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Fuzzy Logic Based Fine-tuning Approach for Robust Load Frequency Control in a Multi-area Power System

Rahmat Khezri,[1] Sajjad Golshannavaz,[2] Shoresh Shokoohi,[1] and Hassan Bevrani[1]
[1]Department of Electrical and Computer Engineering, University of Kurdistan, Sanandaj, Kurdistan, Iran
[2]Electrical Engineering Department, Urmia University, Urmia, Iran

CONTENTS

Abstract—This article addresses the design procedure and numerical validation of a robust fuzzy logic-based fine-tuning approach devised to enhance load frequency control capabilities in multi-area power systems. The founded robust fuzzy logic-based fine-tuning approach is intended for judicial parameter tuning of a proportional-integral controller encountering fault occurrences or severe changes in system loading conditions. Unlike conventional proportional-integral controllers that are generally designed for fixed operating conditions, the outlined approach demonstrates robust performance with power system uncertainties and disturbances. In this context, the projected robustness is principally emanated due to a fuzzy logic extensibility feature, furnishing the established framework to have a proliferated observability on control space. The design procedure of a robust fuzzy logic-based fine-tuning controller is substantially nourished by expert knowledge regarding the overall system performance. Apt fuzzified and defuzzified rule-based mechanisms are wisely included as the key building blocks of the fuzzy inference engine. Extensive numerical studies are launched in a thorough investigation of the proposed approach. As well, the robust fuzzy logic-based fine-tuning performance is compared with that of two extra robust methods, namely the $H\infty$-iterative linear matrix inequality as well as the hybrid genetic algorithm and linear matrix inequality. The obtained results are deeply analyzed.

Keywords: load frequency control, multi-area power system, robust fuzzy logic fine-tuning approach, $H\infty$ method, iterative linear matrix inequality, genetic algorithm, intelligent control, automatic generation control, proportional-integral controller, frequency deviation

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Address correspondence to Dr. Rahmat Khezri, Department of Electrical and Computer Engineering, University of Kurdistan, Sanandaj, PO Box 416, Kurdistan, Iran 66177–15177. E-mail: r.khezri.2014@ieee.org

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1. INTRODUCTION

This is a well-recognized notion that with the aim of achieving reliable power system performance, the system persuasive frequency deviations should be eliminated swiftly. As a general practice, modern power systems utilize two conventional control loops to yield efficient frequency restoration: primary and supplementary loops. In the primary control loop, generation units contribute to frequency regulation with their governors irrespective of load change locations. In encountering a major disturbance, such as a severe change in loading conditions, the primary frequency control loop loses its validity in nominal frequency restoration. Rehabilitating this flaw, a supplementary control loop, called load frequency control (LFC), is sensibly adjoined in the process to curb frequency deviations in the least attainable values [1, 2].

NOMENCLATURE

D	damping constant	y	measured output vector
F	number of membership functions	z	controlled output vector
g, c	mean and range of fuzzy set X	α	area control error participation factor
g_i	crisp variable	β	frequency bias
H	inertia	δf	frequency deviation
K_p, K_i	parameters of proportional-integral controller	δP_c	variations in governor load set-point
M	equivalent inertia constant	δP_d	area load disturbance
R	speed droop characteristic	δP_g	variations of governor valve position
T_g	governor time constant	δP_m	mechanical power change
T_{ij}	tie-line synchronizing coefficient of areas i and j	δP_t	variations of turbine power
T_t	turbine time constant	δP_{tie}	tie-line power variation
u	input vector	θ	centroids of membership functions assigned to output variable
x	state variable vector		
w	disturbance occurrence along with other external input vector	μ_N, μ_Z	membership functions corresponding to fuzzy sets N and Z

In multi-area interconnected power systems, the LFC in each area is responsible for frequency regulation in its own territory as well as affecting the neighboring areas through the interconnected tie-lines [3, 4]. From the structural aspect of LFCs, proportional-integral (PI) controllers are well-regarded as one of the most deployed controllers in devising effective remedies [5]. These controllers make benefit of versatile signals as the inputs, where system frequency deviation, tie-line power variations, and area frequency bias are some of the available options. However, by considering the supplementary effect of all these signals, an additive combination set is defined as a new error signal, called the area control error (ACE) [6]. This sort of input representation endows the input signal with more system performance features. As a conventional design scenario, PI controllers deployed in LFCs are designed based on classical control themes. Consequently, the resultant controller demonstrates a proper response merely around the designated operating point. Due to the perpetual changes in power system structure as well as such uncertainties as load or renewables generation, there is a non-stop variation in a system's operating point. Hence, PI controllers lose their overall generality in handling the LFC requirements. This summarizes the need for investigating and then implementing effective alternatives of PI controllers to yield in a more robust LFC approach.

Some research has been conducted to design an effective LFC approach with a higher degree of robustness. Founded on a model predictive control (MPC) technique, the authors in [7] proposed a new LFC design for multi-machine power system applications. Yazdizadeh *et al.* established a robust multivariable PI differential (PID) controller for a decentralized LFC problem that minimizes the system frequency deviations [8]. A hybrid method, the combination of a genetic algorithm (GA) and linear matrix inequality (LMI) technique, called the hybrid GA and LMI (H-GALMI), was presented to tune PI parameters in [9]. Furthermore, to obtain a more reliable and robust frequency performance scheme, the authors in [10] tuned the PI-based LFC based on the $H\infty$ technique; they also employed the iterative LMI (ILMI) approach to solve the $H\infty$ problem, which resulted in an $H\infty$-ILMI-based controller.

In light of recent transitions in modern intelligence techniques; Bevrani and Hiyama contributed in this context by the effective utilization of fuzzy logic basis, artificial neural networks (ANNs), and particle swarm optimization (PSO) to develop efficient and robust LFC schemes [11]. In a similar attempt, the authors in [12] proposed a multi-agent GA-based reinforcement learning (MARL) sketch to solve the LFC problem. Unlike traditional control theorems that are essentially based on linearized mathematical models of control plants, intelligent approaches, such as the fuzzy logic control scheme, establish the controller directly based on the measurements, long-term experience, and knowledge of domain experts/operators. Specifically speaking, the principal functionality of fuzzy logic-based LFC is to improve the dynamic frequency performance intended for maintaining the system frequency balanced during sudden load changes. Versatile studies deploying fuzzy logic notions have been conducted for efficient LFC designs in interconnected power systems [13–18]. The authors in [14] provided an overview of fuzzy logic contribution on efficient LFC in multi-area power systems. As well, with the aim of improving the LFC performance in a multi-area power system, the gain scheduling of PI controllers has been undertaken through the fuzzy logic approach [15, 16]. An approximation-based adaptive fuzzy logic control scheme was developed for LFC of a multi-machine power system in [17]. More recently, a heuristically optimized fuzzy logic technique based on a PSO intelligence basis has been utilized for appropriate frequency control in power systems hosting remarkable wind energy resources [18, 19]. A similar approach was contemplated for the same in emergent AC microgrids [20, 21]. As a technical obstacle upon the overall generality of the proposed approaches, the structure of the conventional PI controllers would be changed following the system specification changes. Also, no special care has been devoted to comprehensively analyze and then compare the established methodology with the available literature to direct the research and development in the right stream, spotlighting efficient LFC designs. Additionally, as the artificial intelligent techniques are generally dependent on system-inherent characteristics and expert knowledge, the system behavioral identification precision as well as the learning and corrective plans are engaging an indispensible share in effective LFC synthesis procedures.

Ongoing study aims to recruit the fuzzy logic approach to sketch a new LFC technique, called the robust fuzzy logic-based fine-tuning (RFLFT) approach, which is intended to fulfill the declared technical gaps. To do so, the supplementary fuzzy logic corrective loop is suitably superimposed to the principal foundation of the PI controller for adapting gain values encountered with various fault situations. Consequently, through prudent RFLFT design, the conventional PI controller structure has been preserved as valid for steady-state conditions. Hence, there would be no any structural changes for the primary PI controller; that is, the supplemented fuzzy logic corrective loop merely influences the PI performance facing with load disturbances, and hence, no action would be demonstrated in steady-state conditions. This approach is in essence deploying the cooperation of fuzzy logic features and conventional PI controllers to improve the extensibility of the control space investigated in the LFC problem. The proposed RFLFT solution is thus anticipated for appropriate LFC for frequency control purposes. Apt fuzzified and defuzzified rule-based mechanisms are wisely included as the key building blocks of the fuzzy inference engine. The realized controller is fed through the ACE input signal along with its derivative in the fine-tuning process. This signal, as the combination of deviations in system frequency and line power signals along with the area frequency bias, endows the designed controller with higher features regarding the system performance. Extensive numerical studies have been launched in a thorough investigation of the proposed approach. RFLFT performance is compared with that of the two extra methods, namely $H\infty$-ILMI and H-GALMI. The obtained results are assessed in terms of dynamic performance, such as the under-shoot and settling time of system frequency variations. The superior and robust performance of the purported LFC scheme over existing methods is highlighted. The main contributions of the proposed approach are listed as follows:

- Devising a robust fuzzy LFC controller based on the proposed RFLFT approach to be deployed effectively in frequency regulation task;
- Maintaining the basic structure of a PI controller along with extending its robustness through the RFLFT-based corrective loop in disturbances;
- Providing a simple but effective robust controller to be set out in real-world industry applications.

The remainder of this article is organized as follows. Section 2 reviews the LFC strategy in power systems. Section 3 undertakes the design procedure of the proposed RFLFT approach for efficient frequency stabilizing facing sudden changes in the networks condition. Various simulation studies are put forward by Section 4 to deeply analyze the performance of the established frequency control mechanism. Section 5 concludes the article.

2. LFC STRATEGIES IN MULTI-AREA POWER SYSTEMS

Different complicated and non-linear time-varying models have been founded for representing large-scale power systems. In contradiction, with the aim of frequency control analysis, a simplified and low-order linearized model is of higher interest. In this regard and taking into account an isolated power system, the LFC task is limited to restore the system frequency to the specified nominal values. However, to generalize the isolated LFC models to be applicable in interconnected power systems, the control area concept should be respected. Large-scale power systems can be broken up into several control areas. In each control area, the number of generators and loads constitute a coherent group in which all the generators would contribute to cover load variations. These areas are interconnected by high-voltage transmission lines. The trend of frequency variation in each control area is an indicator of power mismatch within both interconnected links and the control area itself. Hence, the LFC strategy in each control area has to control the power generation in its own area along with the interchangeable power with the other areas to effectively stabilize the local frequency.

It is well understood that each generator is equipped with a primary frequency control loop. Also, each control area is

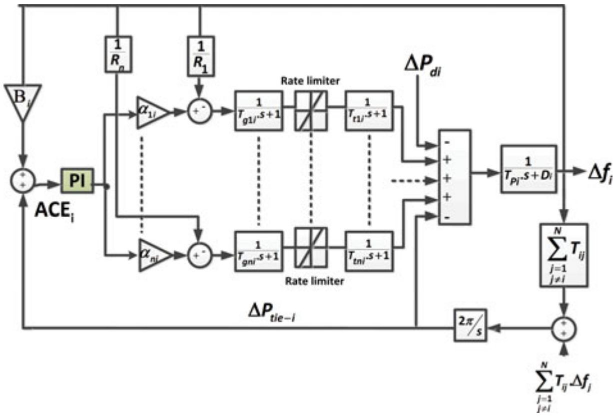


FIGURE 1. Detailed block diagram of area *i* in *N* control area power system.

furnished with a supplementary frequency control loop, LFC, which is superimposed to the primary loop. In a frequency control synthesis procedure, generators are represented with a simple low-order linearized model, including three first-order functions for turbine, governor, and rotating mass units. Belonging to a power system with *N* control areas, Figure 1 illustrates a detailed block diagram for a specific control area, area *i*; this area includes *N* generators. As is obvious, the frequency of the system would experience some fluctuations due to changes occurring in load. Thus, the feedback mechanism as the first frequency control countermeasure comes into play and generates an appropriate signal for the turbines. This signal assists the generating units to track the load changes and restore the system frequency. The overall mathematical relationship between the incremental power mismatch ($\Delta P_m - \Delta P_d$) and the frequency deviations can be expressed as [22]

$$\Delta P_m(s) - \Delta P_d(s) = 2Hs\Delta f(s) + D\Delta f(s). \tag{1}$$

To maintain system security, it is necessary to monitor and then wisely control the fluctuations of δf, which is especially realized through the LFC loop. Subsequently, to reflect the frequency fluctuations in power transfer variations, the total tie-line power change between area *i* and the rest of areas can be expressed as [1]

$$\Delta P_{tie-i} = T_{i1}\Delta f_1 + T_{i2}\Delta f_2 + \cdots + T_{ij}\Delta f_j + \cdots + T_{iN}\Delta f_N. \tag{2}$$

3. MATHEMATICAL FRAMEWORK FOR LFC CONTROLLER DESIGN

3.1. Design Procedure of RFLFT-based LFC Controller

The high complexity and non-linearity of interconnected power systems depreciates the validity of deriving a mathematical model for the investigated systems. Hence, as a suitable alternative, mathematically independent models offer an opportunity to design LFC controllers. As mentioned earlier, many robust controllers have been designed for power system control issues. However, just a few of them are capable of providing adequate robustness for large deviations in system operating conditions. In recent decades, there has been a great transition among the researchers to make benefit of fuzzy logic techniques in handling the control requirements of modern power systems. This trend, introduced by Zadeh in 1965 [23], has been provoked due to its independency against the non-linearity, complexity, and mathematical model extraction of the test system. Hence, nourished through a knowledge-based nature, the fuzzy logic approach is able to rehabilitate the shortcomings of conventional PI controllers in obtaining the optimal performance in various conditions of large-scale power systems. Inspired by these features, the fuzzy logic technique has been preferred herein as the investigated control platform. Following the investigated theme, this section aims to present the design procedure of the RFLFT approach for effective LFC affairs.

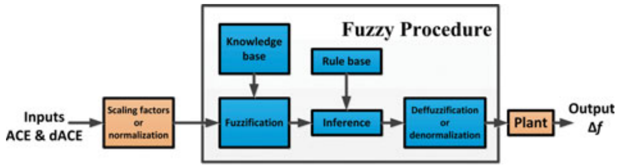


FIGURE 2. General scheme for fuzzy logic (FL)-based LFC.

Although the expert knowledge regarding the investigated plant is the most important factor, in dealing with a fuzzy control mechanism, several steps should be considered. Figure 2 demonstrates a step-by-step procedure to design the RFLFT controller for an LFC system. As it is seen, this course consists of four main steps: fuzzification, fuzzy rule base, inference engine, and defuzzification. For the sake of clarity, each of these steps is now thoroughly explored.

As an indispensible task, appropriate input signals should be allocated in feeding the proposed RFLFT controller. As stated earlier, in an LFC problem, the ACE signal represents a suitable input variable containing more performance features of the system. The ACE of each area in an interconnected power system varies proportionally to its load fluctuations, generating unit conditions, as well as tie-line power. The ACE signal of area *i* accommodating both the frequency and tie-line power deviations can be mathematically represented as

$$ACE_i = \Delta P_{tie,i} + \beta_i \Delta f_i. \tag{3}$$

Here the area bias factor can be computed as

$$\beta_i = {}^{1}\!/_{R_i} + D_i. \tag{4}$$

As Figure 2 demonstrates, in the proposed LFC controller based on the RFLFT approach, the ACE signal along with its derivative are regarded as the input variables. In the following, these crisp values are converted to the corresponding fuzzy values through the fuzzification block. In fact, the fuzzifier converts the crisp input to a linguistic variable using the membership functions stored in the fuzzy knowledge base. Using suitable membership functions, the ranges of input and output variables are assigned with linguistic variables. Then these variables are used to transform the input numerical values into fuzzified quantities. To be more precise, these linguistic variables specify the quality of the control process as they directly model the system characteristics through the expert's knowledge. Herein, the membership functions corresponding to the input variables are arranged as fnegative (N), zero (Z), and positive (P); the membership functions for the output variables are arranged as negative large (NL), negative small (NS), zero (Z), positive small (PS), and positive large (PL). To increase the response of the proposed RFLFT-based LFC system, all membership functions are considered triangular [24]. For this sort of membership functions, the mathematical definition is

$$\mu_g(g_i) = \max\left(0.1 - \left|\frac{g - g_i}{c}\right|\right). \tag{5}$$

The number of membership functions for each variable significantly affects the performance of the fuzzy controller. It is noteworthy that increasing the number of membership functions results in improved performance of the proposed fuzzy-based LFC. However, this case increases the number of rules, which substantially increases the memory requirements. This notice averts the competitive nature of the established scheme for widespread utilization in real-world industry applications. Consequently, the minimum number of membership functions without sacrificing its good performance is assigned for the controller. Figure 3 illustrates the dedicated membership functions for the input and output variables in the proposed RFLFT-based LFC system.

At the second step, the knowledge rule base represents the information storage for linguistic variables as the database and the fuzzy rules shape the skeleton of the control basis. A lookup table is appointed to define the controller output for all possible combinations of input signals. In this regard, the fuzzy system is characterized by a set of linguistic statements in form of "IF–THEN" rules. In other words, the fuzzy conditional statements make the rule set of the fuzzy controller.

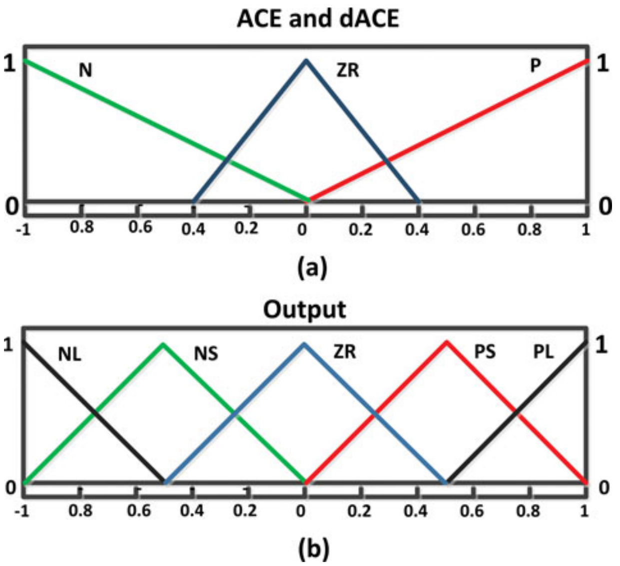


FIGURE 3. Membership functions of fuzzy controller: (a) ACE and its derivative as the inputs and () output.

As the third step in designing the fuzzy controller, the inference engine uses the established "IF–THEN" rules to convert the fuzzy input into the fuzzy output. In fact, fuzzy inference is the kernel of a fuzzy controller. Among the different approaches, the Mamdani inference approach is utilized for the proposed RFLFT controller [25]. As mentioned earlier, two input signals are fed into the designated controller. For representing each of them, three linguistic terms are put forward. Hence, nine different rules are developed for interpreting the output signal. The antecedent part of each rule is composed based on an AND function. The fuzzy rules configurations for the proposed controller are as follows:

IF the ACE is N AND the dACE is N, THEN the output is PB;
IF the ACE is N AND the dACE is Z, THEN the output is PS;
IF the ACE is N AND the dACE is P, THEN the output is NS;
IF the ACE is Z AND the dACE is N, THEN the output is PS;
IF the ACE is Z AND the dACE is Z, THEN the output is Z;
IF the ACE is Z AND the dACE is P, THEN the output is NS;
IF the ACE is P AND the dACE is N, THEN the output is PS;
IF the ACE is P AND the dACE is Z, THEN the output is NS; and
IF the ACE is P AND the dACE is P, THEN the output is NB.

Following the inference engine, the defuzzification block converts the output fuzzy values to their corresponding crisp values based on appropriate membership functions analogous to the fuzzification stage. As the last step, the defuzzification process is commonly tackled based on center of gravity, mean maximum, and weighted average methods to defuzzify the fuzzy control law. Here, the center of gravity method is employed for a defuzzification task [20]. The activation of the ith rule would produce a scalar (ω_i) that is equal to the product of the two antecedent conjunction values. Then, using the center of gravity defuzzification method, the appropriate crisp value

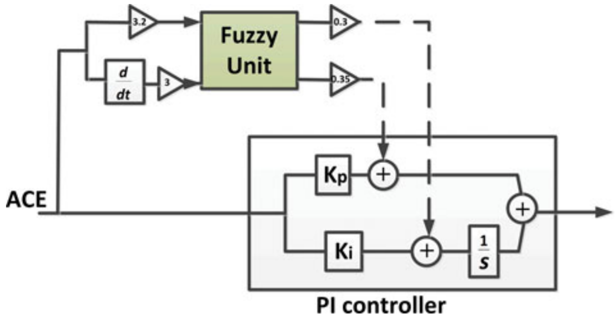


FIGURE 4. Proposed control framework for FL-based LFC.

is generated. The controller output is as follows:

$$Output = \frac{\sum_{i=1}^{F} \omega_i \theta_i}{\sum_{i=1}^{F} \omega_i} = \theta^T \zeta. \tag{6}$$

where

$$\zeta = [\zeta_1, ..., \zeta_i, ..., \zeta_F]^T, \;\; \zeta_i = \frac{\omega_i}{\sum_{k=1}^{F} \omega_k}, \text{ and } \theta^T = [\theta_1 ... \theta_F]. \tag{7}$$

To be more precise, ω_i represents the strength of the ith, rule which is calculated based on interpreting "AND" as a product of the membership values based on the measured values of the ACE and its derivative. For example, the strength of the second rule is determined as

$$\omega_i = \mu_N(ACE) \times \mu_Z(\dot{ACE}). \tag{8}$$

As mentioned earlier, the proposed RFLFT controller has two output control signals. These output signals are suitably adjoined to the conventional PI controller as virtual gains encountering fault situations. Thus, in steady-state conditions, the effect of the RFLFT controller is excluded and the conventional PI controller performs as a safe controller. In other words, the main function of the RFLFT controller is to retune the conventional PI gain values encountering disturbances while letting the steady-state conditions pass with no change. In this viewpoint, the RFLFT controller represents a fine-tuning system supplemented to the conventional PI controller. The structure of the designed RFLFT-based controller is demonstrated in Figure 4. As it is seen, this controller modifies the PI controller parameters to obtain the best LFC performance.

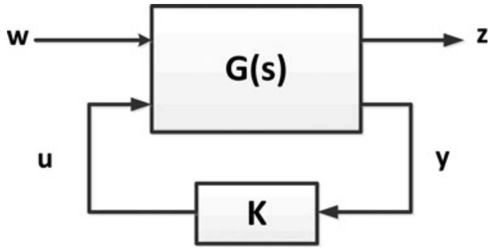


FIGURE 5. Closed-loop system via $H\infty$ control method.

$H\infty$-ILMI	Area 1	Area 2	Area 3
	Area		
K_p	0.0371	0.0465	0.0380
K_i	–0.2339	–0.2672	–0.3092

TABLE 1. PI parameters for $H\infty$-ILMI [10]

3.2. Brief Overview on $H\infty$-ILMI and H-GALMI Approaches for LFC Design

3.2.1. $H\infty$-Static Output Feedback Using ILMI

Generally, robust methods, such as $H\infty$-based strategies, are supposed to be solved based on state-space representation of the investigated system. Assume a linear time invariant system, namely $G(s)$, to be represented with the following state-space model:

$$\begin{cases} \dot{x} = Ax + B_1 w + B_2 u \\ z = C_1 x + Du \\ y = C_2 x \end{cases}. \tag{9}$$

With respect to Figure 5, the main theory behind the static output $H\infty$ approach is to find a static output feedback, $u = ky$, such that the consequent closed-loop system would be internally stable. Likewise, the $H\infty$ norm vector defined as a vector from w to z should be smaller than γ, which is a specified positive number. This statement can be mathematically represented as Eq. (10):

$$\|T_{zw}(s)\| < \gamma. \tag{10}$$

Deploying the static output $H\infty$ control approach in an automatic generation control (AGC) system necessitates elucidating some non-convex system equations that cannot be accomplished utilizing general LMI techniques. Hence, the authors in [10], based on the approach founded in [26], devised an efficient iterative method based on $H\infty$ and LMI methods, called $H\infty$-ILMI. This approach fulfills the shortcomings of the basic LMI technique and enhances the LFC performance.

GALMI	Area 1	Area 2	Area 3
	Area		
K_p	–0.0327	–0.0696	–0.0160
K_i	–0.3334	–0.3435	–0.3398

TABLE 2. PI parameters for GALMI [9]

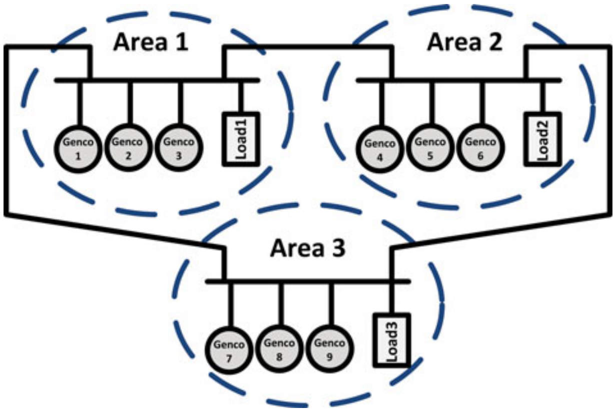


FIGURE 6. Three control area power system.

Table 1 reports the obtained results for $H\infty$-ILMI tuned PI controller gain values.

3.2.2. H-GALMI-based Controller

The GA as a heuristic optimization technique imitates the biological reproduction process in which the most qualified genomes would survive and duplicate themselves to the upcoming generations. Thus, through the iterative generation process and precise inspection of the corresponding space, the GA carefully probes the possible solutions to determine the optimal results. In [9], the GA was used to improve the performance of the LMI approach in efficient LFC design. Hence, the founded procedure is a hybrid method as a combination of the GA and LMI technique, called H-GALMI. Table 2 represents the obtained results for PI controller gain values.

4. SIMULATION RESULTS AND DISCUSSION

4.1. Test Case Specifications

With the aim of evaluating the performance of the proposed RFLFT-based LFC, different scenarios are devised and put under extensive simulation studies. MATLAB/Simulink software (The MathWorks, Natick, Massachusetts, USA) has been selected as the simulation platform. A three-area power system, depicted in Figure 6, has been determined as the test bed to numerically analyze the performance of the established LFC approaches. As this figure demonstrates, each control area consists of three generators. The total contribution of each generator along with the system parameters are gathered in Tables 3 and 4, respectively. In addition to the RFLFT method developed for the PI controller fine-tuning task, two other approaches—$H\infty$-ILMI and H-GALMI—are implemented to yield an effective comparison basis. What is more, the performance of the proposed RFLFT-based LFC will be put under evaluation considering the aforementioned two controllers. Subsequent sections are dedicated to schematically represent the obtained results.

4.2. Simulated Scenarios and Discussions

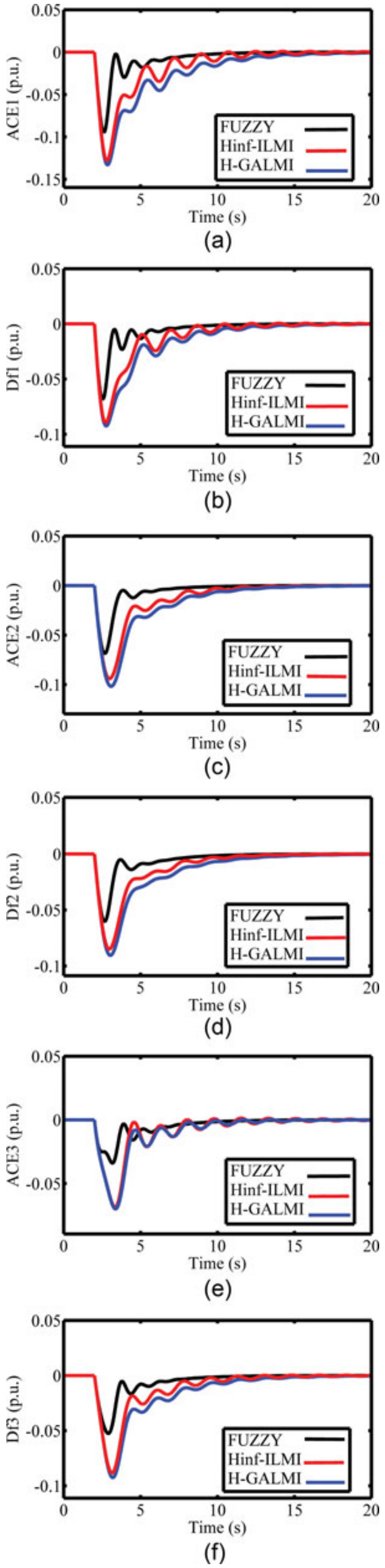
It is a well-known fact that maintaining the power system frequency in constant values depends on active power balance in the bulk system. In other words, preserving the equilibrium between the system loads and generation capacity is the main prerequisite for guaranteeing a desired frequency performance. In large-scale power systems, the system may encounter various load conditions within which the lack of a

GENCO	1	2	3	4	5	6	7	8	9
Generated power (MW)	1000	1200	1000	1100	900	1200	900	1000	1100

TABLE 3. Total generation of GENCOs (MVA$_{base}$: 1000 MW)

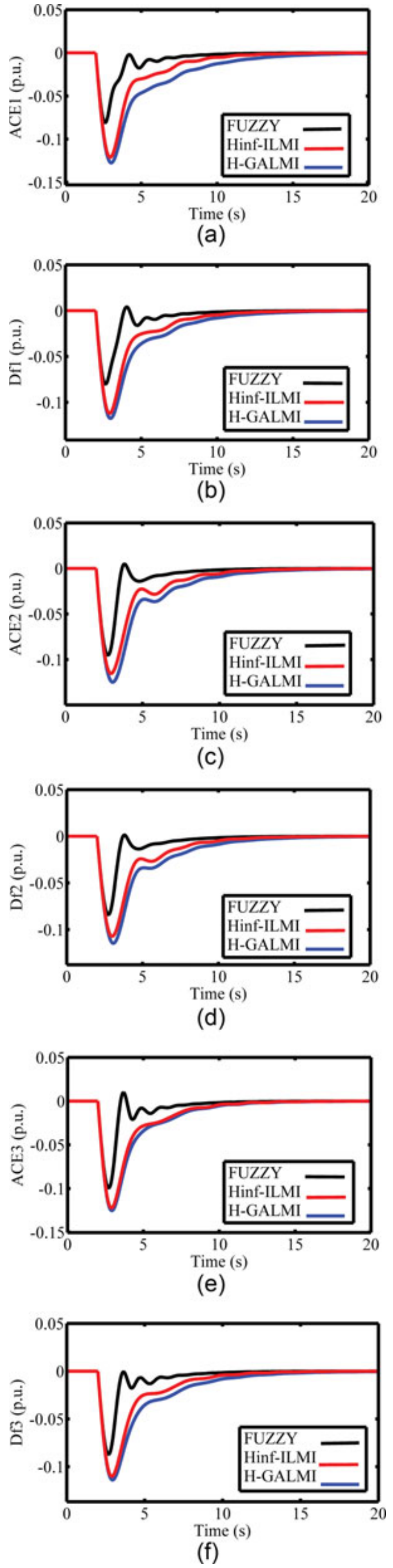
Parameters, MVA$_{base}$ (1000 MW)	GENCO								
	1	2	3	4	5	6	7	8	9
D (p.u./Hz)	0.0150	0.0140	0.0150	0.0160	0.0140	0.0140	0.0150	0.0160	0.0150
T_p (p.u. sec)	0.1667	0.1200	0.2000	0.2017	0.1500	0.1960	0.1247	0.1667	0.1870
T_t (sec)	0.40	0.36	0.42	0.44	0.32	0.40	0.30	0.40	0.4100
T_g (sec)	0.08	0.06	0.07	0.06	0.06	0.08	0.07	0.07	0.08
R (Hz/p.u.)	3.0000	3.0000	3.3000	2.7273	2.6667	2.5000	2.8235	3.0000	2.9419
B (p.u./Hz)	0.3483	0.3473	0.3180	0.3827	0.3890	0.4140	0.3692	0.3493	0.3550
α	0.4	0.4	0.2	0.6	0	0.4	0	0.5	0.5
Ramp rate (MW/min)	8	8	4	12	0	8	0	10	10

TABLE 4. Generation unit parameters



(a) (b) (c) (d) (e) (f)

FIGURE 7. ACE and frequency deviation Δf for scenario 1: (a) area 1 ACE, (b) area 1 Δf, (c) area 2 ACE, (d) area 2 Δf, (e) area 3 ACE, and (f) area 3 Δf.



(a) (b) (c) (d) (e) (f)

FIGURE 8. ACE and frequency deviation Δf for scenario 2: (a) area 1 ACE, (b) area 1 Δf, (c) area 2 ACE, (d) area 2 Δf, (e) area 3 ACE, and (f) area 3 Δf.

suitable control strategy would result in demand–supply imbalances and, hence, system frequency instabilities. Hence, three different scenarios are included for system loading conditions to investigate the robustness and performance of the proposed RFLFT-based LFC. Detailed discussions are provided beneath each scenario to provide a suitable judgment basis.

4.2.1. First Scenario

To model a disturbance in demand–generation balance, a step increase is applied in the demand values of each area. The simulated step changes in loading condition of each area are denoted as follows:

$$\Delta P_{d1} = 100 \text{ MW}, \Delta P_{d2} = 80 \text{ MW}, \Delta P_{d3} = 50 \text{ MW}.$$

The triggering time to apply the step load changes is determined as $t = 2$ sec. Following the mentioned loading variations, the ACE signals and resultant frequency deviations are demonstrated in Figure 7. The performance of the RFLFT-based LFC is depicted by a solid bold line. Furthermore, dotted and dashed lines, respectively, illustrate the performance of the H-GALMI and $H\infty$-ILMI controllers. Compared to the previously designed controllers, adjoining the proposed RFLFT approach in the LFC control task has evidently diminished the ACE signals along with sensibly curbing the frequency deviations both in oscillations amplitude and settling time.

4.2.2. Second Scenario

To examine the robustness of the RFLFT controller against larger disturbances in system loading conditions, the second scenario simulates larger variations in all three areas as follows:

$$\Delta P_{d1} = 100 \text{ MW}, \Delta P_{d2} = 100 \text{ MW}, \Delta P_{d3} = 100 \text{ MW}.$$

Again, the triggering time to apply the step load changes is determined as $t = 2$ sec. Following the deployed step changes, Figure 8 illustrates the ACE signals and frequency deviations acquired for all three areas. Although the simulated disturbance is larger than the first scenario, it is shown that the pro-

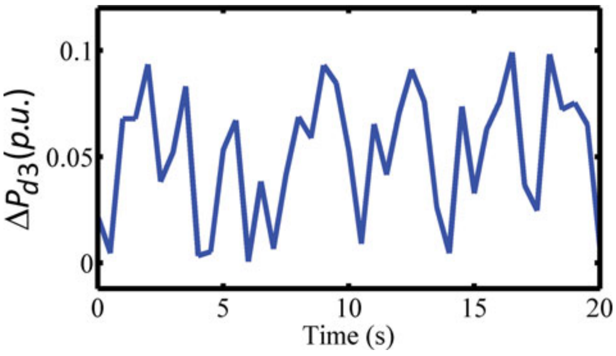


FIGURE 9. Random load demand signal.

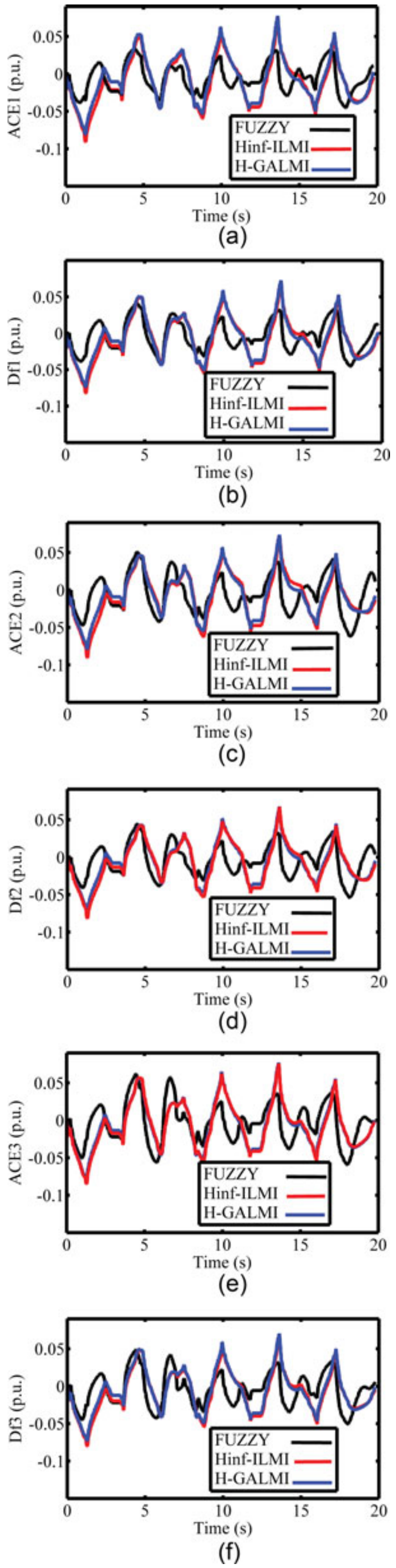


FIGURE 10. ACE and frequency deviation Δf for scenario 3: (a) area 1 ACE, (b) area 1 Δf, (c) area 2 ACE, (d) area 2 Δf, (e) area 3 ACE, and (f) area 3 Δf.

posed RFLFT-based LFC controller has effectively resulted in frequency stabilization of the system. As seen, the under-shoot values in ACE signals are much smaller than the obtained results for the other two methods. Also, both the ACE signals and frequency deviations in all three areas are quickly settled to zero in comparison with $H\infty$-ILMI and H-GALMI approaches. These observations certify the robustness of RFLFT against the larger load disturbances that mainly originate from the extensibility feature of fuzzy logic control.

4.2.3. Third Scenario

The third scenario investigates the performance of the RFLFT approach with a bounded random load change as a more realistic occasion in real-world power systems. The purpose of this scenario is to assess the robustness of the proposed controller against random large disturbances. This behavior is modeled in the form of continuous load variations, as depicted in Figure 9. All three areas are supposed to encounter this sort of variations, wherein

$$0 \leq \Delta P_d \leq 100 \text{ MW}.$$

For this case of analysis, the control area responses are shown in Figure 10. This figure reveals that the established RFLFT controller successfully tracks the load fluctuations and tunes the generation units effectively. These observations demonstrate the fast response of the proposed controller facing random and fast changes in system loading level. Although the previous controllers are enhancing the system performance indicators in the form of preserving constant frequency, the proposed RFLFT-based LFC follows the load changes in a narrower band and with uniform behavior.

5. CONCLUSION

This study intended to assess the performance of a fuzzy logic controller in a robust LFC problem. Initially, an appropriate inference system, including input and output fuzzy rules, was extracted based on expert knowledge regarding the operating system. As mentioned earlier, the robustness feature of the RFLFT controller was achieved through the extensibility capabilities of the fuzzy logic basis. Furthermore, two robust approaches, $H\infty$-ILMI and H-GALMI, were implemented to evaluate the performance of the proposed controller. Encountering step changes in power system loading conditions, it was observed that the proposed RFLFT approach demonstrates a superior response than the former methods, more specifically in terms of restrained undershoots and fast settling of frequency deviations. More remarkably, the extensibility feature of the fuzzy logic approach resulted in more robust performance in RFLFT-based LFC encountering versatile disturbances. As the ending point, constant frequency responses in all numerical studies certified the proposed RFLFT approach as a suitable option for LFC control purposes.

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BIOGRAPHIES

Rahmat Khezri was born in Oshnavieh, Iran. He received his B.Sc. in electrical engineering from Urmia University, Urmia, Iran, in 2011 and his M.Sc. in electrical engineering from University of Kurdistan, Sanandaj, Iran, in 2014. His research interests include frequency control in large-scale power systems, power system stability and control using intelligent methods, wind power integration in power systems, and microgrid control based on artificial intelligence approaches.

Sajjad Golshannavaz received his B.Sc. (with honors) and M.Sc. (with honors) both in electrical engineering from Urmia University, Urmia, Iran, in 2009 and 2011, respectively. He received his Ph.D. from the School of Electrical and Computer Engineering, University of Tehran, Tehran, Iran, in 2015. Currently, he is an assistant professor in the Electrical Engineering Department, Urmia University, Urmia, Iran. His research interests are smart grid technologies, electric power distribution and energy management systems, renewable energies, and distributed generation.

Shoresh Shokoohi was born in Sanandaj, Kurdistan, Iran, in 1987. He received his B.Sc. (with honors) and M.Sc. in electrical engineering from the University of Kurdistan, in 2009 and 2012, respectively. In 2010, he was with the control laboratory of University of Kurdistan as a lecturer. His current research interests are specifically in micro/smart grid control and robust/intelligent control applications in power electronic industry.

Hassan Bevrani received his Ph.D. in electrical engineering from Osaka University, Osaka, Japan, in 2004. From 2004 to 2011, he worked as a post-doctoral fellow, senior research fellow, visiting professor, and professor with Kumamoto University (Japan), Queensland University of Technology (Australia), Kyushu Institute of Technology (Japan), and Osaka University. Since 2000, he has been an academic member with University of Kurdistan, Sanandaj, Iran. He is the author of 3 books, 10 book chapters, and about 150 journal/conference papers. His current research interests include smart grid operation and control, intelligent and robust control applications in power systems, and power electronics industry.