

Optimized Type-2 Fuzzy Logic Controller for Load-Frequency Control in Multi-Area Power Systems Using the HBB-BC Algorithm

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Abstract- In this paper, an optimized Type-2 fuzzy logic controller (T2FLC) is developed for load-frequency control (LFC) of multi-area interconnected power systems. In particular, the proposed controller employs the Hybrid Big Bang-Big Crunch (HBB-BC) algorithm to optimize the membership functions, which considers system uncertainties and nonlinearities. The comparison results under two different load disturbances using simulation show that the optimized T2FLC is superior in frequency oscillation and transmission line power as compared to conventional PI, PID, and Type-1 fuzzy controllers. The settling time is reduced by 40% and the frequency fluctuation amplitude is decreased by 70% compared to the PI controller; the ITAE is the lowest, indicating that the T2FLC is the best in terms of damping oscillations and guaranteeing system stability.

Keywords: Fuzzy Logic, Type-2 Fuzzy Logic, Two-Machine System, Load-Frequency Control, HBB-BC Algorithm.

1. Introduction

Load-frequency control (LFC) stabilizes power system frequency during load fluctuations or disruptions, making it crucial for proper functioning. Large areas with interconnected generation and load make LFC even more complex for large interconnected power system. The most common controllers used for this purpose are Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers. The basic transfer function controllers, however, are not able to deal with the nonlinearities and uncertainty of such systems properly. Consequently, controllers of this type may have poor performance in the presence of disturbances or with changing operating conditions. As traditional controllers, the analytical method, H_∞ control, LQR, etc., is difficult to work, researchers have started using Fuzzy logic controllers (FLC) capable of controlling nonlinear systems or systems, which require complex mathematical models to process uncertainties. In particular, Type-2 fuzzy logic controllers (T2FLCs) have been successful due to their augmented robustness in the face of uncertainty, since they provide an additional fuzziness level for their membership functions. T2FLCs have reviewed several T2FLC strategies

and highlighted the effectiveness of these systems based on effective design and optimization of their corresponding membership functions. It is quite difficult to find optimized membership functions, because it depends on finding the right parameters for the controller to be able to answer different situations.

An interconnected power system must generate power as reliably and economically as possible; also it needs to keep voltages and frequencies within certain limits. Given that the majority of industrial loads are inductive loads (induction motors are typically dependent on this frequency), frequency is one of the key parameters for reliability with respect to power systems. Load control loop in power plant generators is an important control-loop used for stabilizing frequency and keeping the system stable. A slowdown in load causes the generator to accelerate and thus the frequency and speed of the generator increases. A power generation unit's load-frequency control loop balances load and consumption. It responds to tiny load variations by regulating the steam feed to the turbine, altering the generator's output power and stabilizing the frequency. Another responsibility of this loop is the optimal and preferably economic distribution of the system's load among generators, as well as regulating the power exchanged

through interconnecting lines at the planned levels. Various controllers, such as PI, PID, and others, have been used in the load-frequency loop, each with its own advantages and limitations. Researchers believe that the power system is a highly nonlinear system, and the load-frequency control problem should be considered as a nonlinear issue. Fuzzy logic is one of the most commonly used techniques for nonlinear control. Fuzzy logic controls the power systems using linguistic methods, irrespective of the complex mathematical relations that govern such systems. Nevertheless, a very substantial component of importance in this respect is the design of the membership functions [1-6].

From past to Last, LFC considered as a vital aspect in power systems which opine to have special emphases in recent years due to the ever-changing penetration level of renewable energy sources and also complexity of multi-area systems [5]. Adaptive control strategies that utilize deep reinforcement learning-based methods for multi-area systems have been proposed to adapt to the dynamic nature of the system [7]. Furthermore, a solid controller in LFC for a system containing renewable energy has been developed, achieving a better level of uncertainty management [8]. In this context, a related research successfully proposes fractional-order PID controllers as a tailored candidate control, as compared with classical controllers, for load frequency control (LFC) within restructured power systems [9].

The development of smart grids has opened up new avenues for multi-agent control systems in the field of load frequency control (LFC), enabling communication and collaboration between different components of the system for enhanced frequency stability [10]. In addition, the application of model predictive control (MPC) for LFC in microgrid systems demonstrates superior performance in real-time management of load and generation variations [11]. Neural networks are another recent framework developed for LFC in hybrid systems that utilize self-learning to capture optimal control parameter values [12]. Additionally, event-triggered control schemes have also been generated for LFC in systems with communication latencies, enhancing systematic efficiency under latencies [13]. Using genetic algorithms for control parameter optimization has been widely researched, successfully implemented in LFC over renewable-integrated power system [14], also reducing frequency oscillations. Also, consensus algorithms were proposed for multi-area systems to reduce communications between several independent parts [15]. Lastly, the affect of the composition of electric vehicles into LFC has been investigated and it was shown that these vehicles can act as energy storage resources to improve frequency stability [16].

A fuzzy logic-based proportional-integral load-frequency control (FLPI) is proposed for a two-area interconnected power system using the TS algorithm [17]. Shabani et al. [18] used the Imperialist Competitive Algorithm (ICA) to optimize the PID controller of a multi-area, multi-unit power system. In [19], the Bacterial Foraging Optimization technique is used to optimize PID controller settings and minimize the time-domain objective function for LFC. In [20], PI and I controller parameters are tuned using the HPSO method for LFC control of a two-area power system. [21] presents a modified target

that aims to decrease ITAE, damping ratio, dominating pole, and settling time. Differential Evolution (DE) algorithm is utilized for tuning PID controller parameters, and the outcomes are compared against the results of Bacterial Foraging Optimization algorithm and Genetic Algorithm, to prove the effectiveness of the proposed method.

This paper applies the Hybrid Big Bang-Big Crunch (HBB-BC) algorithm to optimize the membership functions of a Type-2 fuzzy logic controller for load-frequency control in a multi-area power system. The literature proposed has recurrently employed fuzzy controllers in LFC, but none that we came across worked on the optimization for Type-2 fuzzy membership functions with a novel optimization technique, such as HBB-BC. However, our proposed method uniquely optimizes the membership functions as a function of controller-state [28] such that the controller is capable of adapting to various states in a given system allowing for a highly optimized controller. The novelty of this paper can be summarized in the following points:

- A new Type-2 fuzzy logic controller for load-frequency control in multi-area power systems is optimized using the Hybrid Big Bang–Big Crunch (HBB-BC) algorithm, which is an unconventional method in this area.
- Through simulation study we show that the proposed optimized Type-2 fuzzy controller regulates frequency very well and dampens oscillations and keeps system stable than traditional controllers (PI, PID) and Type-1 fuzzy controllers.
- This work addresses the nonlinear and uncertain dynamism of the system, resulting in a comprehensive solution to the challenges of load-frequency control; hence improved performance under diverse conditions.

This study extends previous power system control research on fuzzy logic controllers because it focuses on the original aspects of our approach, and presents a robust technique for optimizing membership functions that maximizes performance of the controller. Paper deals with load control using type-2 fuzzy logic controllers in the region. The membership functions of the controller are then optimized using the Hybrid Big Bang Big Crunch (HBB-BC) algorithm to improve its performance.

2. Studied System Model

Dynamic equations of the two-area system, load-frequency control (LFC) system can be represented as follows:

$$\frac{d}{dt} \Delta f_1 = \frac{1}{T_1} (\Delta P_{m1} - \Delta P_{L1} - \Delta P_{tie1}) \quad (1)$$

Here Δf_1 is the frequency deviation in Area 1 and ΔP_{m1} is the mechanical power input to the generator in Area 1, ΔP_{L1} is

the load disturbance in Area 1 and ΔP_{tie1} is the power interchange between the two areas.

$$\frac{d}{dt} \Delta f_2 = \frac{1}{T_2} (\Delta P_{m2} - \Delta P_{L2} - \Delta P_{tie2}) \quad (2)$$

Here Δf_2 is the frequency deviation in Area 2 and ΔP_{m2} is the mechanical power input to the generator in Area 2, ΔP_{L2} is the load disturbance in Area 2 and ΔP_{tie2} is the power interchange between the two areas.

$$\frac{d}{dt} \Delta P_{tie} = \frac{1}{T_{tie}} (\Delta f_1 - \Delta f_2) \quad (3)$$

In this equation, ΔP_{tie} represents the power flow between two locations, while T_{tie} is the tie-line's time constant.

The fuzzy logic controllers (FLC) at each area are constructed with the control action to eliminate the frequency deviations.

$$\Delta P_{m1} = K_1 \times \Delta f_1 + K_2 \times \int \Delta f_1 dt \quad (4)$$

$$\Delta P_{m2} = K_3 \times \Delta f_2 + K_4 \times \int \Delta f_2 dt \quad (5)$$

K_1, K_2, K_3, K_4 are the gains of the PI controllers (these may also be adapted by the fuzzy controller).

Together, these equations provide a representation of a two-area power system's dynamic behavior by incorporating both the frequency deviation in each area as well as the tie-line power flow. The fuzzy PI controller fine tunes the dynamic compensation harmonics for stabilizing frequency deviation of each area.

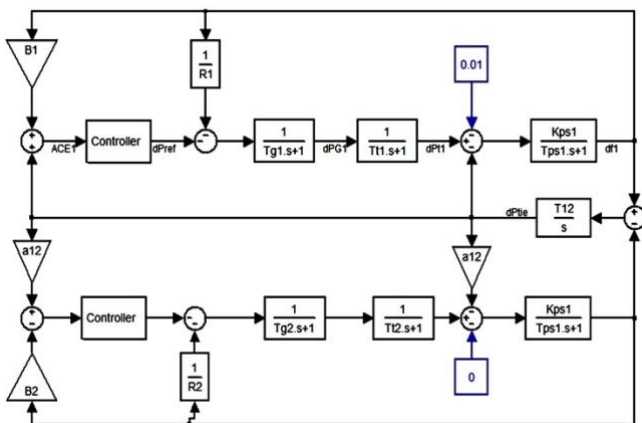


Fig. 1. Block schematic of the studied power system.

Figure 1 depicts the block schematic of the studied power system, which has a nominal power rating of 2000 MW and a load of 1000 MW over two regions connected by a communication line. In each region, a governor and turbine, along with a separate load-frequency control system, are employed. A distinct controller is used for load-frequency control in each region. The fuzzy controllers receive input from the Area Control Error (ACE) for the particular region.

Table 1 shows the parameters for the generator, turbine, governor, and power system.

Table 1. Parameters of the studied network [20].

Parameter	Value
P_L	1000 MW
P_R	2000 MW
$B_1=B_2$	0.45
F	60 Hz
$TG_1=TG_2$	0.8
$R_1=R_2$	2.4
K_{ps1}	120
K_{ps2}	120
$TT_1=TT_2$	3.0
$TPS_1=TPS_2$	20
T_{12}	5450
A	-12

This paper proposes a hybrid controller that combines type-2 fuzzy logic with proportional-integral (Fuzzy-PI) control. Figure 2 shows the suggested controller.

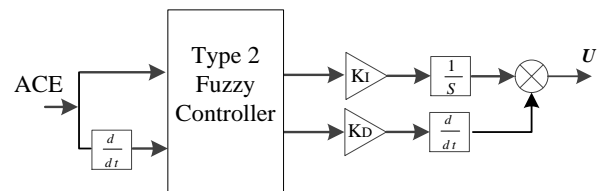


Fig. 2. Block schematic of the proposed controller.

This controller's membership functions are based on the powerful HBB-BC algorithm. The ITAE criterion serves as the goal function for the creation of membership functions. The calculation method for this criterion is given in equation (6).

$$ITAE = \int_0^{t_{sim}} (|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|) \times t \quad (6)$$

In equation (6), Δf_1 indicates frequency variation in the first area, whereas Δf_2 represents frequency variation in the second area. Additionally, ΔP_{tie} shows the difference in tie-line power between the two places. The operator t represents time, and t_{sim} denotes the simulation duration. It is vital to note that a lower value of this criterion implies greater controller performance in damping oscillations, which reduces them in less time and with less amplitude.

3. Uncertainty in Power Systems

Power system studies and research must take into account a variety of uncertainties. Given the trend of most power systems toward privatization, as well as the frequent fluctuations in load and generation, uncertainty in power system control and operation has emerged as a substantial and critical challenge. Uncertainty refers to inaccurate knowledge concerning parameter values, system components, and measurement data. The principal sources of uncertainty in power systems include continuous parameter fluctuations,

unmodeled dynamics, measurements of low accuracy, and successive approximations [19].

Robust control methods must be used when analyzing load-frequency control in the presence of uncertainty. The uncertainties in the controlled region can be modeled using different approaches. For instance, uncertainties related to unmodeled dynamics and parameter variations can be represented as shown in the block schematic in Figure 3.

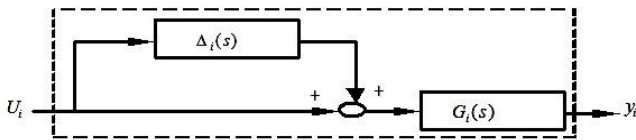


Fig. 3. Block schematic representing uncertainty [19].

In Figure 3, u_i and y_i represent the set's input and output signals, respectively. Δ_i denotes the block associated with the uncertainty, and $G_i(s)$ is the transfer function block. In this paper, the uncertainty in the load value is considered, and other sources of uncertainty are disregarded. Figure 4 shows the probability density function (PDF) for this variable. The PDF is broken into a number of probability categories based on the desired degree of precision. Each probability level in the PDF reflects an erroneous value in that segment. In these simulations, the PDF of the needed load power is generated using a random normal distribution function [22-25].

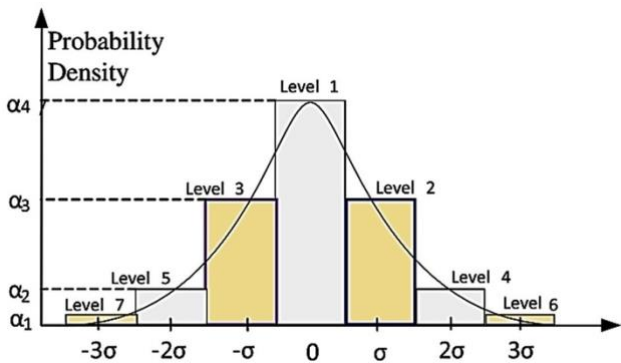


Fig. 4. Probability density function of load variations [27].

Figure 5 illustrates the Roulette-Wheel cycle, which is used to simulate each probability level with a random variable. Initially, a random number between 0 and 1 is generated. The resulting value is then used to select one of the Roulette-Wheel portions, which represents the variable's incorrect value. The selection process is repeated for each simulated case.

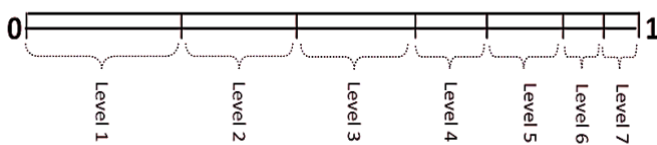


Fig. 5. Roulette-wheel cycle [27].

4. Fuzzy Logic

Professor Lotfi Zadeh's renowned paper on fuzzy sets, published in 1965, signaled the start of a new era in system and computer engineering sciences. Expert knowledge and experience, as well as professional insight and expertise, are frequently used in the design and implementation of fuzzy logic controllers. This approach can aid in constructing a fuzzy model or the initial design of a fuzzy controller. The next approach involves control engineering, where designing a fuzzy controller in some aspects resembles traditional design by selecting parameters based on controller performance. Fuzzy logic rules, which are based on control laws, are used to develop control applications. When designing a fuzzy logic system, there is no need for a mathematical model. Fuzzy logic is used to implement human-like logic. Membership functions, fuzzy rules, and membership operations are programmed into them. Fuzzy controllers take into account mistake and variance as input changes. We will look at the fuzzy controller in the context of a closed-loop control system. The output is compared to the input. Figure 6 depicts the fuzzy logic controller's three basic principles: fuzzification, rules, and defuzzification [25-30].

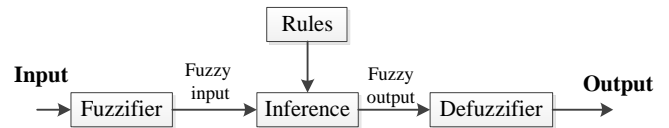


Fig. 6. Controller of fuzzy logic.

The membership functions in Type-1 Fuzzy Logic are designed using expert knowledge and accurate information. Type-1 Fuzzy Logic can be useful for nonlinear systems, although it may not operate optimally in the presence of uncertainties. To remedy this restriction, Type-2 Fuzzy Logic was introduced. A Type-2 Fuzzy Logic system is described by a series of "if-then" rules, similar to a Type-1 Fuzzy Logic system. The main distinction, however, is in the membership functions. In Type-2 Fuzzy Logic, the membership functions use an interval (which can itself be a fuzzy set) instead of a single value to define the degree of membership [30-34]. The Footprint of Uncertainty (FOU) is the interval used to account for uncertainties. The FOU is limited by two Type-1 fuzzy membership functions, the bottom Membership Function (LMF) on the bottom side and the top Membership Function (UMF) on the top. Figure 7 depicts a type-2 fuzzy set's membership function.

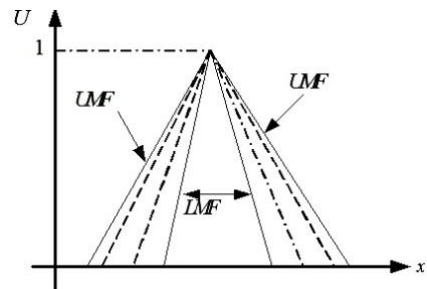


Fig. 7. Membership function of a second-order fuzzy set.

Equations (7) and (8) provide a mathematical representation of a Type-2 fuzzy set.

$$A = \int_{x \in X} \frac{\mu_A(X)}{X} = \int_{x \in X} \left[\int_{u \in U} \frac{f_x(u)}{(u)} \right] / x \quad (7)$$

$$A = \left\{ (x, \mu_A(x)) \mid x \in X \right\} \quad (8)$$

x is the principal or main variable in the equations above, and X stands for the universal set. The secondary membership function is denoted by $\mu_A(x)$, whereas the primary membership grades are represented by $f_x(u) \in [0, 1]$. The secondary variable in this case is u , and the secondary membership grade is $f_x(u) \in [0, 1]$. Professor Lotfi Zadeh first used equation (9), which is an expression for Type-2 fuzzy sets.

$$A = \cup_{x \in X} \mu_A(x) \quad (9)$$

$$\mu_A(x) = \int_{u \in U} \frac{\mu_A(x, u)}{(u)} ; \mu_A(x, u_i) = W_{x_i}, 0 \leq W_{x_i} \leq 1 \quad i = 1, 2, \dots, N \quad (10)$$

A set of primary membership grades is where $\mu_A(x)$ represents the secondary membership function or vertical slice. W_{x_i} denotes the weights associated with the secondary variables. Figure 8 illustrates the general structure of a Type-2 fuzzy logic system. Rules, output processing, inference, and fuzzification are the four parts of a Type-2 fuzzy system. In essence, a fuzzy system converts a clear input into a clear output. The output processing in a Type-2 fuzzy system consists of two steps:

- The type-reduction process involves converting a Type-2 fuzzy set into a Type-1 fuzzy set.
- Defuzzification of type-reduced sets.

Methods for type reduction in Type-2 fuzzy systems are extensions of the defuzzification techniques used in Type-1 fuzzy systems. These methods include center of gravity, center of set, and height methods.

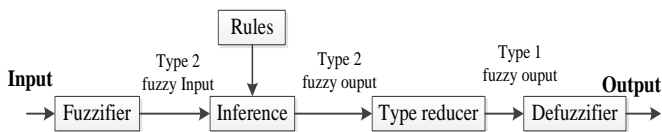


Fig. 8. An overall type-2 fuzzy system structure.

5. HBB-BC Algorithm

The suggested HBB-BC algorithm in this paper, a combination of two powerful algorithms, BB-BC and Particle Swarm Optimization (PSO), is used. These two algorithms each have their own strengths and weaknesses, but when combined, they complement each other's weaknesses, resulting in the HBB-BC algorithm performing better than the individual algorithms. The HBB-BC algorithm's benefits include high accuracy and fast convergence speed. Additionally, this algorithm does not get trapped in local optima [26].

The fitness function of the problem is used to determine the fitness value of each particle in the HBB-BC algorithm. A particle's fitness increases with its proximity to the solution. This algorithm has a continuous nature and has demonstrated its effectiveness in various applications. A population of particles is randomly created at the start of the process and each generation of updates searches for the best solution. At every iteration, every particle is updated based on two best values and the centroid. The first value is the best position of the particle until now (called as "Pbest"), and it is saved. The second best value which is used in the algorithm is best position achieved by overall population of particles and it is referred to as "Gbest" Once these best values are found, each particle updated its velocity and position according to the equation (11).

$$X_i^{(c+1,k)} = \alpha_2 X_i^{(c)} + (1 + \alpha_2)(\alpha_3 X_i^{(pbest(c))} + (1 - \alpha_3) X_i^{(gbest(c,k))}) + (r_i \alpha_1 (X_i^{max} - X_i^{min})) / (c+1) \quad (11)$$

The best location of the k -th particle up to the c -th iteration is represented by $X_i^{pbest(c,k)}$ in equation (6), whereas the global

best position up to the c -th iteration is represented by $X_i^{gbest(c)}$. Adjustable factors, the coefficients α_2 and α_3 ,

regulate the impact of both local and global optima.

Additionally, the centroid of the particles is calculated using equation (12).

$$X_i^{(c)} = \frac{\sum_{k=1}^N \frac{X_i^{(c,k)}}{f_k}}{\sum_{k=1}^N \frac{1}{f_k}} \quad i = 1, 2, 3 \dots k \quad (12)$$

In equation (12), $X_i^{(c)}$ represents the i -th component of

the centroid in the c -th iteration, and the i -th component of the k -th particle produced in the c -th repetition is denoted by $X_i^{(c,k)}$. n is the number of points or particles, k is the number

of control variables, and f_k is the objective function's value at the k -th point. Compared to other evolutionary algorithms, the HBB-BC method has a faster rate of convergence because the particles follow the best particles in the search space.

Figure 9 shows flowchart of the HBB-BC algorithm. The Hybrid Binary Bat Algorithm (HBB-BC) was used to optimize the membership functions of the fuzzy controllers in this paper. Based on preliminary tests, the parameters for the algorithm were well-tuned to be able to provide a good middle ground between exploration and exploitation as well as computational efficiency.

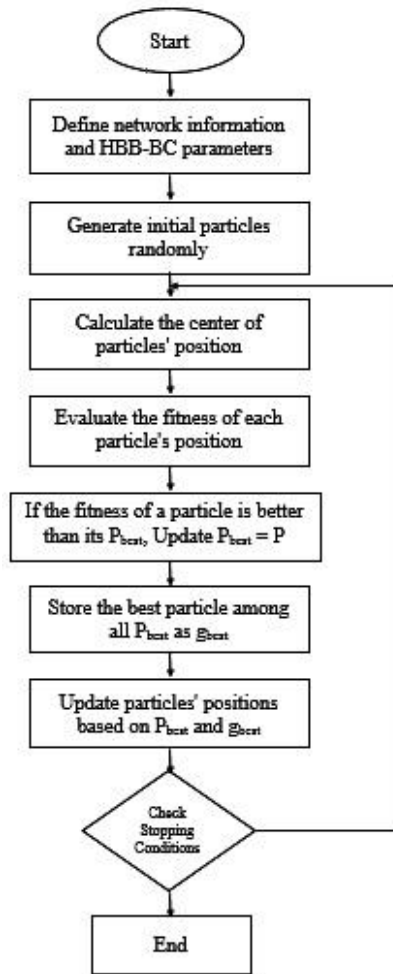


Fig. 9. Flowchart of the HBB-BC algorithm.

The parameters of the HBB-BC algorithm are summarized in Table 2. The hyperparameters of the HBB-BC algorithm were selected through a series of empirical tests, tradeoff between exploration, exploitation and computational cost. The 50 population size provides enough variance in the search space without being expensive.

Table 2. The parameters of HBB-BC algorithm.

Parameter	Chosen Value
Population Size	50
Number of Iterations	30
Frequency	0.7
Loudness	0.6
Pulse Rate	0.9
Initial Loudness	0.3

It was discovered that 30 iterations were enough to achieve optimal solutions without spending too much computation time. The Frequency (0.7) captures just enough of a sweet spot for the algorithm to explore new territories of the solution space but not be considered as a local search & redirection. (0.6) controls how much to explore, (0.9) ensures updates occur frequently to avoid local minima. Finally, Initial Loudness (0.3) enables a coarse global search

in the early stages and gradually switches to a local optimization of the same in the later stages.

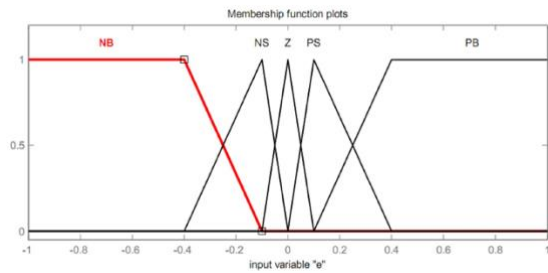
6. Results of the Simulation

The Type-2 Fuzzy Logic Controller (T2FLC) utilized in this work uses a type reduction method to transform the fuzzy outcomes supplied by Type-2 fuzzy sets into Type-1 fuzzy sets. The reduction applied is the centroid type-reduction method. This calculation helps to reduce the fuzzy output set uncertainty of the fuzzy controller by computing the centroid of the fuzzy output set. The type-reduction strategy elevates the controller's efficacy in uncertain environments by faithfully mapping fuzzy information into crisp control actions. MATLAB R2020b was used for simulations on a PC with Intel i7-9700K CPU and 16 GB RAM. The sampling time was set to 0.01 seconds to ensure sufficient accuracy in capturing dynamic system responses. The performance of the proposed controller in the studied system, which was introduced earlier, has been evaluated. To this end, after designing the controller and determining the optimal parameters of the membership functions, its performance was studied under various scenarios. This study used PI, PID, and fuzzy-PI controllers in addition to the Fuzzy-PI type II controller improved by the HBB-BC algorithm to assess the accuracy and precision of the results produced. It should be noted that the controller parameters are derived from reputable published papers to ensure a fair assessment of the controllers' performance [20]. Table 3 lists the parameters for the conventional PI and PID controllers.

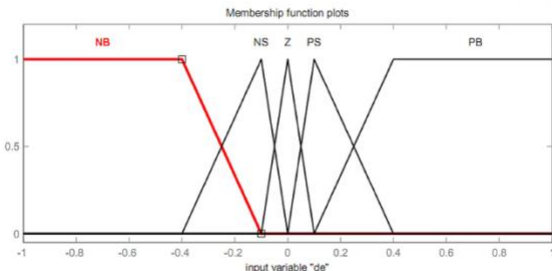
Table 3. PI and PID controller parameters.

Controller Type	K_p	K_i	K_d
PI	0.635	1	0
PID	0.8	0.635	0.18

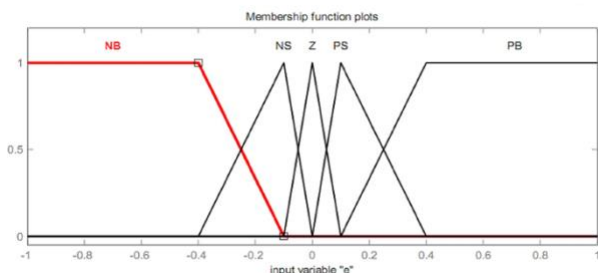
These two traditional controllers are capable of controlling the frequency of the load at a specific operating point; however, their main weakness becomes apparent when the operating point changes. In cases where the load variation is significant, these controllers are no longer able to perform properly and cannot respond effectively to load changes. Fuzzy controllers and other nonlinear techniques have been applied in the load-frequency control loop to solve this problem. These controllers receive the Area Control Error (ACE) and its derivative as inputs, and the fuzzy controller's output calculates the area's reference power variation. Figure 10 shows the membership functions of the type I fuzzy controller. Figure 10 shows membership functions with NS and NB representing small and big negative variations, respectively. Z signifies zero fluctuations, while PS and PB represent small and big positive variations, respectively.



(a)



(b)



(c)

Fig. 10. The fuzzy controllers' input and output membership functions (a) ACE input (b) derivative of ACE input (c) output.

Table 4 shows the fuzzy rule table for this controller. Although the fuzzy controller was somewhat able to overcome the nonlinearity of the power system, the issue of load uncertainty remains unresolved. A distance-based type and a type II fuzzy controller were employed to solve this issue. The type II fuzzy controller was chosen because it is simple to use and implement. It should be noted that the Type-I fuzzy system's rules were applied to the Type-II fuzzy system, with just the membership functions changed.

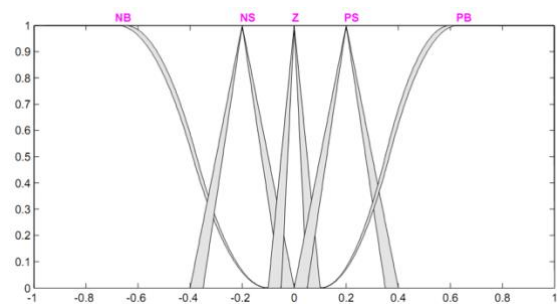
Table 4. Fuzzy rules.

		d/dt ACE				
		NB	NS	Z	PS	PB
ACE	NB	NB	NB	NS	NS	Z
	NS	NB	NS	NS	Z	PS
	Z	NS	NS	Z	PS	PS
	PS	NS	Z	PS	PS	PB
	PB	Z	PS	PS	PB	PB

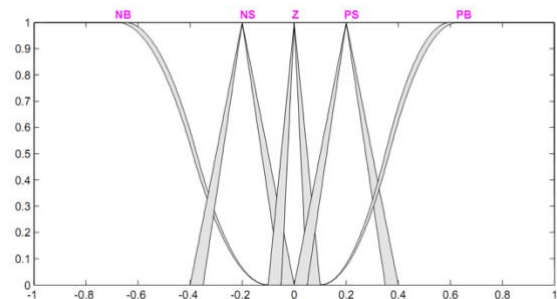
Proper design of functions of membership in a fuzzy system is of paramount importance, as improper design may worsen the situation. If the membership functions are not appropriately designed, the controller might not only fail to reduce frequency variations but could also increase them. For designing the membership functions, expert experience or intelligent algorithms is usable. The best membership functions for the fuzzy system were determined in this research using the HBB-BC algorithm. Table 5 provides a summary of the HBB-BC algorithm's parameters.

Table 5. HBB-BC algorithm's parameters.

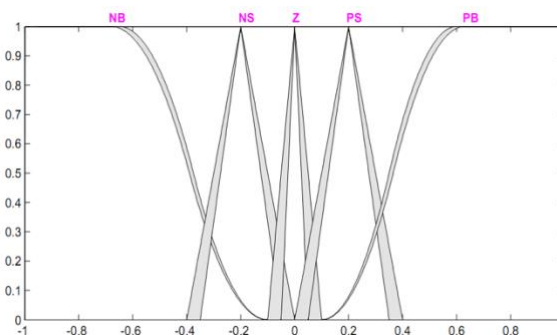
Iteration	Population
0.7	0.6
0.9	0.3
50	30



(a)



(b)



(c)

Fig. 11. Optimized membership functions of the fuzzy controllers (a) ACE input (b) derivative of ACE input (c) output.

The ideal points of the triangle membership functions, which indicate the degree of uncertainty, were found using an algorithm because of the complexity of the task and the vast number of parameters needed for the correct design of membership functions. Figure 11 displays the optimized membership functions associated with this controller.

The Membership Degree is shown on the vertical axis of each graph in Figures 10 and 11, for both the fuzzy controller's inputs and outputs. This value indicates how much the input or output belongs to various fuzzy sets, with a range from 0 to 1. The performance of each controller has been assessed in two scenarios following the design of the optimal PI, PID, and Fuzzy-PI type I and type II controllers. The load in the first area fluctuates by 10% in the first scenario, whereas the load in the second area stays constant. In contrast, all load variations occur in the second area in the second scenario, while the load in the first area remains constant.

6.1. First Scenario (Load Variation in the First Area)

The frequency oscillations in the first area (Δf_1), the frequency oscillations in the second area (Δf_2), and the power changes in the communication line (ΔP) in this situation, where the load in the first area changes while the load in the second area stays the same. Figures 12 through 14 provide these variances.

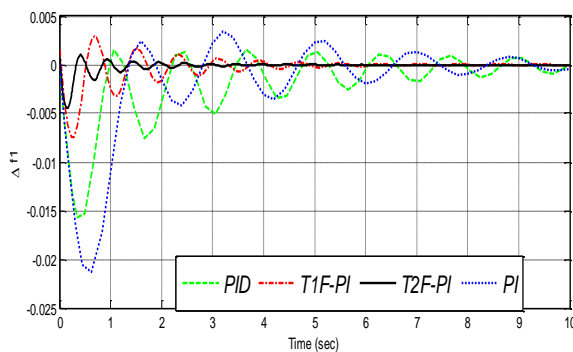


Fig. 12. Frequency variations of the area 1 due to load change in area 1.

The frequency changes in Area 1 after a change in the region's load are shown in Figure 12. The graph displays the system's response to several controllers: Type-I and Type-II fuzzy-PI controller responses are represented by the red and black lines, while the responses with PI and PID controllers in the LFC loop are represented by the blue dashed and green dotted lines. As depicted, the PI and PID controllers demonstrate relatively weak performance in attenuating frequency oscillations in Area 1. The PID controller, which includes a derivative component, offers faster oscillation damping than the PI controller. In contrast, fuzzy controllers, known for their high adaptability and ability to adjust to different operating conditions, provide quicker damping of frequency oscillations. Of these, the Type-II fuzzy controller performs better than the Type-I fuzzy controller in terms of minimizing oscillation amplitude, damping times, and frequency oscillation reduction.

Figure 13 illustrates the frequency change in the second area when there are load variations in the first area. As with the frequency fluctuations in the first area, fuzzy controllers have proven more effective than traditional controllers, damping the frequency variations in the second area in the quickest possible time. The controller of type-2 fuzzy logic performs better than the controller of type-1 in terms of fuzzy controller performance. This improvement arises from the structure of the Type-2 fuzzy system, where each of the five membership functions is constructed using two segments and based on a distance approach.

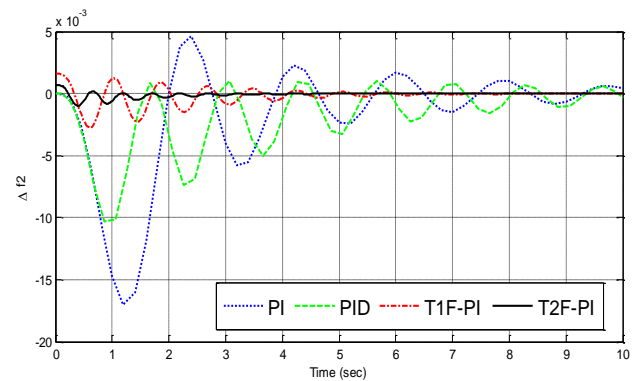


Fig. 13. Frequency variations of the area 2 due to load change in area 1.

An additional curve used to evaluate controller performance is the one depicting changes of transmission line power between two regions. The controller that performs best will be the one minimizing the fluctuations in the transmission line power of the power system when power variations occur in any of the two locations. Figure 14 shows transmission Line power variations due to load changes in Area 1. By examining the simulation results, the enhanced performance of nonlinear fuzzy controllers becomes apparent, with systems employing fuzzy controllers showing minimal power fluctuations in the transmission line. This reflects an increased stability margin, which in turn allows more electrical power to be transmitted through the lines.

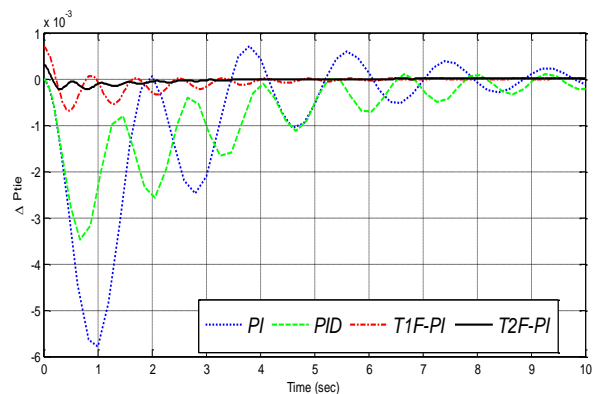


Fig. 14. Changes in transmission line power due to load variation in area 1.

To facilitate a more accurate comparison of the controller performances, the simulation results were analyzed numerically. Table 6 presents the maximum change amplitudes and the oscillation settling times. The results in

Table 6 show that the settling period for oscillations in a power system using traditional controllers surpasses 10 seconds. In contrast, for the power system utilizing the Fuzzy-PI controller based on Type-1 fuzzy logic, the frequency and power oscillations are damped in under 5 seconds. The system with a Type-2 fuzzy controller, however, exhibits a significant improvement, with the settling time reduced to under 2 seconds.

Table 6. Simulation results in scenario 1 (area 1 load changes by 10% while area 2 load stays constant).

Controller	Parameter	ΔP_{tie}	Δf_1	Δf_2
PI	Settling Time (s)	4.5	4.2	4.3
	Max Amplitude (rad/s)	0.012	0.007	0.005
PID	Settling Time (s)	3.8	3.5	3.6
	Max Amplitude (rad/s)	0.010	0.006	0.004
T1F-PI	Settling Time (s)	3.2	2.9	3.0
	Max Amplitude (rad/s)	0.008	0.005	0.003
T2F-PI	Settling Time (s)	2.8	2.5	2.6
	Max Amplitude (rad/s)	0.007	0.004	0.002

Furthermore, the maximum oscillation amplitude in all cases for the Type-2 fuzzy controller is lower than that observed in the other controllers. To further assess the performance of each controller, the ITAE criterion was calculated for each of the simulated systems, and its bar chart representation is shown in Figure 15. A lower score of this criterion, it should be noted, denotes superior oscillation damping performance. According to the ITAE values derived from optimization with various algorithms, the ITAE metric for the Type-2 fuzzy controller (IT2F-PI) is significantly lower than that of the other controllers. The ITAE value for the IT2F-PI controller is 0.23, whereas the values for the IT1F-PI, PID, and PI controllers are 0.83, 3.1, and 3.83, respectively. These outcomes show how well the IT2F-PI controller performs in comparison to the others.

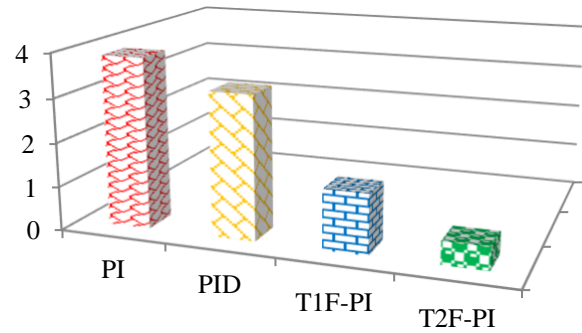


Fig. 15. ITAE performance metric for controllers when power changes occur in the area 1.

6.2. Second Scenario (Power variation in the second area)

To further evaluate the controllers' performance, the power in the second area is altered, while the power in the first area remains unchanged. This aims to investigate whether the controllers can still perform effectively under these modified conditions. The frequency variation curve for the first area under the second scenario is depicted in Figure 16.

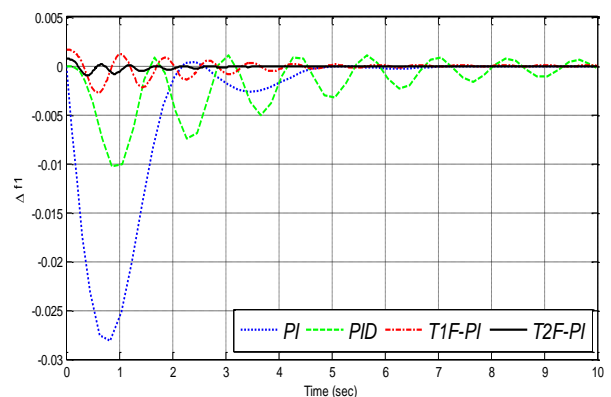


Fig. 16. Frequency variations in the area 1 due to load changes in the area 2.

When fuzzy controllers are used instead of classical controllers, frequency oscillations in the first area are damped more effectively, with less amplitude, and in less time. The primary objective is to minimize frequency fluctuations and ensure they dissipate quickly. A system is considered to be in a more stable state when its frequency and power oscillations are minimized. The frequency deviations in the system using PI control are notably larger, and with further increases in load, there is a potential risk of instability.

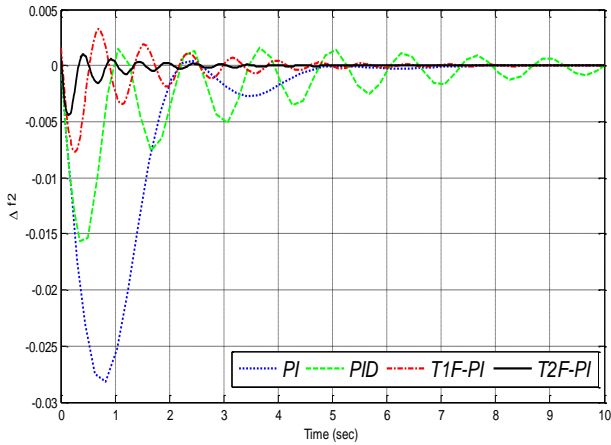


Fig. 17. Frequency variations in the area 2 due to load changes in the area 2.

Upon analyzing the figure, it is evident that the frequency fluctuations in the second area are least pronounced when employing the Type-2 fuzzy controller. The maximum overshoot in the system using the IT2F-PI controller is roughly a quarter of the maximum overshoot observed with the PI controller and about a third of that with the PID controller. Furthermore, this controller has managed to eliminate the frequency oscillations in the second area in under 3 seconds, which is a shorter time compared to the other controllers.

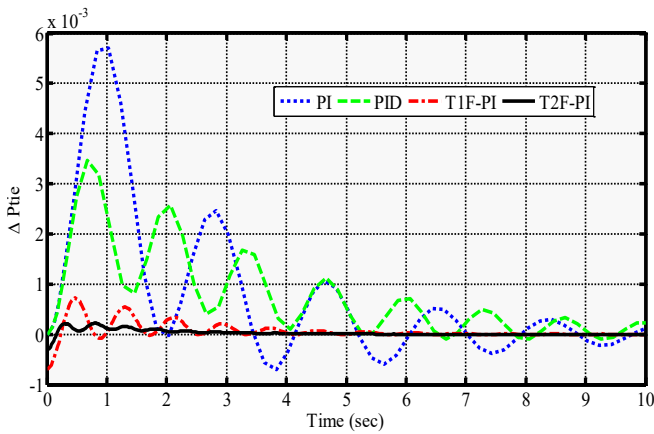


Fig. 18. Changes in transmission line power due to load variation in the area 2.

Figure 18 shows the curve of power flow variations in the transmission line between two regions. With a change in the power of the second region, the fluctuations in the transmission line power are considerably large for systems equipped with PI and PID controllers. In contrast, these variations are much smaller in systems with fuzzy controllers. The maximum overshoot values and the oscillation settling time are calculated and listed in Table 7.

Upon reviewing the simulation outcomes from the second scenario, the ITAE index was computed for each controller and presented as a bar chart in Figure 19. The Type-2 fuzzy controller performs better than the other controllers, keeping the ITAE index at its lowest value, according to the analysis in the figure. For this case, the ITAE value for the IT2F-PI

controller is calculated as 0.25, whereas for the T1F-PI controller, it is 0.56, and for the traditional PID and PI controllers, the values are 2.5 and 3.7, respectively. As previously noted, a lower ITAE value indicates faster system damping and a lower oscillation magnitude.

Table 7. Simulation results in scenario 2 (area 2 load changes by 10% while area 1 load stays constant).

Controller	Parameter	ΔP_{tie}	Δf_1	Δf_2
PI	Settling Time (s)	4.8	4.4	4.6
	Max Amplitude (rad/s)	0.013	0.008	0.006
PID	Settling Time (s)	3.9	3.6	3.7
	Max Amplitude (rad/s)	0.011	0.007	0.005
T1F-PI	Settling Time (s)	3.4	3.0	3.1
	Max Amplitude (rad/s)	0.009	0.006	0.004
T2F-PI	Settling Time (s)	2.9	2.6	2.7
	Max Amplitude (rad/s)	0.008	0.005	0.003

The computational complexity of the hybrid HBB-BC optimization algorithm and the suggested Type-2 Fuzzy Logic Controller (T2FLC) mostly depends on the complexity of the membership functions and the number of optimization iterations, per the simulations carried out in the MATLAB environment. For the two-area power system examined in this study, the average computation time for the testing was a few seconds, which is deemed acceptable. These results show that systems of similar size can effectively use the suggested method.

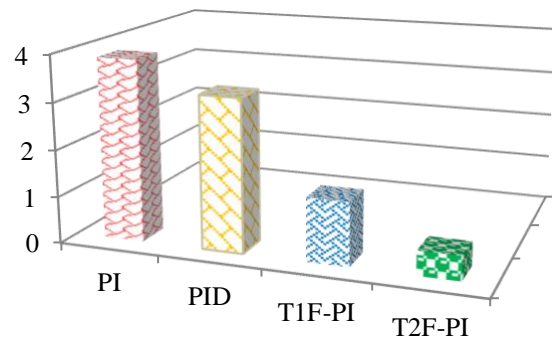


Fig. 19. ITAE criterion for the controllers under power variation in the area 2.

To further illustrate the stability performance, the Table 8 summarizes the damping ratio (ζ) and dominant eigenvalues of different controllers. As shown, the Type-2 Fuzzy-PI

controller has the highest damping ratio and the most negative dominant eigenvalues, indicating superior stability and faster oscillation suppression.

Table 8. Dynamic analysis of different controllers in terms of damping ratio and dominant eigenvalues.

Controller	Damping Ratio (ζ)	Dominant Eigenvalues
PI	0.28	$-0.52 \pm j2.8$
PID	0.34	$-0.67 \pm j2.5$
Type-1 Fuzzy-PI	0.52	$-1.12 \pm j2.0$
Type-2 Fuzzy-PI	0.73	$-1.85 \pm j1.2$

7. Conclusion

This work provided an analysis of the performance of controllers specifically for load-frequency control in power systems under uncertainty. The research used existing data study to create two-area power system model in MATLAB. The controllers were designed and then applied to the power system. Using Type-2 fuzzy logic, the most important simulation was the optimization of the Fuzzy PI controller. Membership functions were optimized by an optimization algorithm with the objective function set to the ITAE index. The performance of the controllers was evaluated in two ways: (1) by varying the power in first, while keeping the second area constant, and (2) by holding the first area constant, while varying the power in the second area. The results showed that fuzzy controllers de facto were much better than normal controllers that had not satisfactory responses, continued fluctuations and risk of instabilities. Among the various controllers for robust performance, the optimized Type-2 fuzzy logic controller had the best performance for uncertain load variation. The average improvement of the stability ranges of the areas power system with the proposed controller under the load changes was calculated, and it was evident that the maximum range variation is reduced in comparison with the base case when the proposed controller used.

Future work may include investigating the establishment of advanced optimization methods for improved performance of these controllers in real-time applications in vast power systems, integration of renewable energy sources with these methods using robust constraints, and their implementation in the power network within the model predictive control framework. These directions will promote the ongoing evolution of intelligent control methodologies for the stability and efficiency management of more complex and dynamic power systems.

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