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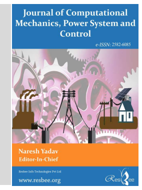

Design and Evaluation of a Load Frequency Controller for a Hybrid Power System Using Fuzzy Logic Tuned by the Bees Algorithm

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Abstract. Load Frequency Control (LFC) is designed to keep system frequency close to its nominal value. This study addresses the problem of frequency variations in a hybrid power system and provides theoretically grounded remedies. These techniques are used in a hybrid power system that combines a Diesel Engine Generator (DEG) with photovoltaic (PV) arrays. A soft optimization technique using the Bees Algorithm (BA) is employed to fine-tune the proposed fuzzy logic controller parameters, aiming for optimal control and dynamic system performance. Implementing a controller for fuzzy logic optimized by the BA, results in improved frequency response of the PV-DEG system, both during and after load disturbances. The suggested method's efficacy is evaluated using MATLAB-Simulink simulations and tests under various load conditions. The results highlight its enhanced performance, demonstrating its effectiveness as a valuable tool for addressing challenges in electrical power systems, particularly in load frequency management. A comparison between a conventional PID controller and a simple fuzzy logic controller was conducted to show the effectiveness of the suggested controller. The results indicate that the Fuzzy Logic Controller tuned by the BA significantly outperforms the other methods.

Keywords: Hybrid Power Systems, Load Frequency Control, Fuzzy Logic Control, Bee Algorithm, PID controller, Power system control and stability.

Nomenclature

Abbreviations	Full Form
LFC	Load Frequency Control
FLC	Fuzzy Logic Controller
BA	Bees Algorithm
PID	Proportional-Integral-Derivative Controller
DEG	Diesel Engine Generator
PV	Photovoltaic

1.Introduction

Over the past few years, hybrid power systems have emerged due to the growing trend of integrating renewable energy sources with conventional power systems. These systems are highly nonlinear and exhibit increasing structural complexity, largely due to capacity expansion and the diverse reliance on multiple energy sources. This complexity and nonlinearity introduce several challenges, with frequency deviation being one of the most critical issues in hybrid power systems. As we know, the load demand in the power system is variable. The load demand is continuously changing throughout the day. The constant fluctuation in load demand requires continuous adjustments in power generation to keep the frequency at its rated value, a process known as LFC in power systems [1].

Handy devices known as DEGs use diesel fuel to generate power. Electricity is produced by these machines using a diesel engine and an electric generator. Diesel generators use combustion to transform a portion of the chemical energy contained in diesel fuel into mechanical energy. A crank is then turned by this mechanical energy to produce electricity. In comparison with other types of generator engines, the Diesel engine compresses more air faster, delivering more power to get work done. Due to this, diesel engines use much higher compression, making their build stronger and more durable. In the DEG, the speed governor controls the engine's fuel input to regulate the rotational speed and maintain a stable output frequency (usually 50Hz) under varying loads. This ensures the generator responds to load changes.

The PV system generates power depending on the availability of solar irradiance. It does not directly control frequency or respond to load changes as quickly as the DEG. Instead, it generates DC power which is then converted to AC using an inverter, and then supplies power to the grid or local loads. In our hybrid system, the speed governor controls the operation of the diesel generator while the PV system operates alongside it to supply additional power. When solar energy is available, the PV system generates most or all of the required power, the DEG may run at a lower load or be switched off completely when the PV system meets the load demand. During times of low solar irradiance, the DEG kicks start to maintain the load. The PV system acts as the primary power source for the majority of the load. This reduces the generator runtime, lowers fuel consumption, and significantly cuts down on CO2 emissions.

The primary role of the LFC loop in power systems is to ensure that the power exchanged between these hybrid power systems remains at predetermined values and that the system's operating generation plants supply the necessary power to accommodate variations in load demand. Power system stability is improved by the LFC loop, which seeks to remove steady-state errors in both frequency variations and tie-line power fluctuations. Additionally, depending on the system's capacity and the severity of disturbances, the LFC loop is responsible for damping the oscillations in frequency and exchanged power, minimizing overshoots and undershoots within a specified time frame [2]. Traditional LFC methods always struggle to adapt to the unpredictable nature of solar power, leading to suboptimal performance The contribution of this paper aims to:

- Design an adaptive control strategy using the FLC tuned by the BA to enhance the stability and reliability of LFC in a hybrid PV-Diesel engine system due to the intermittency of solar energy which results in frequent load frequency fluctuations.
- Justification for the BA over alternative optimization techniques and a comparative evaluation of PID, non-optimized FLC, and BA-tuned FLC.
- Develop a comprehensive framework integrating renewable energy sources (such as solar) with conventional sources (like diesel generators) for improved LFC.
- Provide a practical and effective solution using modern technologies for load frequency challenges in a hybrid power system, thus contributing immensely to power systems engineering.

1.1 Overview of LFC

The efficient management of complex power systems with multiple interconnected control areas aims to generate and distribute electricity reliably while maintaining key variables like voltage and frequency, within reasonable bounds [3]. The generated power must be balanced with the load side demand to achieve this. However, load demand fluctuates over time and affects all power system operating parameters, including scheduled power exchange and frequency. These fluctuations can lead to undesirable consequences, including system instability that could potentially cause a full system shutdown [4]. Integration of dual-area power system models into LFC is a topic of much debate. Traditionally, conventional controllers have been the main focus of LFC research.

Bode, Nyquist, and root locus approaches are frequently used in classical control systems to maximize phase margins and gains [5]. In industries that rely on classical control models, Proportional-Integral-Derivative (PID) control is the most widely used method, accounting for over 90% of control loops [6]. However, with the recent integration of renewable energy sources, power systems have grown larger and more structurally complex. Consequently, conventional control techniques might not be adequate to provide the required degree of accuracy in operation. Over time, a large number of researchers have investigated and put forward several control theories in response to this growing complexity. This has led to the development of several innovative hybrid approaches designed to tackle these emerging challenges. The following paragraphs provide a brief review of the literature on the various methods utilized in this paper.

Numerous studies have investigated LFC approaches utilizing FLCs [7]. This technique has been widely applied to various LFC challenges in power systems. The comparison between fuzzy logic and conventional proportional-integral-derivative (PID) controllers was investigated by [8]. The study concentrated on examining and setting the input/output ranges of the controllers to make it easier to convert a traditional

PID controller that was fine-tuned into a matching FLC. The FLC can provide more effective and desired system responses, according to the data. Since its development, the Bee Algorithm (BA) has garnered significant attention from researchers due to its straightforwardness and its imitation of natural behaviors. The BA was used in [9] to improve the PID controller settings for a two-story structure subjected to seismic stimulation. In this study, the BA-optimized PID controller outperformed the one optimized with the Genetic Algorithm (GA).

2. System Description and Methodology

This section focuses on the suggested FLC, adjusted by the BA, intended for the PV-DEG hybrid power system LFC to stabilize and maintain the power system's frequency at its rated value. The performance is optimized using the Bee Algorithm (BA), which adjusts the variables of the suggested controller to their ideal levels.

Research Gap

Table 1 has been included to compare in detail the proposed method with previous hybrid power system LFC techniques.

Table 1. *Comparison of the proposed method with previous methods*

Method	Overshoot(%)	Settling Time	Computational Complexity	Real-World Implementation
PID Controller	6.6	17.4	Low	Yes
FLC	2.1	12.2	Medium	Moderate
BA Tuned FLC	0.5	6.7	High	Potentially Feasible

In traditional LFC techniques, PID controllers are used but they lack adaptability to non- linerarities. Genetic algorithm and Particle Swarm Optimization have been applied but suffer from convergence issues. The BA algorithm provides superior local search capabilities for controller tuning.

2.1 Hybrid Power System Model

The system consists of a PV array and DEG. The PV system provides primary power, with the DEG stabilizing frequency under load fluctuations. The table 2 below depicts the configuration of the Hybrid Power System.

Table 2. *Hybrid Power System Configuration*

Component	Function
PV System	Generates DC power based on solar irradiance.
Inverter	Converts DC power from the PV system to AC power for the load.
DEG	Provides backup power and stabilizes frequency fluctuations
Load	Represents the power demand that varies over time.
FLC	Regulates load frequency based on system variations.
BA	Optimizes the FLC for better response
Control System	Manages power distribution between the PV system and DEG.

2.2 DEG System

The DEG system model consists of a diesel engine, speed governor, and droop, all connected to the power system. First-order transfer function blocks are utilized in the model to represent the speed governor and turbine. The system's total generator speed governor droop, or governor droop gain R, is what essentially controls the turbine's velocity. Tsg is the standard time constant for the governor. The simulation's time constant describes the mechanical power output after the governor's reaction, which establishes the diesel engine model. In this simplified model, system inertia is represented by the time constant H, and the damping effect from frequency-dependent loads is represented by an identical gain value D. The DEG and speed governor's transfer function equation are as follows:

$$P_{\deg} = -(\frac{1}{R})(\frac{1}{T_{g.s+1}})(\frac{K_{\deg}}{T_{\deg.\,s+1}}) \quad (1)$$

where:
P_{deg} = Diesel Engine Generator Power, R = Speed Regulation,
T_g = Speed Governor Time Constant,
s = Laplace operator,
K_{deg} = Diesel Engine Gain Constant,
T_{deg} = Diesel Engine Time Constant,
H = System Inertia,
D = Damping Effect.

The model sample data obtained from a textbook on Power System Analysis utilized in this DEG system are given below.

Table 3. *The Parameters for the DEG System*

Model Parameters	Definition	Values
$\frac{1}{R}$	Speed regulation	0.05
D	The ratio of the ΔLoad to ΔF (Damping constant).	0.8
PDEG	Diesel Engine Generator Power	100MW
Tsg	Speed Governor Time constant	0.2s
KDEG	Diesel Engine gain constant	KDEG
TDEG	Diesel Engine time constant	5s
SLP	Step Load Perturbation / Profile	0.3pu
F	Nominal Frequency of the system	50Hz
H	Equivalent inertia constant	10

2.3 PV System

The PV system model is illustrated in Fig. 1. It has two outputs: voltage (V) and current (I). The following expression mathematically represents the PV model:

Output current,

$$I = I_{ph} - I_0 \cdot \left[\exp\left(\frac{q.(V + 1.R_s)}{n.K.N_s.T} \right) - 1 \right] - I_{sh} \tag{2}$$

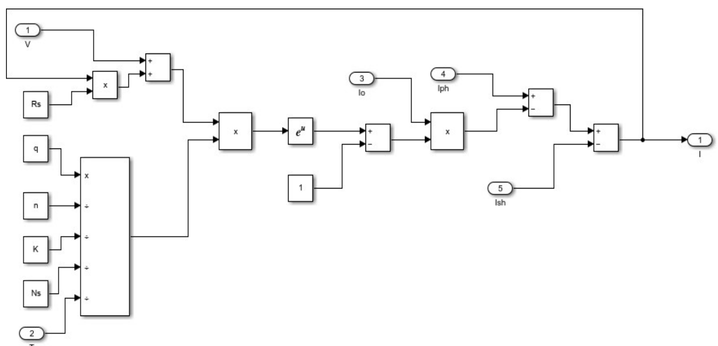

Fig. 1. *The model of the PV System.*

The simulation parameters and values obtained from an existing model utilized in this PV system are given below.

Table 4. *The Parameters for the PV System*

Model Parameters	Definition	Values
Pv	Rated power	200MW
Vmp	Voltage at maximum power (V)	26.4V
Imp	Current at maximum power (A)	7.58A
Iph	Photo-current (A)	Iph
Irs	Reverse saturation current	Irs
I0	Saturation current	I0
Isc	Short circuit current (A)	8.21A
ki	Short-circuit current of the cell at 25◦ C and 1000W/m2	0.0032
T	Operating temperature (K)	T
Tn	Nominal temperature (K)	298
G	Solar irradiation (W/m2)	G
q	Electron charge (C)	1.6 × 10-19
Eg0	Band gap energy of the semiconductor (cV)	1.1
n	The ideality factor of the diode	1.3
K	Boltzmann's constant (J/K)	1.38×10-23
Voc	Open circuit voltage (V)	32.9V
Ns	Number of cells connected in series	54
Np	Number of PV modules connected in parallel	1
Ish	Current through a shunt resistor	Ish
Rs	Series resistance (Ω)	0.221
Rsh	Shunt resistance (Ω)	415.405
Vt	Diode thermal voltage (V)	Vt

The hybrid power system configuration utilized in this study is illustrated in Fig. 2

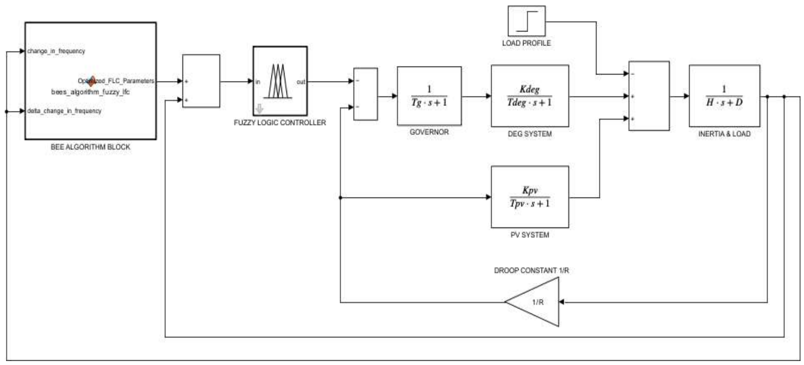

Fig. 2. *The model of the hybrid power generation system.*

From the model, the speed governor in this system senses variations in the generator's speed and modifies the turbine's mechanical output power by controlling the input valve's position [10]. The primary frequency response is the name given to this process. When there is a sudden increase in load, the system frequency is decreased. The governor detects this speed reduction and instructs the turbine to open its valve, thereby increasing the power generation to maintain stable operation. The system frequency is stable at 50 Hz when the generated power aligns with the increased load demand.

Similarly, if there is a sudden decrease in demand, the system frequency experiences an overshoot. Upon detecting a rise in frequency, the governor instructs the turbine to partially close its valve, thereby reducing the power output to maintain stable operation. The frequency then stabilizes at 50 Hz once the generated power matches the reduced load demand. Due to this scenario, the turbine valve functions as the output, while the frequency deviation (ΔF) serves as the input in response to the frequency change.

2.4 A Case Study on the System's Model

A case study was carried out and the following parameters were utilized. The hybrid power system rated 300MW was subjected to a sudden increase in load demand of 90MW.

(Note: Model sample data were obtained from a textbook on Power System Analysis by Hadi Saadat).

1. The system saw an abrupt rise in the demand for a load of 90MW, Therefore, Change in load power in MW,

   $\Delta PL_{MW} = 90MW$

2. The new system power after load change, P_{new}

$$P_{new} = P_{rated} + \Delta PL_{MW}. \tag{3}$$

$P_{new} = 300MW + 90MW = 390MW$

3. Change in load power in Per Unit, $\Delta PL_{p.u}$

$$\Delta PL_{p.u} = \frac{P_{new} - P_{rated}}{P_{rated}} \tag{4}$$

$$\Delta PL_{p.u} = \frac{390-300}{300} = \frac{90}{300} = 0.3\,p.u$$

4. Nominal or reference frequency, $Fref$ = 50 Hz
5. Steady-state change in frequency in Per Unit, $\Delta Fp.u$

$$\Delta F_{p.u} => \frac{1}{R} = \frac{\Delta PL_{p.u}}{\Delta F_{p.u}} \tag{5}$$

Therefore,

$\Delta F_{p.u} = R \times \Delta PL_{p.u}$

$\Delta F_{p.u} = 0.05 \times 0.3 = 0.015$

$\Delta F_{p.u} = -0.015$ (since ΔF is –ve during an undershoot)

6. Steady-state change in frequency in Hertz, ΔFHz

$$\Delta F_{Hz} = \Delta F_{p.u} \text{ x } F_{ref} \ . \tag{6}$$

ΔFHz = -0.015 x 50 = -0.75Hz

7. The new system frequency after load change,

$$F_{new} = F_{ref} + \Delta F_{Hz} \ . \tag{7}$$

$Fnew$= 50 + (-0.75) = 49.25Hz

The system's new frequency after a sudden load increase of 90MW obtained from the Simulation is illustrated below.

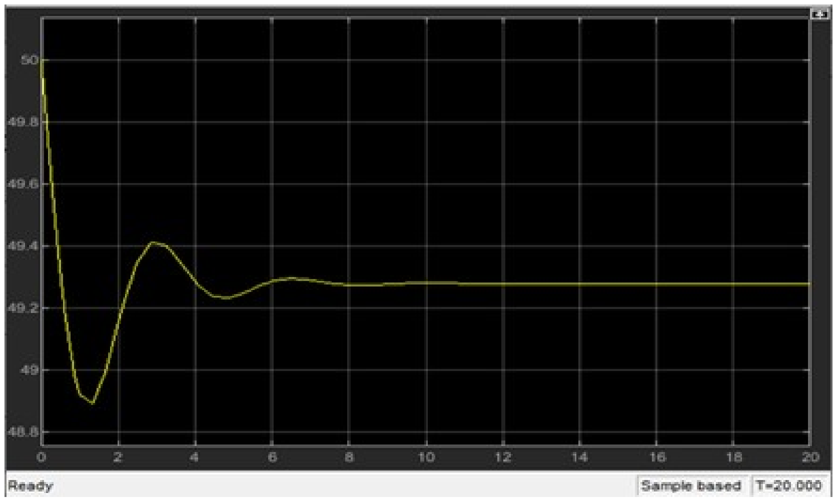

Fig. 3. *The new system's frequency without a controller after a sudden load increase of 90MW.*

From Fig. 3, it was noted that the system frequency remained at 49.25Hz, that is, the frequency did not return to the nominal or reference frequency of 50 Hz and this can be dangerous to the power system by resulting in a system collapse, or imbalance between power generation and load demand.

To correct this, a controller was added to the system, this controller was set to enable the system's frequency to return to the nominal or reference frequency of 50Hz after a load disturbance. This brings the system to a stable point hence ensuring a balance between power generation and load demand. For this, two different controllers were utilized for the system. (PID controller and FLC) and both were compared in terms of rise time, settling time, and overshoot.

2.4.1 PID Controller Design for the System

In a power system, The PID controller is frequently used to return the voltage, frequency, and other parameters to their initial or normal values. But it's crucial to adjust the PID controller's settings. For the system, to return the frequency to the nominal or reference frequency of 50Hz after a load disturbance or increase of 90MW, the PID controller was connected to the feedback loop. The controller was used to tune the system properly to reduce the overshoot and have a faster response. The following transfer function represents the PID controller:

$$P + I\frac{1}{s} + D\frac{N}{1 + N\frac{1}{s}} \tag{8}$$

P = Proportional gain, I = Integral gain, D = Derivative gain, N= Filter Coefficient.

Table 5. *The PID Controller Parameters and their Values.*

Control Parameters	Values
P	17.421
I	15.564
D	0.6332
N	158

The system's frequency after a sudden load increase of 90MW with a PID controller connected to the feedback loop obtained from the Simulation is illustrated below.

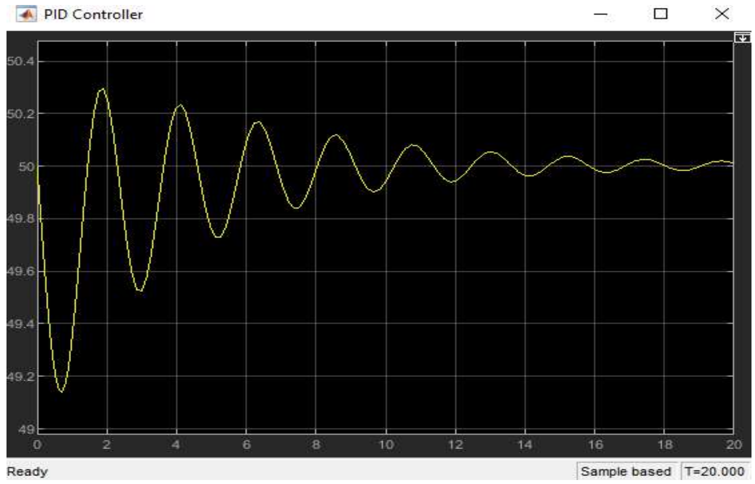

Fig. 4. *The system's frequency with a PID controller connected after a sudden load increase of 90MW.*

2.4.2 FLC Design for the System

Intelligent methods such as Fuzzy Logic have gained significant popularity in research due to their enhanced control performance compared to traditional techniques, owing to their greater resilience and stability. The fuzzy logic concept was introduced by Prof. L.A. Zadeh in 1965[11]. Initially, Zadeh published the foundational ideas of Fuzzy Logic, which offers a more effective approach to handling real-world complexities compared to Boolean algebra because it deals with the trueness of a value from a set point. A FLC system comprises three primary stages: fuzzification, inference engine (also known as the knowledge base), and defuzzification [12]. The FLC is represented in Fig. 5.

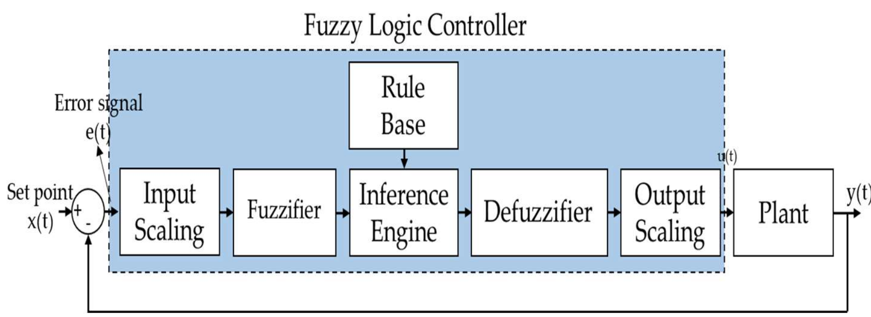

Fig. 5. *Typical structure of the FLC .*

2.4.2.1 Determination of Input and Output Variables.

Defining the range for the input and output variables as a membership function for the PV-DEG power system is essential to give various rules for varying loads.

i. Input Variable

For us to establish the minimum and maximum range for the input, we use the following calculation:

ΔF = Measured frequency - Reference Frequency

Case 1: In the absence of load variations, that is, when the load demand matches the power generation, the system frequency will remain stable at 50 Hz.

Therefore, the ΔF will be 50 -50 = 0 Hz and due to this, the system will be stable.

Case 2: In the case of an increase in load demand, the power system frequency will drop below 50 Hz, and as a result, the system will suffer from an undershoot. The change in frequency for different scenarios may be provided as follows:

ΔF = 47.5Hz – 50Hz = -2.5Hz

ΔF = 49.0Hz – 50Hz = -1.0Hz

Case 3: In the case of a decrease in load demand, the power system frequency will rise above 50 Hz, and as a result, the system will suffer from an overshoot. The change in frequency for different scenarios may be provided as follows:

ΔF = 52.5Hz – 50Hz = 2.5Hz

ΔF = 51.0Hz – 50Hz = 1.0Hz

Given these increases and decreases in load demand, we will assume a frequency change range of ±2 for the system.

Given the change in load demand, the input of the system or change in the frequency range of ±2 and delta change in the frequency range of ±0.5 were used. Therefore,

Input variable = ΔF = [-2 +2] range and ΔΔF = [-0.5 +0.5] range.

This implies that the input range for the frequency changes spans from -2 to +2 and the rate of change in frequency spans from -0.5 to +0.5. Subsequently, these ranges were partitioned into various membership functions to assign specific rules to different input values. However, it may be noted that for the system, the triangular membership function was preferred and utilized due to its simplicity and linearity in the fuzzification approach. The max-min method was used in the aggregation of the input sets. The input range with its corresponding membership functions assigned arbitrarily is illustrated in the following fig. 6.

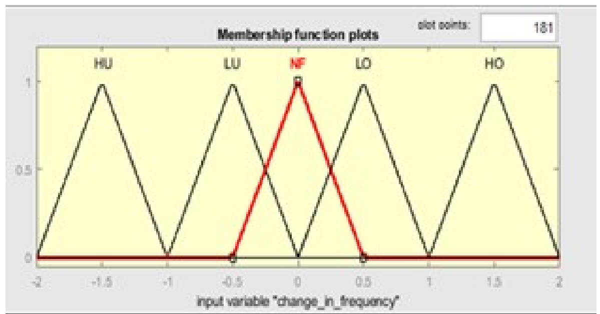

Fig. 6. *Input ranges with membership degree (a).*

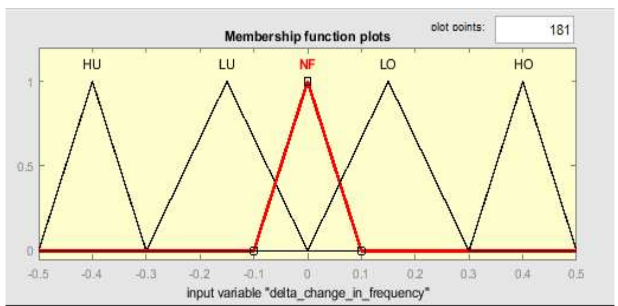

Fig. 7. *Input ranges with membership degree (b).*

where:

HO = High Overshoot, LO = Low Overshoot, NF = Normal Frequency, LU = Low Undershoot, HU = High Undershoot.

ii. Output variable

Next, we need to define the range for the output variable. The turbine valve position ranges from 0 to 1, where 0 denotes Fully Closed and 1 denotes Fully Open. We must divide this output range into several membership functions to apply specific rules to various input values. The turbine valve position or output range and its associated membership functions assigned arbitrarily are illustrated in Fig. 8.

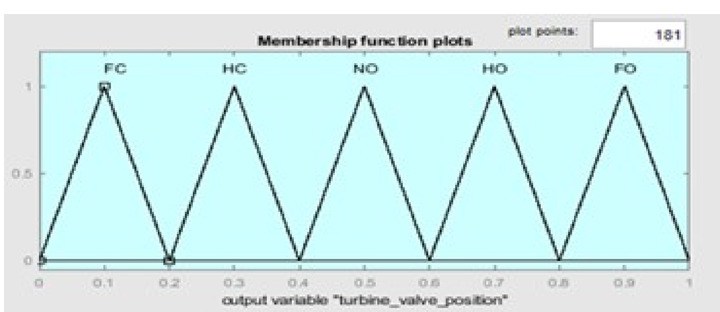

Fig. 8. *Output ranges with membership degree.*

where:

FC = Full Close, HC = Half Close, NO = Normal Open HO = Half Open, FO = Full Open.

2.4.2.2 Fuzzification of Input Variables

Fuzzification, the process of transforming numerical input values into fuzzy sets, is the initial step in fuzzy system computations. Fuzzification is the process of employing membership functions kept in the fuzzy knowledge base to convert exact input values into linguistic variables (terms humans understand). This process turns exact quantities into fuzzy quantities. This system uses the triangular membership functions for the input and output variables to simplify and demand less computing power. The "Mamdani" interface tool is employed for the fuzzification process in this controller. For the fuzzification process, we consider the following cases.

Case 1: For this power system, consider the scenario where a load increase causes the system frequency to drop to 49 Hz.

ΔF = 49.0Hz – 50Hz = -1.0Hz, now this -1Hz is a crisp input number. Next, to convert this precise number into a fuzzy linguistic variable, we need to determine the membership function that the number falls into. Referring to Fig. 7, we observe that a -1Hz change in frequency falls within the membership of LU, indicating that LU represents the fuzzy linguistic variable for a -1Hz change in frequency.

Fuzzy linguistic variable of -1Hz = LU (Low Undershoot)

Rule-based Inference engine

In this stage, we assign decision or control actions based on the fuzzified linguistic input values. To do this, membership functions that define the fuzzy sets and fuzzy IF-THEN rules are used. Next, we formulate the rules for this system and configure them within the FLC.

Rule 1: If the change in frequency is NF and the delta change in frequency is NF rate, then the turbine valve position should be PO. That is, the frequency is at the nominal value and stable. So, the normal position of the turbine valve is partially open reflecting the steady-state power balance and ensuring the system operates at nominal frequency before any disturbance occurs.

Rule 2: In the case of a significant increase in load demand, if the change in frequency is HU and the delta change in frequency is NF rate, then the turbine valve position should be PO. That is, the frequency is significantly below the nominal value but stable; a partial valve opening is required to stabilize the system.

Rule 3: In the case of a significant increase in load demand, if the change in frequency is HU and the delta change in frequency is LU rate, then the turbine valve position should be FO. That is, the frequency is still significantly below the nominal value but dropping slowly; a full valve opening is required to increase power generation and stabilize the system.

Rule 4: In the case of a significant increase in load demand, if the change in frequency is HU and the delta change in frequency is HU rate, then the turbine valve position should be FO. That is, the frequency is significantly below the nominal value and dropping rapidly; a full valve opening is required to increase power generation and stabilize the system.

Rule 5: In the case of a slight increase in load demand, if the change in frequency is LU and the delta change in frequency is HU rate, then the turbine valve position should be FO. That is, the frequency is slightly below nominal and dropping rapidly; a full valve opening is required to increase power generation and stabilize the system.

Rule 6: In the case of a slight increase in load demand, if the change in frequency is LU and the delta change in frequency is LU rate, then the turbine valve position should be PO. That is, the frequency is slightly below nominal and dropping slowly; a partial valve opening is required to stabilize the system.

Rule 7: In the case of a significant decrease in load demand, If the change in frequency is HO and the delta change in frequency is NF rate, then the turbine valve position should be PO. That is, the frequency is significantly above nominal and stable; a partial valve opening is required to stabilize the system.

Rule 8: In the case of a significant decrease in load demand, If the change in frequency is HO and the delta change in frequency is LO, then the turbine valve position should be FC. That is, the frequency is significantly above nominal and rising slowly; a full valve closing is required to reduce power generation and stabilize the system.

Rule 9: In the case of a significant decrease in load demand, If the change in frequency is HO and the delta change in frequency is HO, then the turbine valve position should be FC. That is, the frequency is significantly above nominal and rising rapidly; a full valve closing is required to reduce power generation and stabilize the system.

Rule 10: In the case of a slight decrease in load demand, if the change in frequency is LO and the delta change in frequency is HO rate, then the turbine valve position should be FC. That is, the frequency is slightly above nominal and rising rapidly; a full valve closing is required to reduce power generation and stabilize the system.

Rule 11: In the case of a slight decrease in load demand, if the change in frequency is LO and the delta change in frequency is LO rate, then the turbine valve position should be PO. That is, the frequency is slightly above nominal and rising slowly; a partial valve opening is required to stabilize the system.

The rules for the system from the MATLAB- Simulink is shown below.

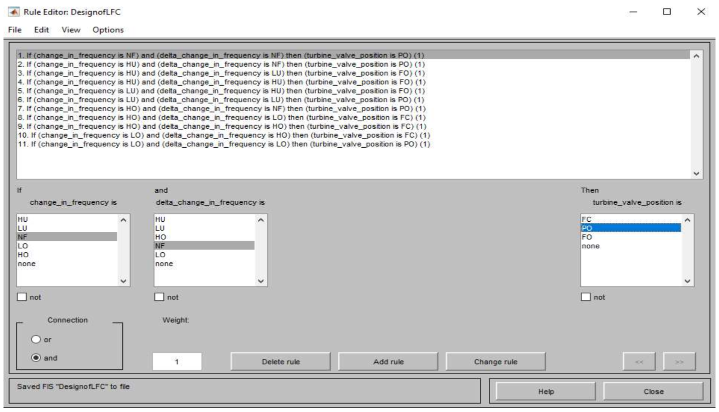

Fig. 9 *Rules for this system are configured within the FLC*

2.4.2.3 Defuzzification Stage

Defuzzification is the process of translating fuzzy values derived from composition into a precise numerical value. Just as fuzzification converts exact values into fuzzy ones, defuzzification translates fuzzy quantities into specific, crisp values. This step is crucial because physical system controllers require discrete signals. For instance, PO represents a linguistic variable rather than a numerical value, so it must be defuzzified into a precise number. According to Fig. 9 this context corresponds to partially opening the turbine valve since the change in frequency and delta change in frequency is NF or 0. The frequency here is stable at the nominal value.

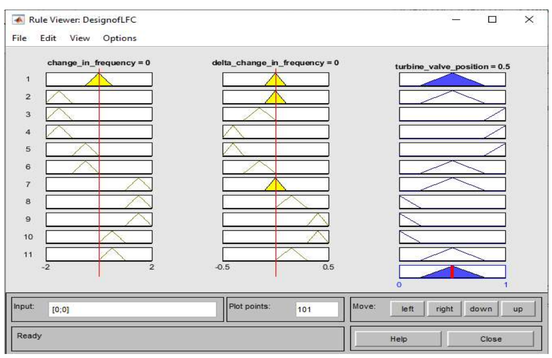

Fig. 10. *Rule viewer of the input variable at about 1 Hz and the corresponding turbine valve position.*

In the defuzzification stage of this study, the fuzzy output variable of the controller is transformed into an exact numerical value using the "Centroid" technique. This method determines the position at which a vertical line would divide the aggregate set-in half. It can be mathematically expressed as

$$COG = \frac{\int_a^b x.\mu_{A(x)} dx}{\int_a^b \mu_{A(x)} dx} \quad (9)$$

COG is the output variable (crisp value), μA (x) is the membership degree and x being the value. The Numerator $\int_a^b x.\mu_{A(x)} dx$ represents the moment about the origin (the first moment). The denominator $\int_a^b \mu_{A(x)} dx$ represents the area under the membership function curve.

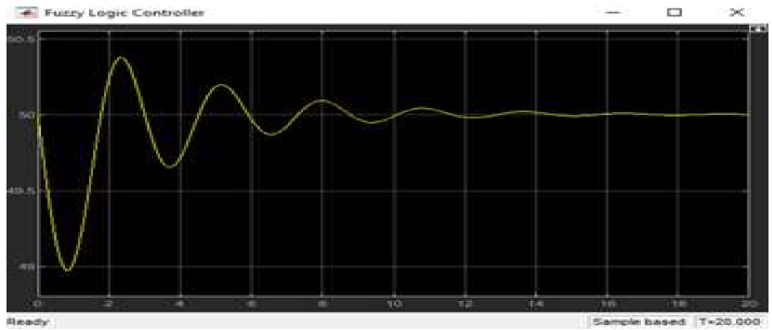

Fig. 11. *The system's frequency with a simple FLC connected after a sudden load increase of 90MW.*

Objective function:

Modern controller design demands both stable performance and a rapid response. However, achieving both simultaneously is often challenging in practice. Therefore, controller design involves balancing quick response with excellent stability, which can be achieved by selecting and tuning the controller through an optimization algorithm that minimizes a well-chosen cost or objective function. Typically, performance criteria that assess the system's total closed-loop response serve as the basis for the objective function utilized to tune the controller.

Using the recommended procedures in this study, the absolute error multiplied by time is integrated using the Integral of Absolute Error (ITAE). This criterion penalizes persistent greater mistakes more severely and concentrates on minimizing errors during the initial transitory reaction. Control systems tuned using ITAE tend to achieve faster settling times compared to those tuned with ISE [13]. The suggested FLC is developed by minimizing the Integral Time Absolute Error (ITAE) cost function. ITAE was chosen because of how well it reduces overshoot/undershoot and settling time. The mathematical formulation of the objective function is given by:

$$ITAE = J = \int_0^{Tsim} t.\,(|\Delta F(t)| + |\Delta\Delta F(t)|)\,dt \tag{10}$$

Where:

J or ITAE = This is the performance index value that the system tries to minimize.

$Tsim$ = The total simulation time over which the performance is evaluated.

ΔF(t) = The frequency deviation, which is the difference between the actual frequency and the nominal frequency at time t (e.g., 50 Hz).

$\Delta\Delta$F(t) = The rate of change of the frequency deviation at time t. t

= Time variable.

2.5 BA

A new optimization technique called the BA was motivated by how honeybees forage for food. This population-based metaheuristic algorithm, first presented by Pham in 2006, finds optimal solutions by imitating the natural search techniques of bees [14].

The BA Mechanism

The suggested BA and the Artificial Bee Colony (ABC) algorithm both utilize local and global search strategies, but they differ significantly in their approach to neighborhood searches. Unlike ABC, which employs a probabilistic method for neighborhood searches, the BA relies on fitness evaluation to guide its search strategy. The BA's flowchart is described in Fig. 12. below. Scout bees are initially dispersed at random around the search area. From greatest to lowest, these scout bees rank the fitness values of the places they visit (for a maximization issue). The best-performing spots are subsequently called "selected sites" and are picked for searches inside neighborhoods. The algorithm does a local search around these selected locations by allocating more bees to the sites that score better and fewer to the sites that rank lower. To choose the finest ones, each site's fitness values are considered. The BA then proceeds to randomly scan the remaining sites in its global search phase. A single bee will be selected for each site throughout the global search phase. One of the three termination requirements, enumerated in the following order, had to be met before the algorithm would stop. If the found answer matches the real optimum value, it is the first thing to check. The number of iterations that were predetermined is attained in the second place. Third, should there be no appreciable improvement to the ensuing solutions [15]. The flowchart of the BA algorithm is represented as Fig. 12.

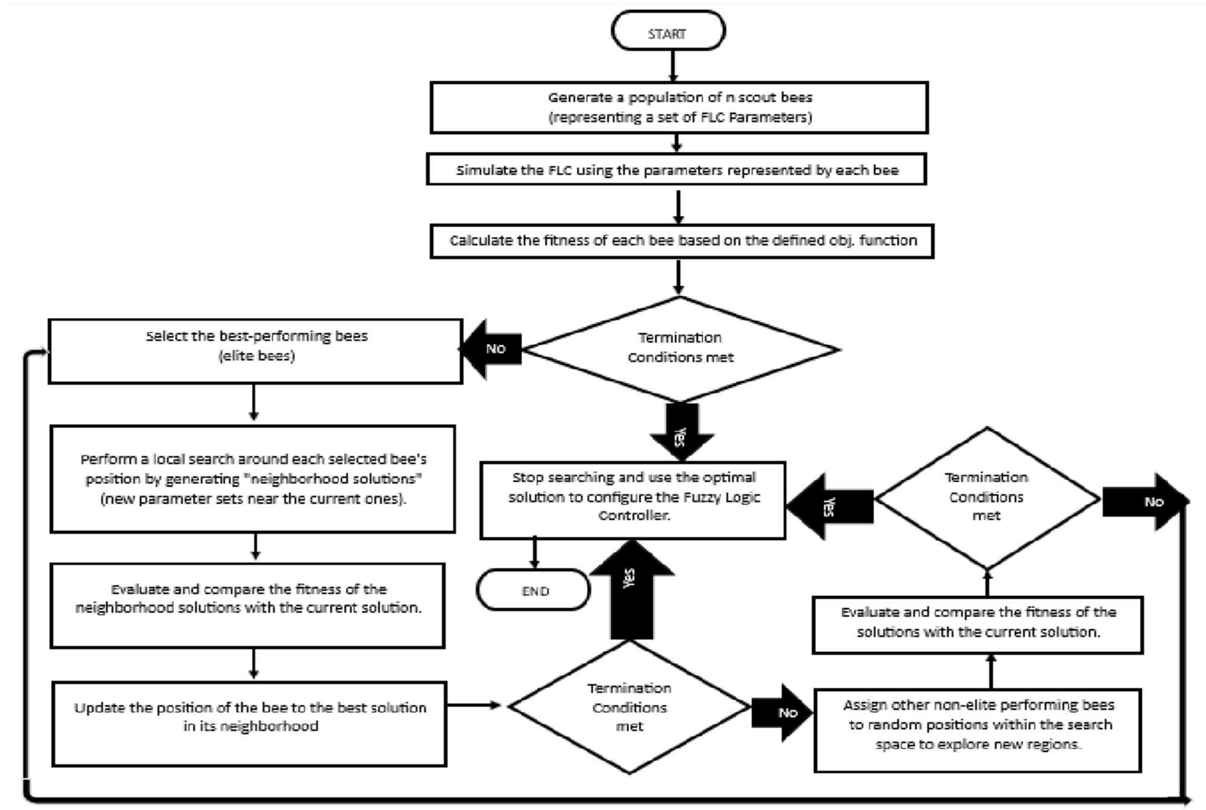

__Fig. 12.__ Flowchart for the BA algorithm

2.5.1 Parameters for the BA

The algorithm requires the configuration of several parameters, such as the number of sites (n), the number of sites chosen for neighborhood search from these n sites (m), the number of top-rated (elite) sites among the m selected sites (e), the number of bees assigned to the best e sites (nep), the number of bees assigned to the remaining (m-e) selected sites (nsp), the neighborhood size for each patch chosen during local search (ngh), and the final criterion. The configuration parameters and their values are obtained from an existing configuration [16] utilized are given below.

Table 6. *The BA Parameters*

Parameters	n	m	e	nep	nsp	ngh	Max. Iteration
Values	30	10	3	10	3	0.1	100

The system's frequency after a sudden load increase of 90MW with a FLC tuned by the BA connected to the feedback loop is represented below.

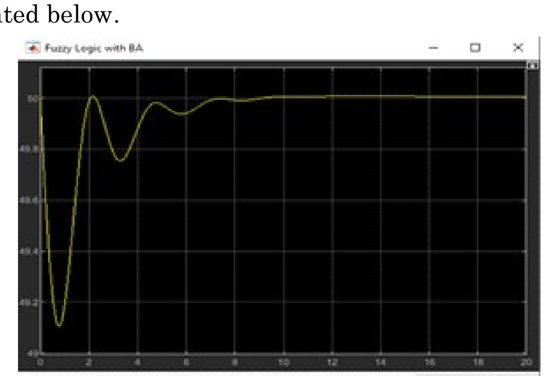

__Fig. 13.__ The system's frequency with a FLC tuned by the BA connected after a sudden load increase of 90MW

3. Results and Discussion

This section describes time-domain simulation research that was carried out on an Intel(R) Core (TM) i5-2450M CPU @ 2.50GHz x64-based processor computer using MATLAB software (2023a). Analysis is also done on the power system's simulation data. The results show that, compared to the PID controller and the simple FLC , the Fuzzy Logic control structures tuned with the BA significantly reduced frequency overshoot, undershoot, rise time, and settling time in the power system. Although, parameters within the system, including the damping coefficient D, speed regulator R, system inertia coefficient H and turbine governor time constant Tg,

are subject to a continuous fluctuation, which can lead to a significant degradation in the performance of close-loop systems. There was comparatively less focus on these issues in the course of this research. The following is how the results are shown.

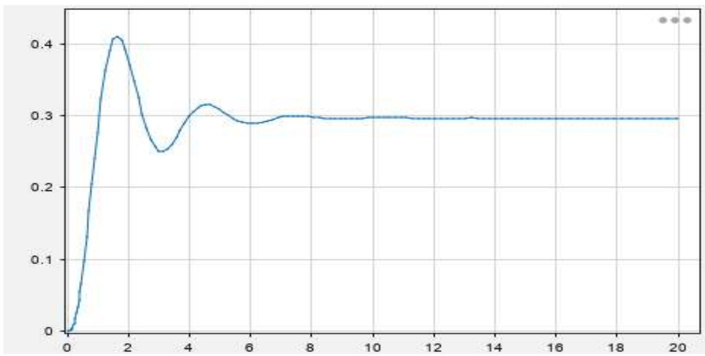

Fig. 14. *Variation in load profile (pu)*

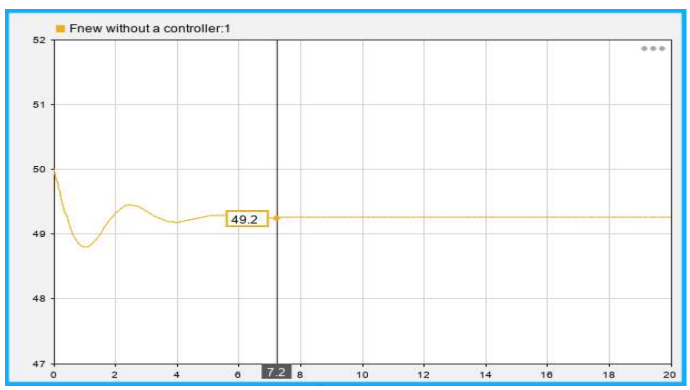

Fig. 15. *Variation in frequency without a controller for 20 seconds*

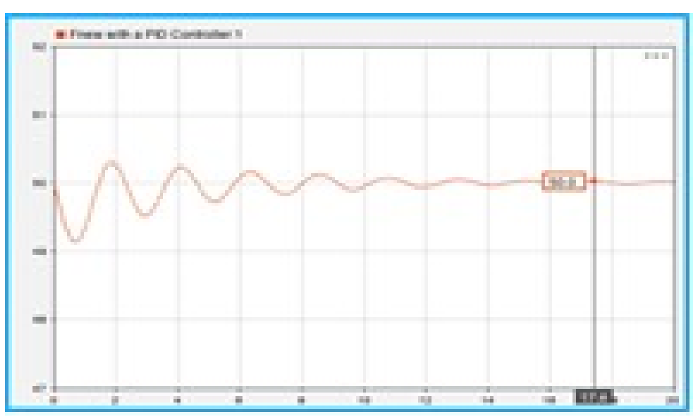

Fig. 16. *Variation in frequency with the PID controller for 20 seconds*

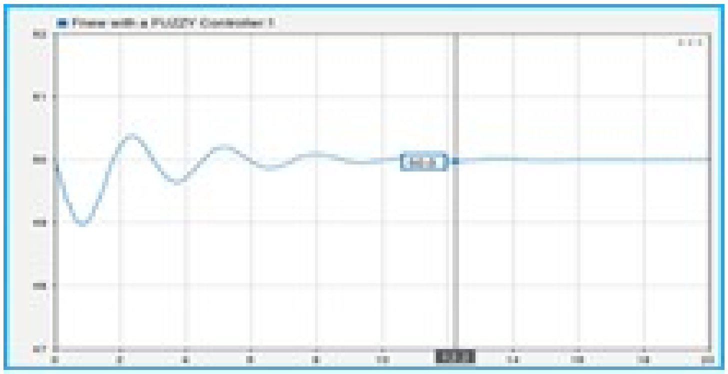

Fig. 17. *Variation in frequency with the simple FLC for 20 seconds*

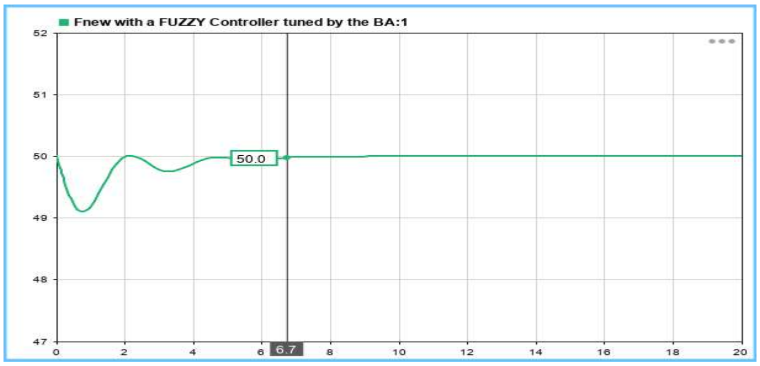

Fig. 18. *Variation in frequency of the FLC tuned by the BA for 20 seconds*

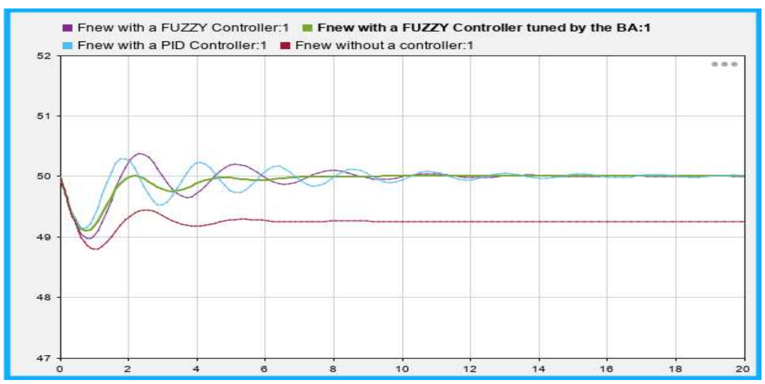

Fig. 19 *Comparison of the frequency variations between the PID controller, the basic FLC, and the FLC tuned by the Bee Algorithm for 20 seconds.*

Table 7. *Performance Evaluation of the Suggested System's Control Methods.*

Transient response / Controllers connected	PID Controller	Non-optimized FLC	FLC tuned by the BA
Error	0	0	0
Rise time (secs)	1.22	0.723	0.41
Settling time (secs)	17.4	12.2	6.7
Overshoot / Undershoot	6.6%	2.1%	0.5%

The performance of three different controllers is evaluated the BA-FLC exhibits the faster rise time which is due to BA's ability to optimize fuzzy logic rules resulting in rapid system response. The settling time indicates that the BA-FLC reduces oscillations, ensuring faster frequency stabilization. This detailed analysis justifies the selection of the BA-FLC approach as the most effective LFC for hybrid power systems.

4. Discussions

The BA-FLC shows superior performance in simulations, but real-world challenges include communication delays, hardware limitations, and cost considerations. Sensitivity analysis and computational efficiency must be assessed for real-time application. Future work should focus on hardware-in-the-loop simulations and microgrid testing for validation.

5. Conclusion and Recommendation

This research explores the use of the BA to optimize the FLC in the LFC of a hybrid system. Commonly utilized traditional PID controllers sometimes struggle to manage frequency variations in these hybrid systems. The simulations show that the BA- optimized FLC considerably decreases frequency deviation more efficiently in the event of a sudden disruption. Compared to the previous study in [10], these results demonstrate that the BA-optimized FLC performs better than the conventional PID controller and the basic FLC in several areas, including settling time, rise time, overshoot, frequency deviation reduction, and transient mitigation. The BA was selected because of its exceptional effectiveness as an optimization tool and its extensive use in LFC.

Compliance with Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows the ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

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