International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V71I7P222

Volume 71 Issue 7, 223-232, July 2023

Original Article

Different Fuzzy Logic–Based Load-Frequency Controllers for Interconnected Power Systems – A Comparative Study Applied in Vietnam

Thi-Mai-Phuong Dao[1], Ngoc-Khoat Nguyen[2,*], Duy-Trung Nguyen[2]

[1]*Faculty of Electrical Engineering, Hanoi University of Industry, 298 Cau Dien Street, Bac Tu Liem District, Hanoi, Vietnam*
[2]*Faculty of Control and Automation, Electric Power University, 235 Hoang Quoc Viet Street, Hanoi, Vietnam*

[*]*Corresponding Author : khoatnn@epu.edu.vn*

Received: 04 May 2023 Revised: 20 June 2023 Accepted: 23 June 2023 Published: 21 July 2023

Abstract *- Load-Frequency Control (LFC), a chief part of automatic generation control, plays an indispensable role in the stability and economy of an interconnected electric power grid. The major objective of this control methodology is to force the system frequency to be stable at a nominal value (i.e. f = 50 Hz) or fluctuate around this value, satisfying an acceptable tolerance. A huge number of control strategies have been successfully applied for the LFC. Among them, fuzzy logic technique-based controllers – one of the most efficiently intelligent control methods have been gained by both researchers and technicians. This paper concentrates on investigating a comprehensive comparative study of different kinds of fuzzy logic-based LFC strategies. These controllers, combined with a well-known evolutionary optimization mechanism, e.g. Genetic Algorithm (GA), to determine an adaptive structure, can completely solve the LFC problem of an interconnected power system. Simulation results in a five-control-area power network model related to a practical large-scale power system in Vietnam implemented by MATLAB/Simulink environment demonstrate the dominant applicability of the PID-like fuzzy logic LFC controllers over other counterparts.*

Keywords *- LFC, PID, PID~FLC, Optimization, GA.*

1. Introduction

A large-scale electric power grid in a nation consists of many generation power plants. Each typical power station normally comprises several crucial units such as a governor, turbine or prime mover and generator [1]. They can also be defined as a control area in an interconnected power system. Each large power network may include a number of control – areas, as shown in Fig. 1. It should be noted that two control areas are connected via a transmission line technically defined as a tie line. Exchange power, including importing and exporting electricity between two control areas via the tie-line, is also named tie-line power.

It is an undeniable fact that electric loads depending upon users are randomly and continuously changeable over time, leading to an imbalance of powers in an interconnected power network. As a result, the network frequency has deviated from the nominal value, e.g., 50Hz, affecting the system's stability and electric power quality [2-11,26]. Fig. 2 illustrates frequency fluctuation with several control criteria due to load changes. This oscillation might be somewhat different from a typical transient (see Fig. 2). Normally, when load variation occurs, the network frequency will be decreased. Besides, the control area tie-line powers vary, causing biases from scheduled values. Eventually, a huge number of parameters will be affected in this context, leading to an inevitable deterioration of the economic efficiency of the network. Therefore, it should be extremely important to design a good control solution, named load-frequency control (LFC), enabling the power system back to normal stability.

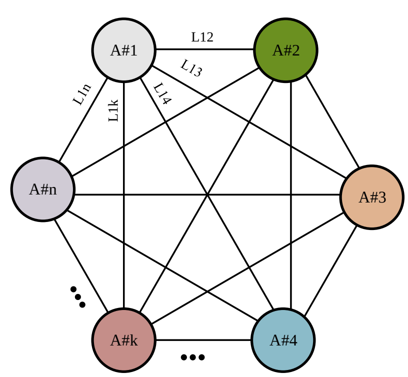

Fig. 1 A typical model of an *n*-control – area power system

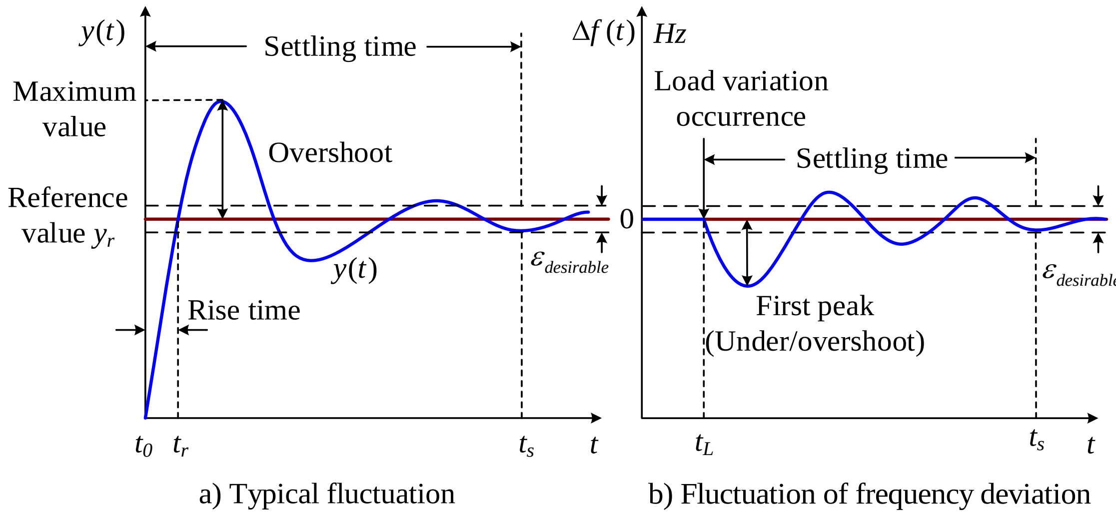

Fig. 2 Major control criteria related to transient responses (a) A typical fluctuation (b) Frequency deviation response due to load changes

Based on the tie-line bias method, a numerous number of LFC controllers have been designed. With conventional LFC regulators, such as Integral (I), Proportional – Integral (PI) and Proportional – Integral – Derivative (PID), good control performances of the system may not be obtained [13-15]. Fuzzy logic control (FLC) – based strategies have been applied for decades as a perfect replacement for conventional regulators such as PI and PID [25]. These control methodologies with dominant artificial intelligence abilities outperform their traditional counterparts. For instance, they may not require control plants that have enough known parameters. In contrast, they are executed depending only on the understanding or experiences of operators and/or experts about the systems under consideration. The working principle of an FLC-based control system is based on a set of proper fuzzy logic rules in the form of IF–THEN relations, which are only created by operators or experts.

When designing a proper FLC strategy, especially applied to the LFC issue, it is necessary to determine three factors that strongly affect the control quality of the system. These factors include:

- Determination of membership functions.
- Establishment of fuzzy logic rules.
- Selection of input/output scaling coefficients.

This paper focuses on proposing a comprehensive procedure to design several LFC controllers applying fuzzy logic techniques following the above three factors. A well-known metaheuristic optimization technique, genetic algorithm (GA), is chosen to determine these factors. In addition to the conventional PID controller, three FLCs, namely P~FLC, PI~FLC and PID~FLC, will be investigated and compared to determine the best control solution for the LFC issue.

Some of the main contributions obtained from the current study include:

- An investigation of different fuzzy logic–based controllers, namely P~FLC, PI~FLC and PID~FLC, is presented.
- An entire procedure to design an effective PID~FLC applying the GA optimization technique will be provided.
- The application of different fuzzy logic–based control models for the LFC of a practical interconnected electric power grid in a Vietnam case study.

The rest of this paper is as follows. Section 2 presents two types of LFC controllers: conventional ones and fuzzy logic-based counterparts. Next, Section 3 proposes a PID-like FLC under the present study. Section 4 focuses on simulation processes and discussions to verify the effectiveness of the proposed control methodology. Finally, the conclusions and future work will also be provided in Section 5.

2. LFC Controllers

2.1. Conventional LFC Regulator

As part of automatic generation control (AGC), the LFC aims to dampen the network frequency fluctuation to satisfy an acceptable tolerance. In an interconnected power grid, such a control methodology also forces the tie-line power deviations to meet allowable errors, ensuring an ability to bring the system back to stability after unwanted load changes. According to the operation principle of the AGC, the LFC considered the secondary control loop, is executed in several seconds against load variations. It means that the control scheme needs to eliminate the net frequency oscillations after load change occurrence under an acceptable settling time. The Integral (I) regulator was the first suitable choice from this perspective. This kind of LFC controller can bring the steady state back to the system; however, the control performances are only obtained in a poor evaluation. The improving types of such conventional regulators are PI and PID. A typical equation describing the PID regulator in parallel structure is as follows [1,13]:

$$W_{PID}(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{1}$$

Where K_p, T_i and T_d denote proportional, integral time constant and derivative time coefficients, respectively.

2.2. Fuzzy Logic Controller

2.2.1. Typical PID – like Fuzzy Logic Architecture

The overall diagram of basic functional blocks of a conventional PID-type FLC is shown in Fig. 3. Here, three input factors, namely k_1, k_2 and k_3, together with output.

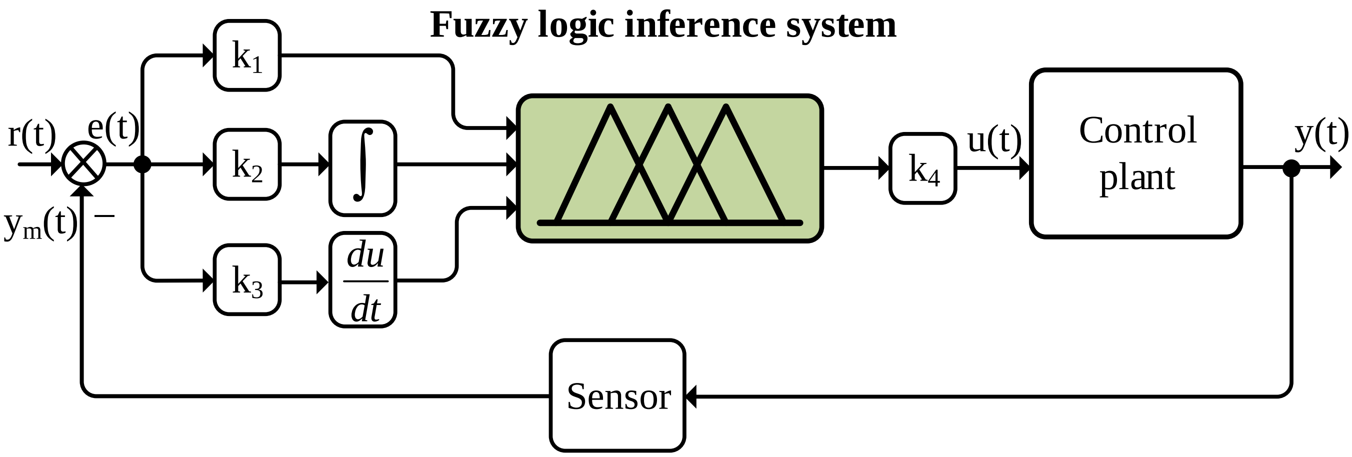

Fig. 3 A conventional PID-like fuzzy logic control model

One k_4 is embedded corresponding to three coefficients of the traditional PID regulator, as shown in (1). The control signal as the output of the FLC inference can be computed as follows:

$$\begin{cases} u(t) = k_4\left[k_1 e(t) + k_2 \int e(t)dt + k_3 \frac{de(t)}{dt}\right] \\ W_{PID\sim FLC}(s) = K_{p\_FLC}\left(1 + \frac{1}{T_{i\_FLC}s} + T_{d\_FLC}s\right) \end{cases} \tag{2}$$

Where, $K_{P\text{-}FLC}$, T_{i_FLC} and T_{d_FLC} calculated from four coefficients k_i $(i = \overline{1,4})$ are factors in accordance with three PID factors as indicated in (1). Remember that these factors need to be determined in order to design such a PID-like FLC controller.

2.2.2. Evolutionary Optimization Technique – based PID – like Fuzzy Logic Inference Structure

As illustrated in Fig. 3, each FLC inference model contains three crucial units: scaling factors, membership functions and fuzzy logic rule base. It is clear that these components strongly affect the performance of a control system applying FLC controllers. To determine them, operators typically use a *try-and-error* method similar to the traditional PID tuning mechanism. However, this kind of scaling manner might not obtain efficiency well enough, especially for a complicated control plant such as large-scale power systems in the LFC issue. In this context, a strong optimization mechanism is more suitable to ensure high control criteria. Fig. 4 describes the principle of using such a proper optimization method to fulfill the design of an adaptive FLC system.

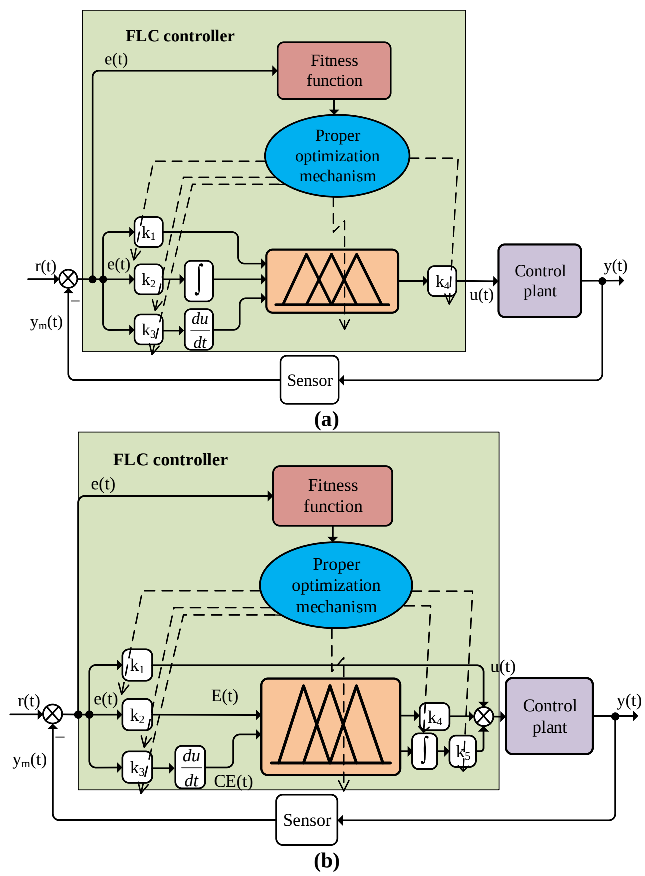

Fig. 4 The FLC applying an efficient optimization mechanism (a) The typical FIS structure (b) The proposed FIS structure

In fact, two categories of PID-like FLC structures are applied, as shown in Fig. 4 (a) and Fig. 4(b). The second one is technically employed in most control problems due to its easier fuzzy logic rule base design. It should be obvious from this illustration that the optimization mechanism employs a fitness function or objective candidate to determine five scaling factors k_i and other components of the FLC, i.e., membership functions and fuzzy rules. One of several typical objective functions can be:

$$f_{obj} = \int_0^{\tau} |e(t)| t dt \tag{3}$$

Where τ denotes the simulation time used for running the optimization mechanism, remember that selecting a suitable fitness candidate may depend on specific control system requirements under consideration.

3. An Adaptive Load-Frequency Control Strategy

A large-scale power network normally consists of several control areas. Each control area is comprised of three fundamental components: the governor, turbine, and generator. A typical model representing such a control area is depicted in Fig. 5. It is noted that turbines in a power plant are classified into many types, which three ones are widely used, including non-reheat, reheat, and water turbines. These turbines can be mathematically modelled by applying the linearization method transfer functions presented in [1]. Suppose hydraulic or water turbines are typically selected as they are still being applied the most in Vietnam, together with the other two components, speed governor and generator. In that case, they have the following transfer functions:

(i) The speed governor:

$$W_g(s) = \frac{\Delta g(s)}{\Delta x_e(s)} = \frac{1}{1+s.T_g} \tag{4}$$

(ii) The hydraulic turbine:

$$W_t(s) = \frac{\Delta P_m(s)}{\Delta g(s)} = \frac{1-T_w s}{1+0.5T_w s} \tag{5}$$

(iii) The generator, together with the load:

$$W_{Gen}(s) = \frac{\Delta\omega(s)}{\Delta P_m(s)-\Delta P_e(s)} = \frac{1}{Ms+D} \tag{6}$$

The simulation parameters are given in the table 2.

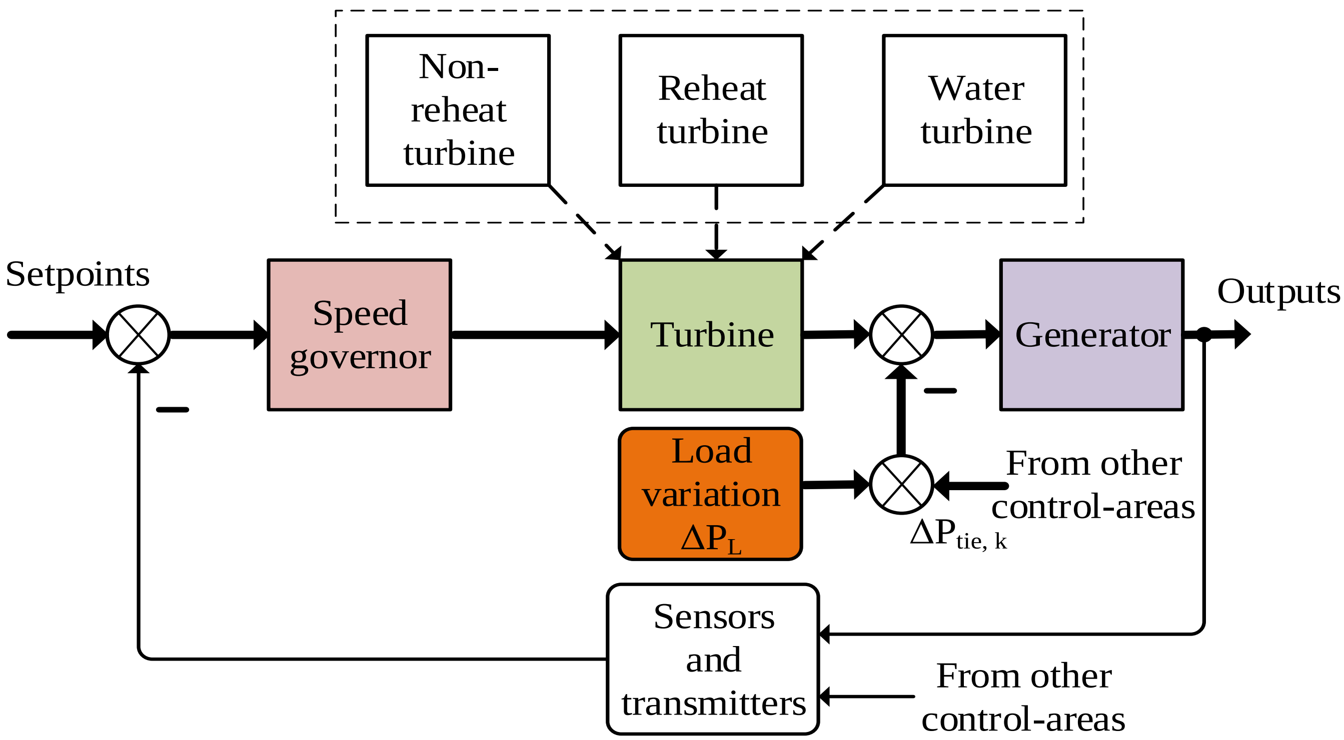

Fig. 5 A typical control – an area in an interconnected power system

Now, let us apply the FLC presented in Fig. 4 to the LFC problem. The control diagram is depicted in Fig. 6. Unlike Fig. 4, the output signal considered here is frequency deviation $\Delta f_i(t)$.

According to the tie-line bias control idea, from this deviation related to tie-line power change, it is necessary to compute the control signal ACE (t) – area control error as expressed below:

$$ACE_i(t) = \Delta f_i(t) + B_i \Delta P_{tie,i}(t) \tag{7}$$

where B_i is a constant factor for each particular control – area. This control signal will be used as the input of the PID-like FLC mentioned in Fig. 6.

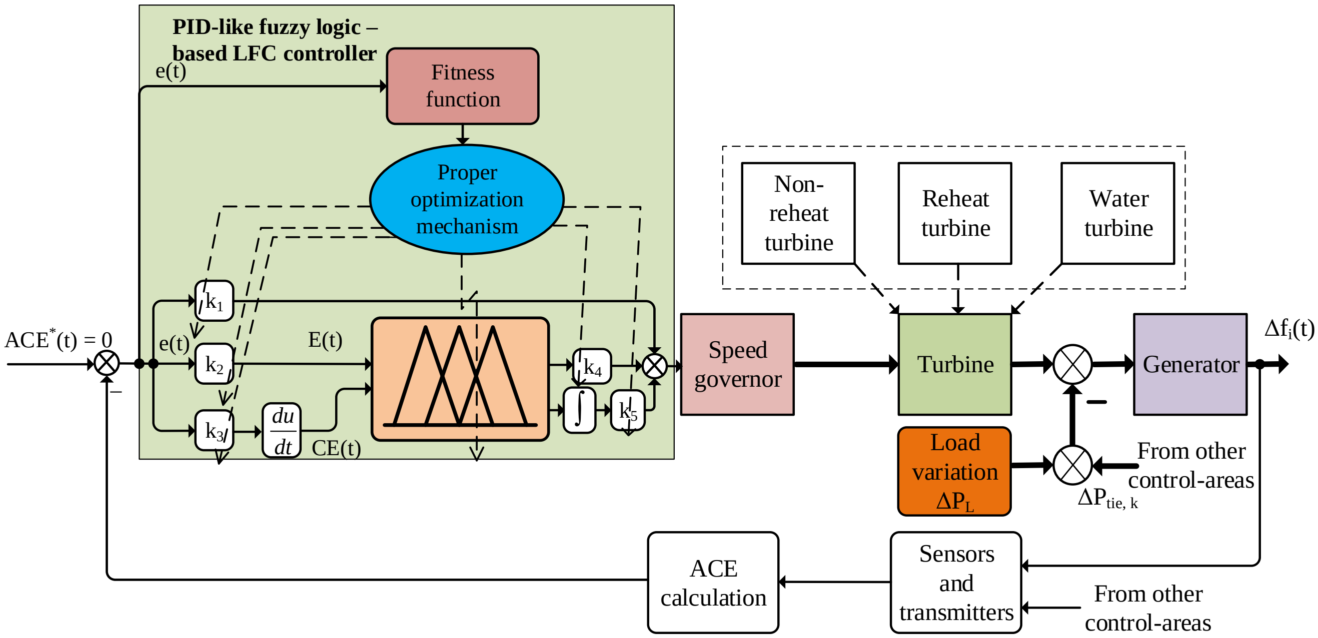

Fig. 6 A FLC – based load -frequency control strategy for an interconnected power grid

4. Simulation Results and Relevant Analysis

This section proposes a simulation model of a major interconnected electric power grid in the North of Vietnam. This network composes of five control areas corresponding to five crucial power stations: three hydropower plants (Sonla, Hoabinh and Tuyenquang) and two thermal power stations (Phalai and Uongbi). They are numbered consecutively from one to five (#1 to #5). The simulation parameters corresponding to these five areas are shown in Table 2.

To simplify the simulation process, genetic algorithm (GA), one of the most well-known optimization methods [18-22], will be applied to determine five factors k_i ($i = \overline{1,5}$), fuzzy rule inference and membership functions according to the working principle presented in Fig. 6.

A MATLAB/Simulink tool–based fuzzy logic model used in the configuration of the FLC is presented in Fig. 7. With the GA mechanism, the optimal FLC structure being successfully fulfilled with rule base as well as membership functions is depicted in Table 1 and Figs. 8-9. It is noted that the membership functions of the output with five levels given in Table 1 cannot be shown here because of using Sugeno fuzzy inference system.

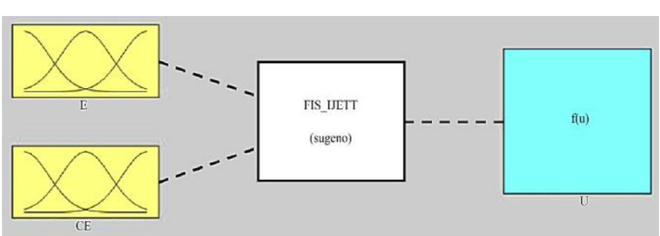

Fig. 7 Fuzzy inference system using MATLAB under study

Table 1. An optimal fuzzy logic rule base

U		E		
		NEG	**ZE**	**POS**
DE	**NEG**	PB	PS	ZE
	ZE	PS	ZE	NS
	POS	ZE	NS	NB

NEG – Negative, ZE – Zero, POS – Positive
PB – Positive Big, PS – Positive Small, NS – Negative Small, NB – Negative Big

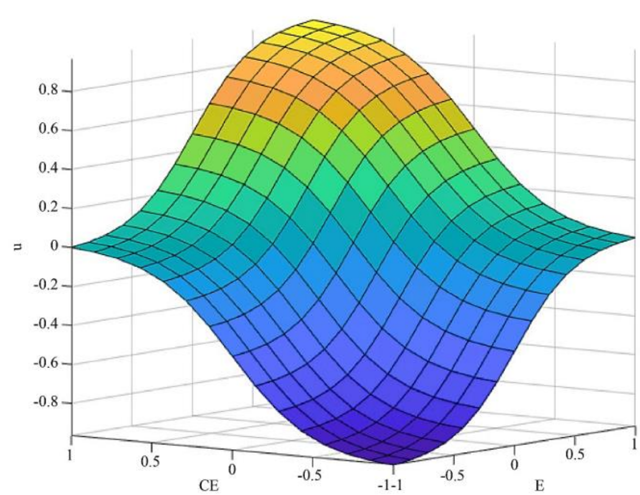

Fig. 8 Fuzzy rule set in 3D illustration

Table 2. Simulation parameters for five areas

Area #4 with non- reheat turbine	Value	Area #5 with Reheat turbine	Value	Area #1, #2, #3 with hydraulic turbines	Value
M_4(p.u.s)	9	M_5 (p.u.s)	8	T_{w1} (s)	1.0
D_4 (p.u./Hz)	1.1	D_5 (p.u./Hz)	1.3	T_{w2} (s)	1.1
T_{ch4} (s)	0.3	T_{ch5} (s)	0.3	T_{w3} (s)	0.8
T_{g4} (s)	0.1	T_{g5} (s)	0.2	Tg (s)	5
R_4 (Hz/p.u.)	0.05	R_5 (Hz/p.u.)	0.05	M1, 2, 3 (p.u.)	10
B_4 (p.u./Hz)	18	B_5 (p.u./Hz)	20	D1,2,3 (p.u.)	1
T_4 (p.u./rad)	21.6	T_5 (p.u./rad)	20.9	T_{ij} (s)	0.07

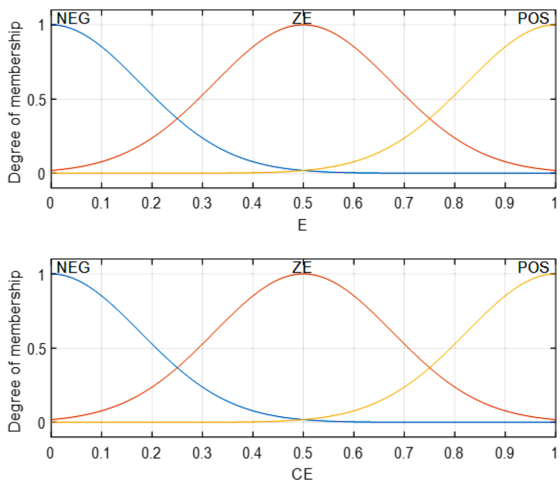

Fig. 9 Membership functions of two inputs

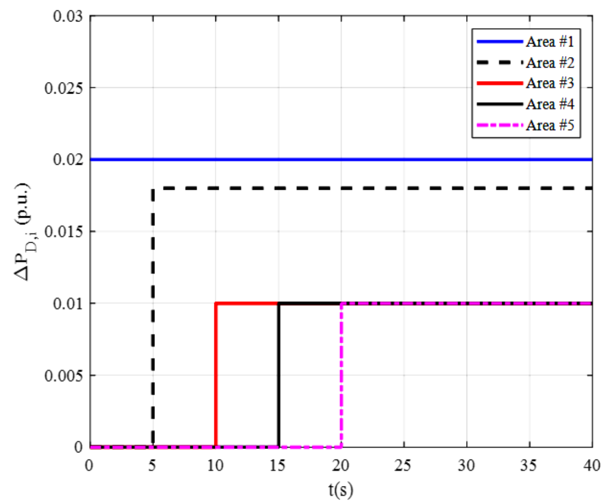

Fig. 10 Load variations in five control-areas

Changes in loads in five control areas, as mentioned earlier, are plotted in Fig. 10. It is noted from this simulation scenario that these load variations are assumed to appear at different instants. Now consider several major control criteria as shown in Fig. 2; simulation results regarding frequency fluctuations are depicted in Figs. 11 – 15.

Assuming that in addition to a conventional PID regulator, three fuzzy logic–based LFC controllers will be taken into account: P-FLC, PI-FLC and PID-FLC. The last two FLC controllers apply the same rule set and membership functions, except for the P-FLC with the simplest configuration. Control performances resulting from these FLC controllers will also be illustrated and compared.

In Fig. 11, the oscillations of network frequency at the first and fifth areas are plotted. Even if the load change in this control area is launched at zero-instant, the frequency deviations are also affected at other instants due to the interconnection characteristic.

Figure 12 presents a comparison between the other three areas (2, 3 and 4) with regard to the system frequency variations. It is obvious from these figures that the three FLC controllers obtain much better control quality compared to the traditional PID counterpart.

Figs. 13-16 continue depicting comparison among these FLC controllers. While Fig. 14 shows absolute values of overshoots and/or undershoots in accordance with the frequency fluctuations,

Figs. 15 - 16 considers other major control indexes, settling time, with an allowable 1- percent of the frequency tolerance.

Obviously, the PID – like FLC controller achieves the best control performance over the other four ones, leading to the highest feasible applicability of the proposed control methodology to be demonstrated.

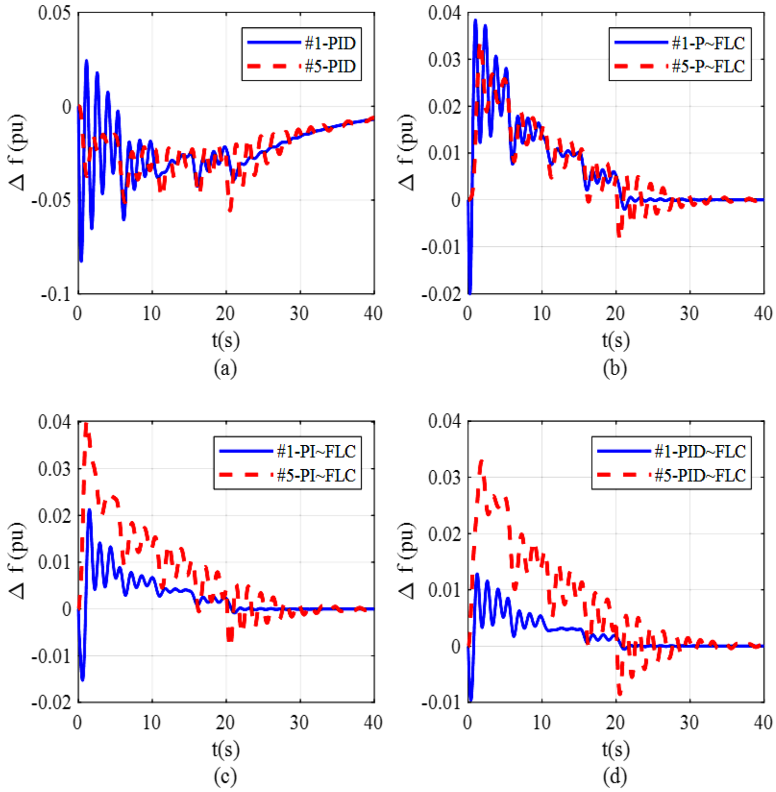

Fig. 11 A comparison of frequency changes in Area #1 and Area #5

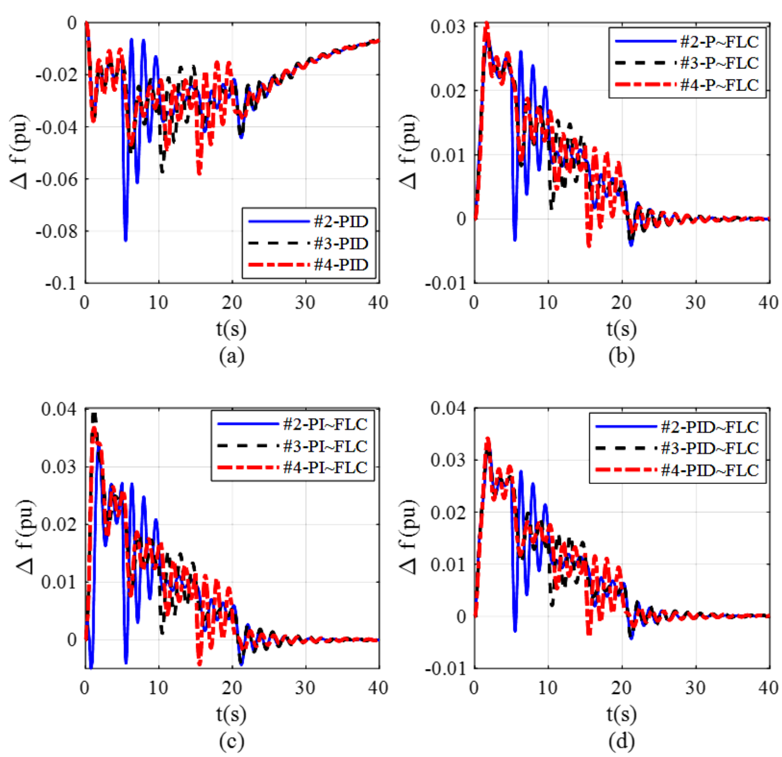

Fig. 12 A comparison of frequency changes in Area #2, Area #3 and Area #4

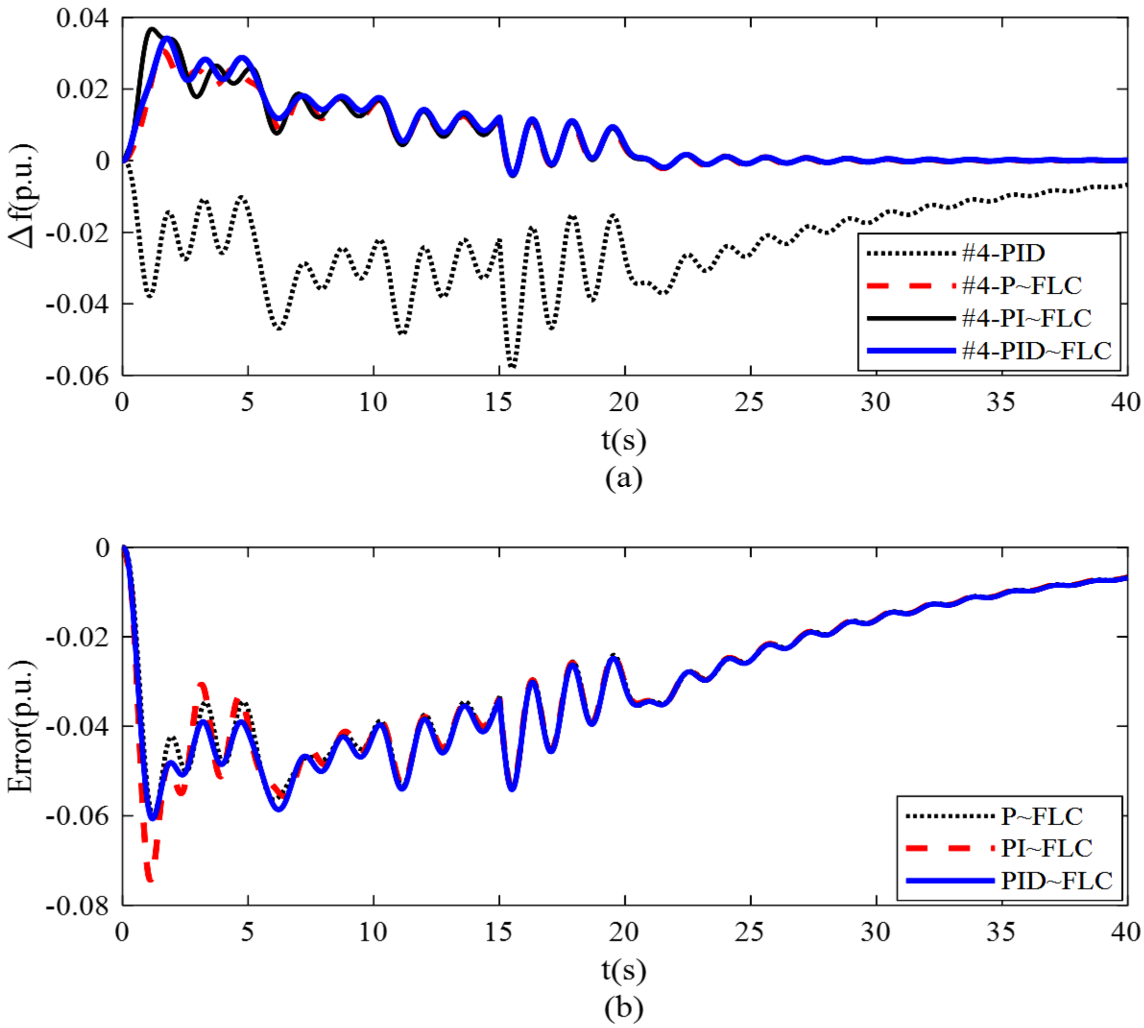

Fig. 13 A comparison of frequency changes in Area #4 for different LFC controllers

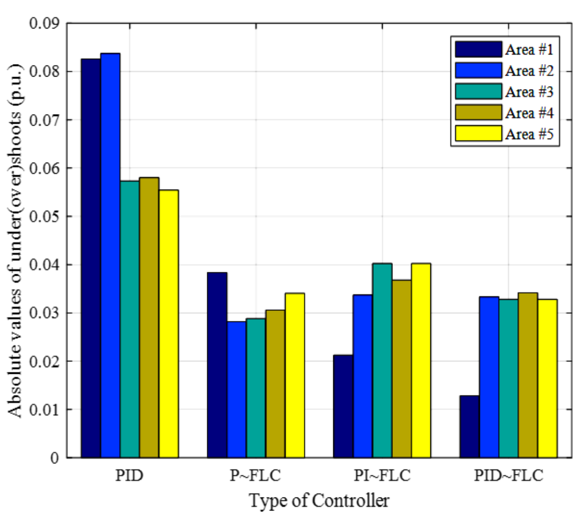

Fig. 14 Comparison of frequency changes in all five control – areas regarding overshoots or undershoots (absolute values)

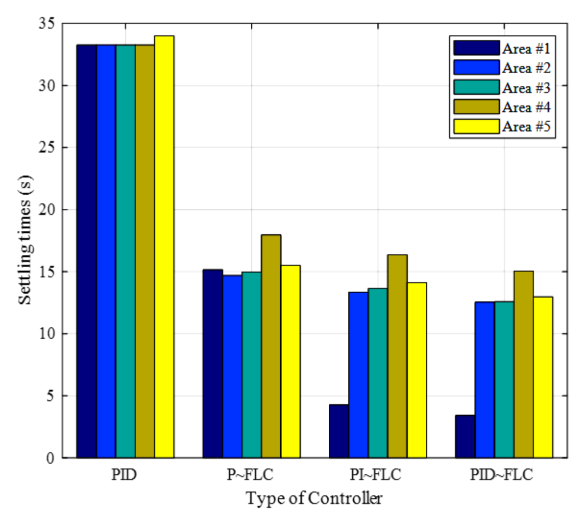

Fig. 15 A comparison of frequency changes in all five control areas regarding the settling times in response to an acceptable 1% tolerance

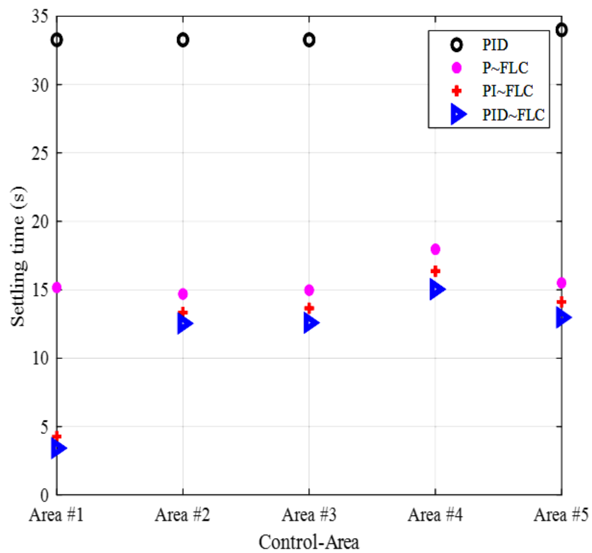

Fig. 16 A comparison of frequency changes in all five areas regarding settling times in response to 1% tolerance (continued)

5. Conclusion and Future Work

An investigation of different LFC controllers has been conducted in this paper. A five–control – areas power system model related to a practically large-scale electric power grid in Vietnam has also been considered for the demonstration goal. It should be clear that the PID-type FLC, one in integration with a GA optimization technique, is much better than other existing counterparts in such a scenario. The GA mechanism has been selected to determine major components of the fuzzy logic inference structure, adapting the complex and nonlinear characteristics of the interconnected power system in dealing with the LFC problem.

Feasible simulation results verified the dominant applicability of the proposed FLC – based LFC scheme. As a result, the PID-like FLC should be the best choice for the LFC problem in an interconnected electric power grid. Future work inspired by this study should be a further improvement of the proposed control strategy to an *n*-control-area large-scale power grid. In this future perspective, a feasible combination of fuzzy logic and artificial neural network can also be taken into account.

References

[1] P. Kundur, *Power System Stability and Control*, McGraw-Hill, New York, 1994. [Publisher Link]

[2] V. Devaraj, and M. Kumaresan, "An Elite LOA-TFWO Approach for Load-Frequency Control of Islanded Micro-Grids Incorporating Renewable Sources," *International Journal of Engineering Trends and Technology*, vol. 70, no. 10, pp. 166-187, 2022. [CrossRef] [Publisher Link]

[3] Nishant Jakhar, Rainu Nandal, and Kamaldeep, "Design of a Rule-based Decisive Model for Optimizing the Load Balancing in a Smart Grid Environment," *International Journal of Engineering Trends and Technology*, vol. 70, no. 8, pp. 97-103, 2022. [CrossRef] [Publisher Link]

[4] Guorui Zhang, "EPRI Power Systems Dynamics Tutorial," *EPRI Palo Alto*, USA, 2009. [Google Scholar]

[5] P.S.R. Murty, *Operation and Control in Power Systems*, BS Publications, India, 2008. [Google Scholar] [Publisher Link]

[6] Hadi Saadar, *Power System Analysis*, PSA Publishing LLC, New York, 2011. [Google Scholar] [Publisher Link]

[7] G.F. Richard, *Power System Dynamics and Stability*, CRC Press LLC, Boca Raton, 2001.

[8] Shashi Kant Pandey, Soumya R. Mohanty, and Nand Kishor, "A Literature Survey on Load-frequency Control for Conventional and Distribution Generation Power Systems," *Renewable and Sustainable Energy Reviews*, vol. 25, pp. 318-334, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[9] Hassan Bevrani, and Takashi Hiyama, *Intelligent Automatic Generation Control*, CRC Press, 2016. [Google Scholar] [Publisher Link]

[10] Allen J. Wood, Bruce F. Wollenberg, and Gerald B. Sheble, *Power Generation, Operation, and Control*, Willey-Interscience, 2013. [Google Scholar] [Publisher Link]

[11] Hassan Bevrani, and Takashi Hiyama, *Intelligent Automatic Generation Control*, CRC Press, New York, 2011.

[12] Trung K.Ngo, Cong H. Nguyen, and Tan D.Vu, "Study on Implementation of Hedge Algebra Based Controller in Real Systems," *SSRG International Journal of Electrical and Electronics Engineering*, vol. 3, no. 11, 2016. [CrossRef] [Publisher Link]

[13] Ngoc-Khoat Nguyen et al., "Designing an Effective Hybrid Control Strategy to Balance a Practical Inverted Pendulum System," *International Journal of Engineering Trends and Technology*, vol. 70, no. 5, pp. 80-87, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[14] Jianping Guo, "The Load Frequency Control by Adaptive High Order Sliding Mode Control Strategy," *IEEE Access*, vol. 10, pp. 25392-25399, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[15] H. Shayeghi, H.A. Shayanfar, and A. Jalili, "Multi-stage Fuzzy PID Power System Automatic Generation Controller in Deregulated Environments," *Energy Conversion and Management*, vol. 47, no. 18-19, pp. 2829-2845, 2006. [CrossRef] [Google Scholar] [Publisher Link]

[16] Archana Tahiliani, and Amit Panchal, "Dynamic Response Analysis through Conventional Methods and Fuzzy Logic for Automatic Load Frequency Control," *SSRG International Journal of Electrical and Electronics Engineering*, vol. 1, no. 2, 2014. [CrossRef] [Publisher Link]

[17] S. Divya, and M. Balaji, "Development and Performance Analysis of Fuzzy Logic Tuned PID Controller for Level Process using PLC," *SSRG International Journal of Electrical and Electronics Engineering*, vol. 5, no. 2, 2018. [CrossRef] [Publisher Link]

[18] Z.M. Al-Hamouz, and H.N. Al-Duwaish, "A New Load Frequency Variable Structure Controller using Genetic Algorithm," *Electric Power Systems Research*, vol. 55, no. 1, pp. 1-6, 2000. [CrossRef] [Google Scholar] [Publisher Link]

[19] A. Demirorem, S. Kent, and T. Gunel, "A Genetic Approach to the Optimization of Automatic Generation Control Parameters for Power Systems," *European Transactions on Electrical Power*, vol. 12, no. 4, pp. 275-281, 2002. [CrossRef] [Google Scholar] [Publisher Link]

[20] D. Rerkpreedapong, A. Hasanovic, and A. Feliachi, "Robust Load Frequency Control using Genetic Algorithms and Linear Matrix Inequalities," *IEEE Transactions on Power Systems*, vol. 18, no. 2, pp. 855-861, 2003. [CrossRef] [Google Scholar] [Publisher Link]

[21] Anupama Huddar, and P.S. Kulkarni, "A Robust Method of Tuning the Feedback Gains of a Variable Structure Load Frequency Controller using Genetic Algorithm Optimization," *Electric Power Components and Systems*, vol. 36, no. 12, pp. 1351-1368, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[22] F. Daneshfar, and H. Bevrani, "Load-frequency Control: A GA-based Multi-agent Reinforcement Learning," *IET Generation, Transmission and Distribution*, vol. 4, no. 1, pp. 13-26, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[23] Krosuru Anuradhika, and Puja Dash, "Genetic Algorithm-Based Load Frequency Control of a Grid-Connected Microgrid in Presence of Electric Vehicles," *Sustainable Energy and Technological Advancements, Advances in Sustainability Science and Technology*, pp. 435-447, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[24] T. Shanthi, C. Selvakumar, and S.U. Prabha, "Design of Fuzzy Logic Controller for Speed Control of DC Motor Fed from Solar PV System," *SSRG International Journal of Electrical and Electronics Engineering*, vol. 4, no. 3, 2017. [CrossRef] [Publisher Link]

[25] Ngoc-Khoat Nguyen, and Duy-Trung Nguyen, "A Comparative Study on PI – and PD – Type Fuzzy Logic Control Strategies," *International Journal of Engineering Trends and Technology*, vol. 69, no. 7, pp. 101-108, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[26] Guolian Hou et al., "Design of PSO-based Fuzzy Gain Scheduling PI Controller for Four-area Interconnected AGC System after Deregulation," *The 2011 International Conference on Advanced Mechatronic Systems*, 2011. [Google Scholar] [Publisher Link]