ON DESIGN OF ROBUST PI-BASED FUZZY LOGIC CONTROLLERS FOR LOAD-FREQUENCY CONTROL IN A LARGE-INTERCONNECTED POWER SYSTEM

Ngoc-Khoat NGUYEN   **Prof. Dr. Qi HUANG**
School of Energy Science and Engineering, University of Electronic Science and Technology of China
Chengdu, Sichuan 611731, China, Phone: +86 13088051248, Email: khoatnn@epu.edu.vn

Thi-Mai-Phuong DAO
College of Electrical Information Engineering
Changsha, Hunan 410100, China, Phone: +86 15200931744, Email: bkblackrose@yahoo.com

Abstract: *This work concentrates on an important control mission to guarantee the network frequency at its nominal value of 50Hz in a large-modern and multi-area interconnected power system. Actually, during the operation of such a power system, its frequency is usually affected by many types of perturbations that load disturbance is a typical case. Such effect causes the imbalance between active power and load demand which makes the frequency changeable and power network unstable. In order to stabilize the network frequency to restore the steady state of the power system, this work proposes efficient controllers using fuzzy logic technique. These fuzzy logic controllers based on the principle of PI regulators are applied usefully in a four-area interconnected power system as a typical case of a large-modern electric grid in reality. Also, simulation results obtained in this study verify the outstanding control features of the proposed controllers in comparison with conventional Integral controllers.*

Key words: *Large-modern power system; frequency; tie line power; Intergral; PI- FL.*

Nomenclature

i	index of the i^{th} generation area, $i = 1, 2, 3, 4$
f_i	real frequency, Hz
f_n	nominal frequency, $f_n = 50$Hz
Δfi	change of frequency, p.u.
$\Delta P_{D,i}$	load increment, p.u.
$T_{G,i}$	time constant of governor, sec
$T_{T,i}$	time constant of non-reheat turbine, sec
M_i	generator inertia constant, p.u.
D_i	load damping factor, p.u. MW/Hz
T_{ij}	tie-line time constant, sec
$P_{tie,i}$	tie line power flow, p.u.
$\Delta\ P_{tie,i}$	deviation of tie line power flow, p.u.
B_i	bias factor, MW/p.u. Hz
R_i	speed regulation, Hz/MW
ACE_i	area control error
s	Laplace operator

1. Introduction

Traditionally, power systems are built to convert natural energy sources, such as hydro and thermal energy into electric power to serve the needs of industrial operation and civil life. During the operation of such power systems, it is necessary to ensure properties of the stability, safety, continuity and economy. These performances can be achieved successfully if the standard generation requirements are satisfied as [1]:

(1) the balance between the generation and the load demand has to be met;

(2) the system voltage profile has to be maintained within acceptable limits;

(3) the network frequency must be maintained at its nominal values of 50Hz or 60Hz;

(4) the tie line power flows also have to be guaranteed at the scheduled values.

Three first conditions are normally required for all of the power systems in reality while the last requirement is only added for a large-scale power system consisted of many interconnected generation stations. In this work, we will focus on modeling and controlling large-modern multi-area interconnected power systems, so that all of four above requirements have to be implemented.

Due to the changeable needs of users in using practice, loads in a power grid are also affected to vary frequently. This leads to the imbalance between the real power and the load demand and thus the third requirement mentioned above must be implemented immediately to guarantee the stability of power systems [2]. Also, in a large-interconnected power system, tie line powers relating to the change of the network frequency have to be maintained according to the fourth above requirement. As a result, load-frequency control (LFC) strategy has been carried out as a necessary part of automatic generation control for a power system. The main objectives of such LFC schemes are to reduce the deviations of both frequency and tie line power to satisfy the acceptable tolerances in order to restore the steady state of large-modern power systems. In this work, we will design a model of a four-area non-reheat interconnected power system as a typical case of large-modern power networks. In order to solve the LFC issue mentioned above, we also propose an efficient application of intelligent controllers based on fuzzy logic technique. These controllers are designed to implement the solution of LFC based on tie-line bias control strategy as discussed in [3-4]. According to this control method, the definition of ACE (Area Control Error) is used to make sure that both deviations of the frequency and tie line power flow are controlled to meet all of the desired requirements. Using ACEs as the input signals of the fuzzy logic controllers [5-9], the PI (Proportional-plus-Integral) type is also chosen as the principle of the proposed controllers in this work. Therefore, both ACE and its derivative are fully used to achieve the better control features, such as the smaller overshoots and the shorter settling times compared with the conventional controllers using Integral regulators. The dominant effectiveness of the PI-based fuzzy logic controllers proposed in this study will be demonstrated by simulation process using different load conditions for a four-area interconnected power system built earlier.

2. Modeling of four-area interconnected power systems

Due to the complexity and diversity of large-scale power systems in practice, models of four-area interconnected power grids are selected typically to study in this work as shown in Fig. 1. It is the fact that such models are also complicated (see Fig. 1), and they depend particularly on building strategies of electric powers in each country. Therefore, we only choose a typical case study of such four-area interconnected power systems as illustrated in Fig. 1(d). In this case, each generation area is interconnected with each other area by tie lines to exchange the power demands.

Each generation area as shown in Fig. 1 consists of three main parts: governor, non-reheat turbine and generator units. When dealing with the LFC issue, the transfer functions of these units for the area #*i* can be expressed in the order as follows [3-4]

$$G_{Governor,i}(s)=\frac{1}{T_{G,i}.s+1}, \qquad (1)$$

$$G_{Turbine,i}(s)=\frac{1}{T_{T,i}.s+1}, \qquad (2)$$

$$G_{Generator,i}(s)=\frac{1}{M_i.s+D_i}. \qquad (3)$$

The parameters used in the above equations can be found clearly in nomenclature as mentioned earlier.

Subsequently, the model of the i^{th} area can be given as:

$$\Delta F_i(s)=\frac{1}{M_i.s+D_i}\left[\Delta P_{G,i}(s)-\Delta P_D(s)-\Delta P_{tie,i}(s)\right], \qquad (4)$$

$$\Delta P_{T,i}(s)=\frac{1}{T_{T,i}.s+1}\Delta P_{G,i}(s), \qquad (5)$$

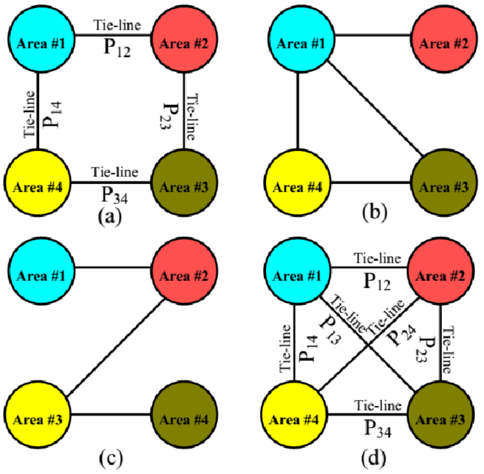

Fig. 1. Simple models of four-area interconnected power systems

$$\Delta P_{G,i}(s)=\frac{1}{T_{G,i}.s+1}\left[\mathrm{U}(s)-\frac{1}{R_i}\Delta F_i(s)\right], \qquad (6)$$

$$\Delta P_{tie,i}(s)=2\pi\sum_{j=1,j\neq i}^{4}\frac{1}{s}T_{ij}\left[\Delta F_i(s)-\Delta F_j(s)\right]. \qquad (7)$$

The equation of ACE for the area #*i* is expressed as

$$ACE_i(s)=\Delta P_{tie,i}(s)+B_i.\Delta F_i(s). \qquad (8)$$

The above model of a four-area interconnected power system can be used to solve the given LFC issue as shown in Fig. 2. This model built in Matlab/simulink environment uses effective controllers that are based on fuzzy logic technique which will be discussed in the following section.

3. PI-based fuzzy logic controllers for LFC

In order to deal with the complicated control issues, modern control techniques such as fuzzy logic and neural network have been applied widely in industrial systems, particularly in LFC problem mentioned earlier. Since a large-scale multi-area interconnected power system is practically built with the inherent attributes of nonlinearity, we have designed controllers based on fuzzy logic technique as the best choice of LFC solution for the following reasons:

(1) fuzzy logic is a thinking process of users incorporated in control strategy, thus it is not necessary to know clearly and fully parameters of the control system;

(2) fuzzy logic controllers can utilize efficiently the incomplete information to make a good control decision which only depends on the knowledge of users;

(3) when applying fuzzy logic rules, it is easy to set up successfully a HMI (Human Machine Interface) which is very useful in control strategies.

According to [10-12], each fuzzy logic controller consists of three processes as indicated below:

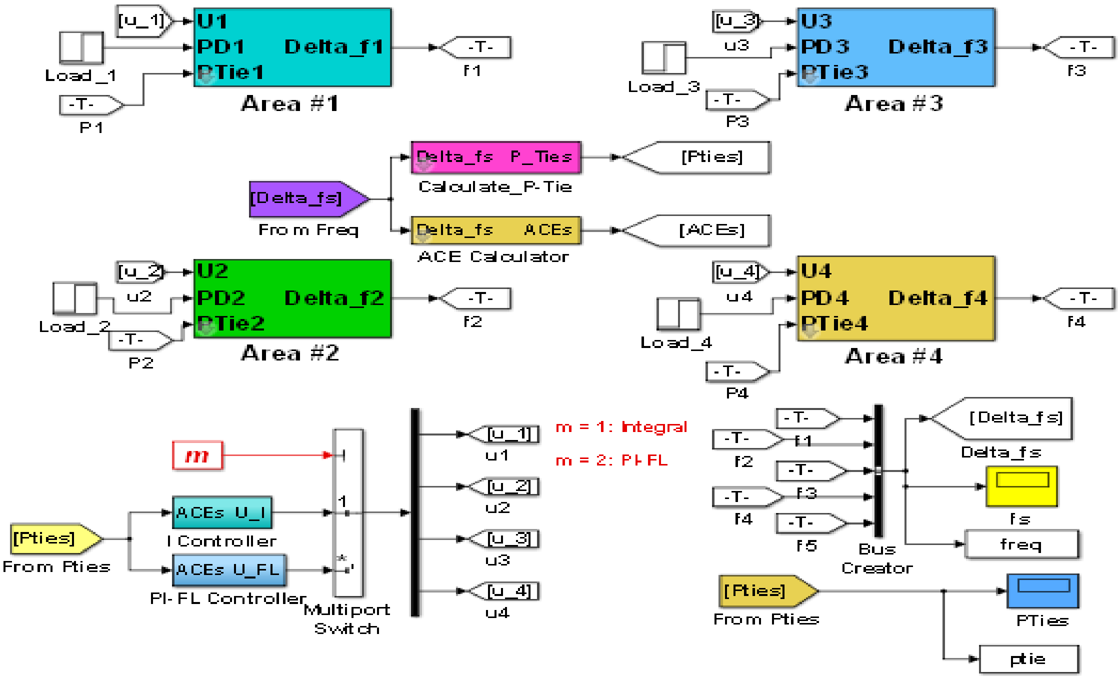

Fig. 2. Matlab/simulink model of the four-area interconnected power system using different controllers

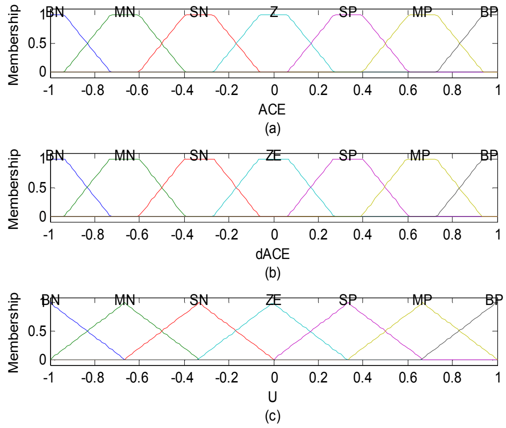

Fig. 3. Membership functions of the PI-based fuzzy logic controllers

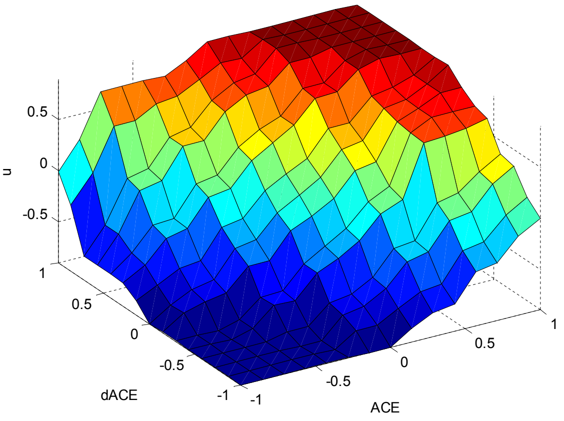

Fig. 4. A 3D graph of membership functions

Table 1
A 49-rule matrix for the proposed fuzzy logic controllers

ACE	*dACE*						
	BN	**MN**	**SN**	**ZE**	**SP**	**MP**	**BP**
BN	BP	BP	BP	MP	MP	SP	ZE
MN	BP	MP	MP	MP	SP	ZE	SN
SN	BP	MP	SP	SP	ZE	SN	MN
ZE	MP	MP	SP	ZE	SN	NM	MN
SP	MP	SP	ZE	SN	SN	MN	BN
MP	SP	ZE	SN	MN	MN	MN	BN
BP	ZE	SN	MN	MN	BN	BN	BN

(1) fuzzification is the process of making a crisp quantity into fuzzy by carrying considerable uncertainties and it can be represented by membership functions;

(2) fuzzy rule base is used to process and evaluate control rules;

(3) defuzzification is the process of conversion of a fuzzy quantity to a crisp quantity that can be used to make the corresponding signal control for the system.

For the solution of LFC, based on tie-line bias control strategy, we use both ACE and its derivative as inputs signals of each fuzzy logic controller. According to the principle of this controller, its output signal, U, can be obtained as

$$U_i(t) = K_u.u_i(t) = K_u\left[\frac{1}{K_e}\int ACE_i(t)dt + \frac{1}{K_{de}}.ACE_i(t)\right] \quad (9)$$

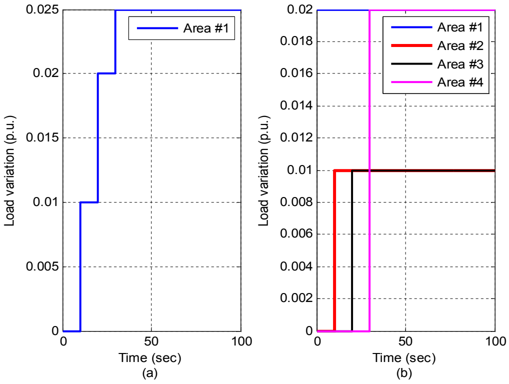

Fig. 5. Two load variation conditions for simulation

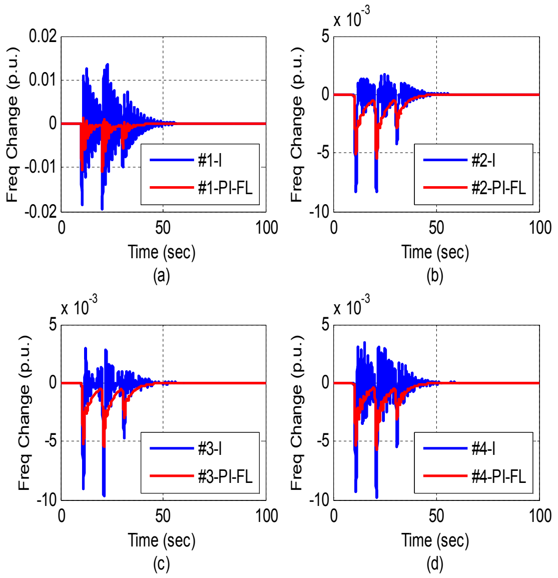

Fig. 6. Changes of frequency in each area for the first simulation case

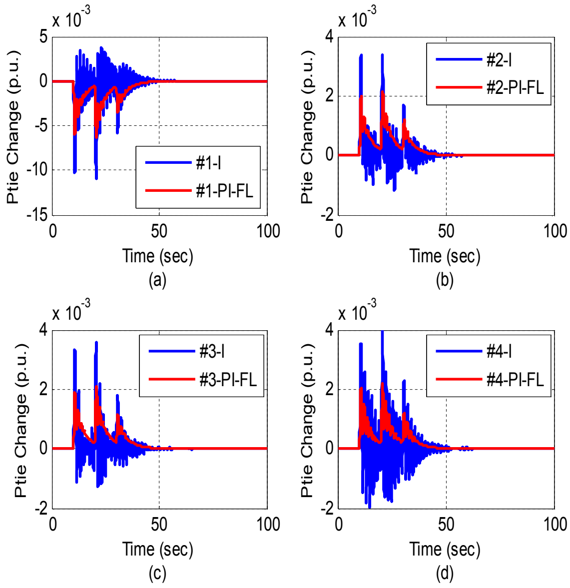

Fig. 7. Deviations of tie line power in each area in the first simulation case

where K_e, K_{de} and K_u are tuned factors of ACE, derivative of ACE and output signal U, respectively. From (9), it is easy to yield the following equation

$$U_i(t) = K_P.ACE_i(t) + K_I.\int ACE_i(t)dt. \qquad (10)$$

In (10), factors of $K_P = \dfrac{K_U}{K_e}$ and $K_I = \dfrac{K_U}{K_{de}}$ are respectively similar to the proportional and integral coefficients of a PI regulator. Therefore, our fuzzy logic controller can be called as a PI-based fuzzy logic controller.

Basically, there are many types of membership functions and a lot of methods of defuzzification process that can be applied in control practice using fuzzy logic controllers. For our work, *trapezoidal* membership functions, *trapmf*, are used for inputs of ACE and dACE, while *triangular* membership function, *trimf*, is applied for output signal U. The shapes of these memberships can be seen clearly in Fig. 3 and Fig. 4. The corresponding fuzzy rule base is also indicated in Table 1. This rule matrix built is based on the general control considerations as:

(a) if both inputs are zero, then maintain the present control of output signal;

(b) if ACE(t) is not zero however it is slightly changing, then maintain the present control state;

(c) if ACE(t) is varying significantly, then modify the control signal based on the magnitude and sign of ACE(t) and dACE(t) to force ACE(t) towards zero.

In Table 1, seven logic levels are used for all membership functions of inputs and output. To verify the effectiveness of the proposed controllers, the following section will carry out simulation process using Matlab/Simulink software in comparison with the conventional Integral controllers.

4. Simulation results and discussion

Because of the frequent load variation, to obtain an entire evaluation of the PI-based fuzzy logic controllers and conventional Integral controllers for LFC solutions implemented in the power grid model built earlier, let us now consider two common cases of load variation conditions as shown in Fig. 5. In Fig. 5(a), load change only appears in the first area at different instants of 10(sec), 20(sec) and 30(sec) with the corresponding magnitudes of 0.01(p.u.), 0.02(p.u.) and 0.025(p.u.). In the second case as illustrated in Fig. 5(b), load variations occur in all of four areas as: 2% at 0(sec), 1% at 10(sec), 1(%) at 20(sec) and 2% at 30(sec) in the areas #1, #2, #3 and #4, respectively.

Simulation results of the first case can be seen clearly in Fig. 6, Fig. 7 and Fig. 8 for both frequency and tie line power deviations. Also, simulation results of the second case are depicted in three Figures of 9, 10 and 11. According to these results, it is very clear to assert that PI-based fuzzy logic controllers have

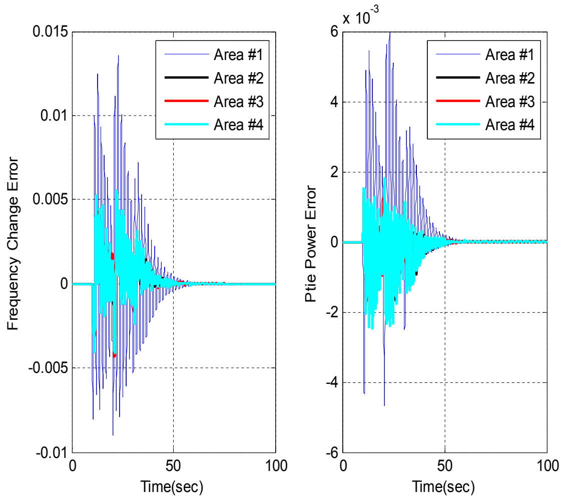

Fig. 8. Frequency and tie line power change errors in each area for the first simulation case

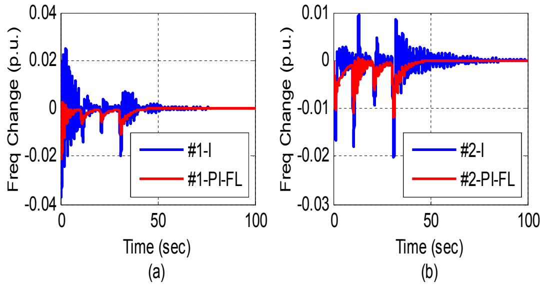

Fig. 9. Frequency changes in the second simulation case

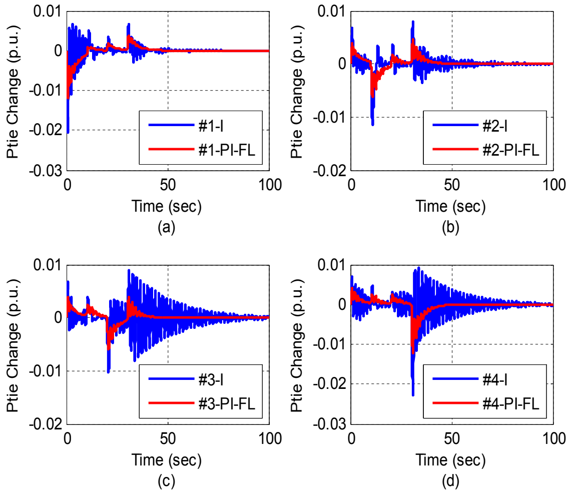

Fig. 10. Changes of tie line power in the second case

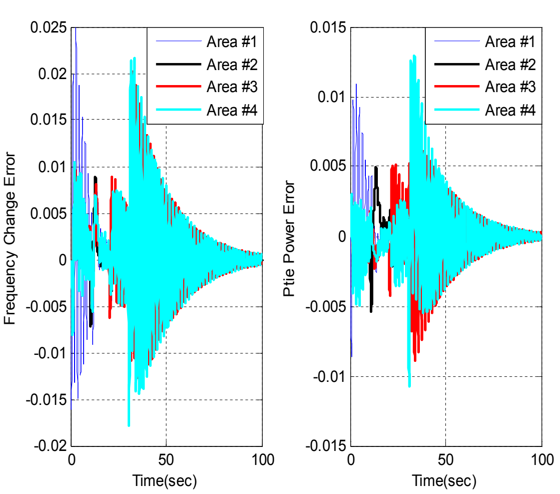

Fig. 11. Frequency and tie line power change errors in each area for the second simulation case

obtained the better control performances in comparison with the Integral controllers. Their overshoots and settling times are much smaller than the integral controllers'. This confirmation can also be demonstrated by calculating the numerical values as indicated in Table 2 and Table 3.

5. Conclusion

In this study, PI-based fuzzy logic controllers have been built successfully to apply in a four-area interconnected power system to solve the problem of LFC. Different load perturbation conditions are also fed to this power model corresponding to two simulation cases to implement the LFC issue mentioned in this paper. Using Matlab/Simulink software version 2013a, their simulation results obtained, such as much smaller overshoots and shorter settling times compared with the Integral controllers have verified the dominant feature of the proposed controllers. Because of the complexity of large-modern power systems, however, it may be necessary to improve such controllers with the programmable logic rules to adapt more efficiently. One of the best control solutions in the future is to combine with the artificial neural network technique to design the desired controllers to deal with the complex LFC problems in practice.

Appendix

Parameters of the proposed power system model

$T_{G1} = 0.08$, $T_{G2} = T_{G3} = 0.1$, $T_{G4} = 0.09$
$T_{T1} = 0.3$, $T_{T2} = T_{T3} = 0.25$, $T_{T4} = 0.32$
$M_1 = 0.15$, $M_2 = M_3 = 0.2$, $M_4 = 0.25$
$D_1 = 0.0083$, $D_2 = D_3 = 0.010$, $D_4 = 0.012$,
$T_{ij} = 0.071$

Table 2
A numerical comparison of two controllers for the second simulation case

		Area #1	Area #2	Area #3	Area #4
First overshoots (p.u.)	Integral	-0.0195	-0.0084	-0.0097	-0.0098
	PI-based FL	-0.0108	-0.0054	-0.0055	-0.0057
Settling times (sec)	Integral	44.8652	35.8198	34.5245	36.1658
	PI-based FL	35.0441	34.6628	34.6290	34.5556

Table 3
A numerical comparison of two controllers for the second simulation case

		Area #1	Area #2	Area #3	Area #4
First overshoots (p.u.)	Integral	-0.0370	-0.0203	-0.0226	-0.0367
	PI-based FL	-0.0209	-0.0119	-0.0122	-0.0191
Settling times (sec)	Integral	52.0000	61.7305	87.0969	88.9056
	PI-based FL	39.6376	40.2468	40.1577	40.8115

Acknowledgment

This work is supported by the Natural Science Foundation of China (NFSC, Grant No. 51277022). The authors also would like to thank Mr. Thanh-Minh Nguyen, email-*ngockhoai2010@yahoo.com.vn*, for his simulation discussions.

References

1. Richard, G. F., Power System Dynamics and Stability. Boca Raton: CRC Press LLC, pp. 10-150, 2001.
2. Damien, E., Mevludin, G., and Wehendel, “Power Systems Stability Control: Reinforcement Learning Framework,” *IEEE Trans. on Power Systems*, Vol. 19, No. 1, pp. 427-435, Feb, 2004.
3. Hadi, S., Power System Analysis, TMH edition, pp. 100-210, 2002.
4. Murty, P., Operation and Control in Power Systems. BS Publications, pp. 242-280, 2008.
5. Sharifi, A., Sabahi, K., Aliyari, S., Nekoui, M.A., and Teshnehlab, M., “Load Frequency Control in Interconnected Power System using Multi-Objective PID Controller,” In: 2008 *IEEE International Conference on Soft Computing in Indutrial Applications (SMCia/08)*, pp. 217-221, Jun. 2008.
6. Ateeth, K.T.,, Harikrishna, N., and Vigneesh, P., “Decentralized Control of Multi-Area Power System Restructuring for LFC Optimization,” In: 2012 *IEEE International Conference on Power Electronics, Drives and Energy Systems*, pp. 106-112, Dec. 2012.
7. Subbaraj, P., and Manickavasagam, K., "Generation Control of Interconnected Power Systems Using Computational Intelligence Techniques ", *IET Gener. Trans. Distrib*, vol. 1, no. 4, pp. 557-563, 2007.
8. Vinod, K., “ Intelligent Controllers for Automatic Generation Control”, *IEEE Trans.on Power System*, vol. 14, no. 2, pp. 557-574, 1999.
9. Gaddam, M., Akula, R., “Automatic Generation Control Using Fuzzy Logic”, In: *8th International Conference on Development and Application systems*, May 25-27, 2006.
10. Ali, M. Y. and Ayman, A. A., “Non-linearities in Fuzzy Approach for Control A Two-Area Interconnected Power System,” In: *Proc. IEEE International Conference on Mechatronics and Automation*, pp. 706-711, Aug. 2010.
11. Timothy, J. R., Fuzzy Logic with Engineering Application. Willey, 3rd edition, pp. 50-151, March, 2010.
12. Hassan, M.A.M, and Malik, O.P., "Implementation and Laboratory Test Results for a Fuzzy Logic Self-tuned Power System Stabilizer", *IEEE Trans. on Energy Conversion*, vol. 8, no. 2, pp. 221-228, Jan 1993.