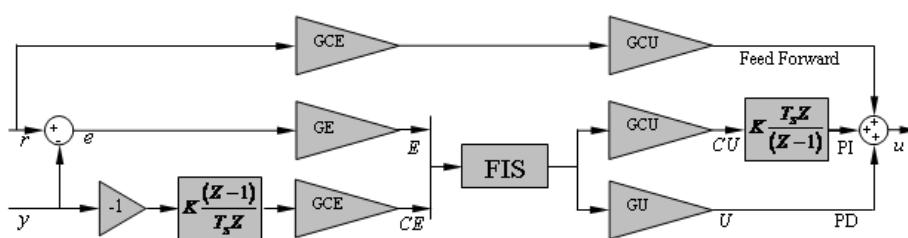


Fig. 2. Fuzzy PID controller structure.

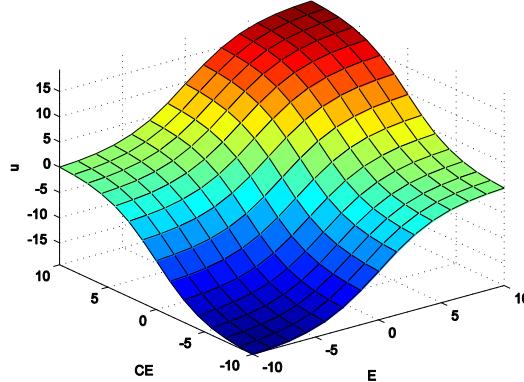


Fig. 3. The 3-D nonlinear control surface of fuzzy PID controller

To achieve the best performance of interconnected power system shown in Fig. 4, optimal solutions of the proposed control strategy are taken into account as an optimization problem and multi-objective genetic optimization algorithm will be used to solve it.

B) Optimization problem

It should be that the design purpose of fuzzy PID controller in each area is to damp the frequency and tie-line power flow deviations. Thus, the purpose is formulated as the minimization of objective function F represented by:

$$F = f_1 + f_2 + f_3 \quad (1)$$

Where

$$f_1 = \int_{t_1=0}^{t_2=t_{sim}} t |\Delta f_1(t)| dt \quad (2)$$

$$f_2 = \int_{t_1=0}^{t_2=t_{sim}} t |\Delta f_2(t)| dt \quad (3)$$

$$f_3 = \int_{t_1=0}^{t_2=t_{sim}} t |\Delta P_{tie}(t)| dt \quad (4)$$

Where t_{sim} is the simulation time period. To compute the objective function, the time-domain simulation of the system model considering all limits of control signals is carried out for the simulation period. The design problem can be formulated as the following constrained optimization problem, where the constraint is the parameter bounds:

$$\begin{aligned} GCE^{\min} &\leq GCE \leq GCE^{\max} \\ GE^{\min} &\leq GE \leq GE^{\max} \\ GCU^{\min} &\leq GCU \leq GCU^{\max} \\ GU^{\min} &\leq GU \leq GU^{\max} \end{aligned} \quad (5)$$

5. Multi objective optimization algorithm

A) Multi-objective optimization problem and Pareto solutions

In a multi-objective optimization problem (MOP), several objectives can be optimized. So, a MOP differs from a single-objective optimization problem (SOP). In a single-objective optimization problems, the overall goal is to acquire the best single design solution, while in MOPs, with several and probably inconsistent objectives, there is usually no single optimal solution. Therefore, the decision maker is needed to choose a solution from a finite set by making compromises. A suitable solution should provide for acceptable performance over all objectives [20]. A general formulation of an MOP includes a number of objectives with a number of inequality and equality constraints. Mathematically, the problem can be represented as follows [20]:

$$\begin{aligned} &\text{Minimize/Maximize } f_i(x) \quad \text{for } i=1,2,\dots,n. \\ &\text{Subject to} \\ &g_j(x) \leq 0 \quad j=1,2,\dots,J \\ &h_k(x) \leq 0 \quad k=1,2,\dots,K \end{aligned} \quad (6)$$

where $f_i(x)=\{f_1(x),\dots,f_n(x)\}$; n denotes the number of objectives; $x=\{x_1,\dots,x_p\}$ is a vector of decision variables; p denotes the number of decision variables.

The MOP can be solved by two approaches. The first one is the classical weighted-sum approach. In this approach, the objective function is formulated as a weighted-sum of the objectives. But the problem lies in the correct selection of the weights or utility functions to characterize the decision-makers preferences. The second approach called Pareto-optimal solution can be used to solve this problem. The MOPs usually have no unique or perfect solution, but a set of non-dominated, alternative solutions, known as the Pareto-optimal set. Assuming a minimization problem, dominance is defined as follows:

A vector $\mathbf{u}=(u_1,\dots,u_n)$ is said to be dominate $\mathbf{v}=(v_1,\dots,v_n)$ if and only:

$$\forall i \in \{1,\dots,n\}, u_i \leq v_i \wedge \exists i \in \{1,\dots,n\}; u_i < v_i \quad (7)$$

A solution $x_u \in u$ is said to be Pareto-optimal if and only if there is no $x_v \in u$ for which $v=f(x_v)=(v_1, \dots, v_n)$ dominates $u=f(u_v)=(u_1, \dots, u_n)$.

Pareto-optimal solutions are also called efficient, non-dominated, and non-inferior solutions. The corresponding objective vectors are simply called non-dominated. The set of all non-dominated vectors is known as the non-dominated set, or the trade-off surface, of the problem. A Pareto-optimal set is a set of solutions that are non-dominated with respect to

each other. While moving from one Pareto solution to another, there is always a certain amount of sacrifice

in one objective to achieve a certain amount of gain in the other.

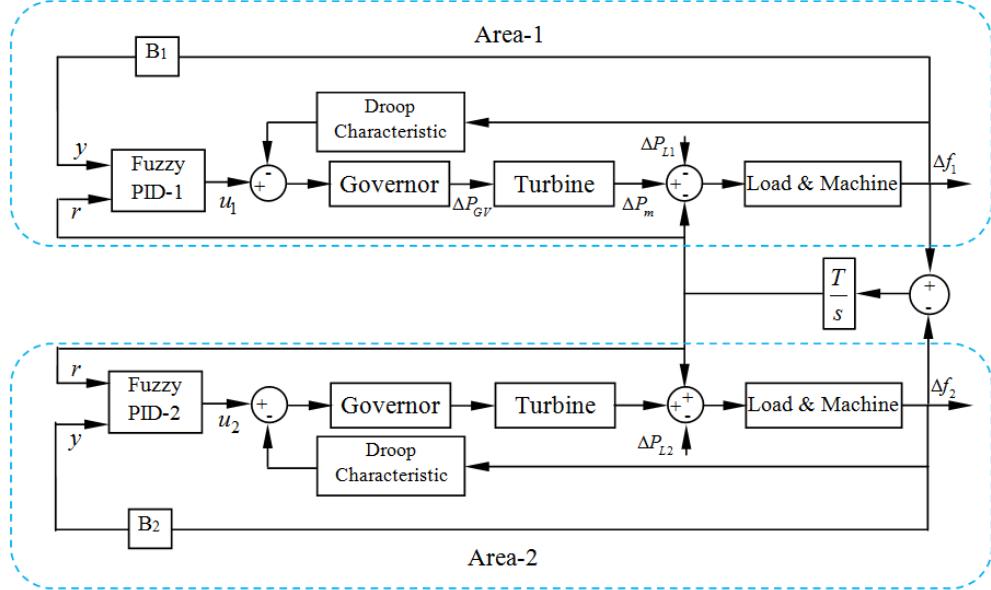


Fig. 4. Control configuration for the LFC problem along with the fuzzy-PID.

The elements in the Pareto set has the property that it is impossible to further reduce any of the objective functions, without increasing, at least, one of the other objective functions. A complete explanation about Pareto-optimal solution can be found in [20].

B) GA method for generating Pareto solutions

The ability to handle complex problems, involving features such as discontinuities, multi-modality, disjoint feasible spaces and noisy function evaluations reinforces the potential effectiveness of GA in optimization problems. Although, the conventional GA is also suited for some kinds of multi-objective optimization problems, it still difficult to solve those multi-objective optimization problems in which the individual objective functions are in the conflict condition.

Being a population-based approach; GA is well suited to solve MOPs. A generic single-objective can be easily modified to find a set of multiple non-dominated solutions in a single run. The ability of GA to simultaneously search different regions of a solution space makes it possible to find a diverse set of solutions for difficult problems with non-convex, discontinuous, and multi-modal solutions spaces. The crossover operator of GA exploits structures good solutions with respect to different objectives to create new non-dominated solutions in unexplored parts of the Pareto front. In addition, most multi-objective GA does not require the user to prioritize, scale, or weigh objectives. Therefore, GA has been the most popular

heuristic approach to multi-objective design and optimization problems.

Pareto-based fitness assignment was first proposed by Goldberg [24], the idea being to assign equal probability of reproduction to all non-dominant individuals in the population. The method consisted of assigning rank 1 to the non-dominated individuals and removing them from contention, then finding a new set of non-dominated individuals, ranked 2, and so forth. In the present study, before finding the Pareto-optimal individuals for the current generation, the Pareto-optimal individuals from the previous generation are added. The number of Pareto-optimal individuals is limited, when it exceeds the defined number. This is done by calculating a function of closeness between the individuals given as below:

$$D(x) = (\min|x - x_i| + \min|x - x_k|)/2 \quad (8)$$

where $x \neq x_i \neq x_k$ are individuals on the Pareto-surface. The individual with smaller value of D (distance to the other points) is removed. This process continues until the desired number of points is achieved. Besides limiting the number of points this also helps to keep the diversity of the Pareto-set and obtain better spread surface. How to limit the Pareto-optimal set has briefly been explained in [20].

6. Simulation Results

In this section, the simulation results on an interconnected power system are provided. It should be noted that the optimization process is run several times and the best parameters are then selected from between obtained results. In this paper, MATLAB is

used to implement the optimization algorithm and to simulate the cases.

A) Generation of Pareto solution set

In this paper, Pareto solutions are generated by GA for the fuzzy PID gains in each area so as to minimize the objective function F . To apply GA, a number of parameters should be determined. A proper selection of the parameters has an impact on the speed of convergence of the algorithm. The parameters used for the multi-objective genetic algorithm (MGA) are provided in Table 1.

Table.1.
Parameters used in multi-objective genetic optimization algorithm.

parameter	Value/Type
Maximum generations	100
Population size	50
Mutation rate	0.01
Number of Pareto-surface individuals	11

The objective function is evaluated for each individual by simulating the example power system, considering a $\Delta P_{L1}=0.2$ at $t=0$. The optimization is terminated by the pre-specified number of generations. In this paper, the number of individuals in the Pareto-optimal set is selected 11. In addition,

the best compromise solution from the obtained Pareto set is chosen by a Fuzzy-based approach. The j th objective function of a solution in a Pareto set f_j is represented by a membership function μ_j defined as:

$$\mu_j = \begin{cases} 1, & f_j \leq f_j^{\min} \\ \frac{f_j^{\max} - f_j}{f_j^{\max} - f_j^{\min}}, & f_j^{\min} < f_j < f_j^{\max} \\ 0 & f_j \geq f_j^{\max} \end{cases} \quad (9)$$

where f_j^{\min} and f_j^{\max} denote the maximum and minimum values of the j th objective function, respectively.

For each solution i , the membership function can be obtained from the following equation.

$$\mu^i = \frac{\sum_{j=1}^n \mu_j^i}{\sum_{i=1}^m \sum_{j=1}^n \mu_j^i} \quad (10)$$

where n and m denote the number of objectives functions and the number of solutions, respectively. The solution having the maximum value of μ^i is the best compromise solution. The obtained Pareto solution set; values of objective functions (f_1, f_2 and f_3) associated with the Pareto solutions and the membership function values of each solution are given in Table 2. In Table 2, Pareto solution set are shown by MGA-x; $x=1, 2, \dots, 11$. As seen in Table 2, MGA-8 ($\mu^8=0.115812$) has maximum membership function value. So, results obtained in MGA-8 are the best compromise solution and should be selected as optimal gains.

Table.2.
Pareto solutions, objective functions and value of memberships

Solution	Fuzzy PID-1					Fuzzy PID-2			f_1	f_2	f_3	μ^i
	GCE	GCU	GE	GU	GCE	GCU	GE	GU				
MGA-1	3.76	8.12	6.10	4.11	5.69	3.31	6.37	2.08	0.010129	0.024147	0.082783	0.067045
MGA-2	3.77	8.12	6.11	4.12	5.69	3.27	6.43	2.03	0.010270	0.024139	0.084585	0.054333
MGA-3	3.79	8.25	6.19	4.16	5.54	3.21	6.45	2.01	0.010628	0.023710	0.080150	0.100362
MGA-4	3.77	8.28	6.27	4.15	5.61	3.24	6.45	2.03	0.010911	0.023754	0.079626	0.099490
MGA-5	3.76	8.12	6.10	4.11	5.69	3.31	6.37	2.08	0.010129	0.024147	0.082783	0.067045
MGA-6	3.81	8.27	6.13	4.13	5.63	3.28	6.39	2.07	0.010599	0.023925	0.080635	0.083313
MGA-7	3.82	8.30	6.27	4.14	5.59	3.22	6.42	2.02	0.011106	0.023667	0.077952	0.104209
MGA-8	3.83	8.34	6.38	4.16	5.54	3.18	6.46	1.99	0.011775	0.023446	0.075787	0.115812
MGA-9	3.85	8.42	6.41	4.16	5.53	3.18	6.46	1.99	0.012552	0.023354	0.074254	0.112422
MGA-10	3.79	8.20	6.12	4.13	5.65	3.23	6.40	2.01	0.010344	0.023920	0.081129	0.086972
MGA-11	3.84	8.42	6.41	4.16	5.51	3.18	6.45	1.99	0.012497	0.023329	0.07434	0.114997

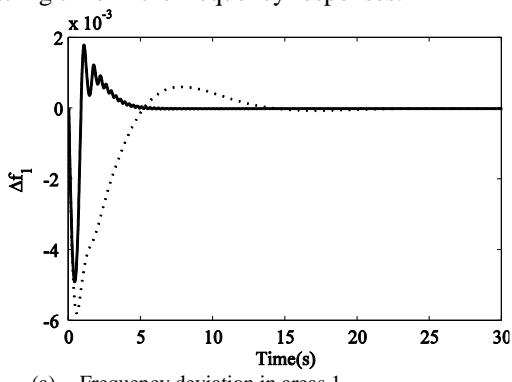
In order to demonstrate the effectiveness of proposed approach in solving the LFC problem, a comparative study is carried out between results obtained from the proposed approach, the method proposed in [21] and conventional PI controller. As mentioned in the introduction, a symmetric tuning algorithm in which a maximum peak resonance specification (MPRS) has been suggested to solve the LFC problem.

For the first simulation, a $\Delta P_{L1}=0.2$ (an increase in load) is applied to area-1 at $t=0$. The frequency deviation in areas 1 and 2, and tie-line power flow deviation are shown in Fig. 7 (a-c), respectively. As seen in this figure, there is a steady-state error in the dynamical responses of power system in the absence of supplementary controller loop. This may lead to losing the stability of the power system.

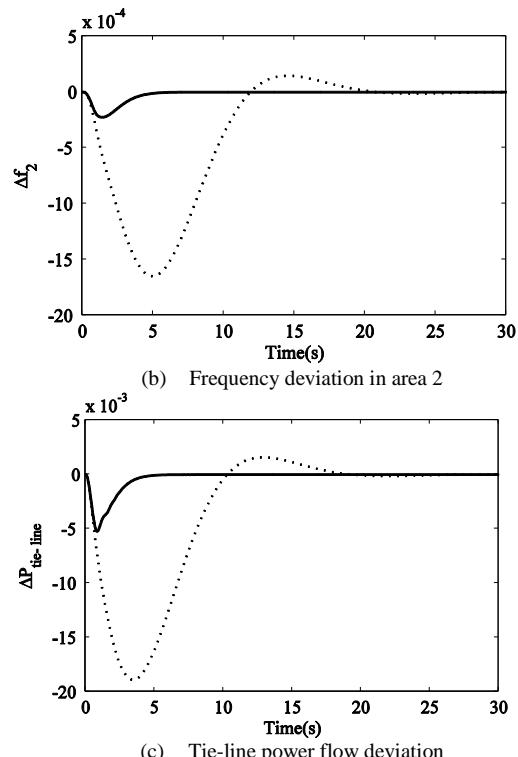
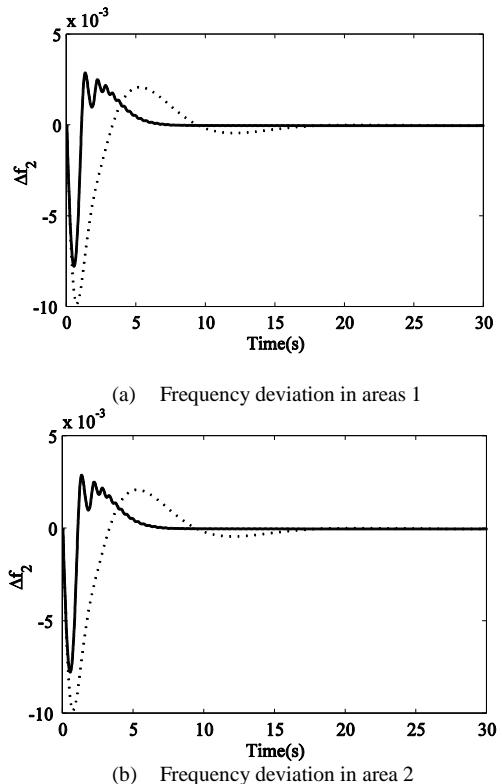
The proposed approach makes the power system have a smoother response compared to the MPRS method. In fact, when the electrical load is increased in one of the areas, the frequency of both areas and tie-line power flow will fall into a value less than allowable value. If no controller is designed for such a situation, the interconnected power system will certainly become unstable. Also, if the designed controller has a slow performance, the governor system may no longer be able to eliminate the frequency deviations. On the other hand, a well-designed controller for the LFC problem should be able to prevent the further frequency drop following a load disturbance. It is clear from Fig. 7 (a-b) that the proposed approach prevents further drop of frequency of both areas following an increase load.

To show the effectiveness and robustness of proposed approach, it is assumed that a $\Delta P_{L2}=0.2$ is occurred in area-2 at $t=0$. Figs. 8 (a-c) illustrate the frequency deviation of areas and tie-line power flow deviations, respectively. Again, it is evident from these figures that the performance of proposed approach is much better than the other methods.

Table 3 compares the different methods in terms of settling time. As seen in Table 2, the proposed approach is considerably reduced the settling time in the frequency responses.



(a) Frequency deviation in areas 1

Fig. 5. Responses of power system to a $\Delta P_{L1}=0.2$ 

(b) Frequency deviation in area 2

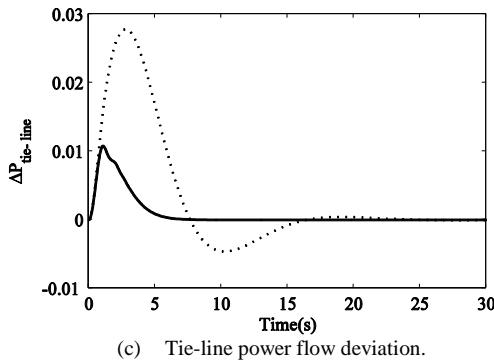
Fig. 6. Responses of power system to a $\Delta PL_2=0.2$

Table.3.

Comparison performance of different methods in terms of settling time (in sec).

	Load disturbance applied to Area-1			Load disturbance applied to Area-2		
	Δf_1	Δf_2	ΔP_{tie}	Δf_1	Δf_2	ΔP_{tie}
Proposed approach	4.41	5.58	4.95	6.36	6.74	6.20
MPRS	12.68	19.03	17.32	18.69	15.12	15.36
Conventional PI	14.35	22.97	24.70	22.85	19.30	23.24

7. Conclusion

In this study, a new structure and effective of the fuzzy PID-type LFC is proposed to solve the load frequency control in interconnected power systems. The main objective is to eliminate the deviations in the frequency of different areas and tie-line power flow with the minimum settling time. Accordingly, three objective functions which reflect the dynamic of power system are used. A multi-objective optimization algorithm is then utilized to simultaneously minimize these objectives. Several simulations are used to demonstrate the effectiveness and robustness of proposed approach. All simulation results show that the proposed approach make the power system have a smooth dynamic with a low settling time. Due to the flexibility of proposed control structure, the proposed approach can be extended to larger power systems.

Appendix

Parameters used for model shown in Fig. 1:
Area-1: $H=5$, $D=0.6$, $T_g=0.2$, $T_T=0.5$, $R=0.05$, $B_1=20.6$.
Area-2: $H=4$, $D=0.9$, $T_g=0.3$, $T_T=0.6$, $R=0.0625$, $B_2=16.9$.

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