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An Efficient Load Frequency Control for Multiple Power Systems Using Fuzzy Logic-Proportional Integral Derivative Controller

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ABSTRACT- To ensure that customers receive a steady and dependable supply of electricity, power systems must operate and be under control. One of the main problems encountered during interruptions to the system is irregular electrical power flow through interconnected power areas and frequency aberrations. Therefore, the load frequency control system (LFC) was used to reduce frequency variations and provide a stable power flow in multiple-areas power system. This study presents several techniques for controlling the load frequency in two area power systems employing a combination of fractional order proportional integral derivative (FOPID) and fuzzy logic-proportional integral derivative (FPID) controllers and comparing them to conventional controllers (PID). MATLAB/Simulink is used to simulate the overall system. The error is estimated using the integral of time-weighted squared error (ITSE) goal function. In this paper, the settings of the suggested FOPID controller were adjusted using the zebra optimization algorithm (ZOA). Moreover, the settings of the traditional PID controller were modified using a fuzzy logic controller. To evaluate the effectiveness of the controllers and their superiority in handling disturbances, compared each of the controllers using the following three factors: overshoot, settling time, and peak time. The simulation's conclusions indicate unequivocally that the FOPID-ZOA controller works better than the fuzzy-PID and PID-ZOA controllers. Research has improved the quality of the ZOA-based controller FOPID, which is a very successful method for controlling load frequency in two-Area power systems. In the end, customers gain from this distinct solution's substantial contribution to power distribution stability, which guarantees a steady supply of electrical power even in the event of network troubles.

Keywords: Fractional order PID (FOPID); Fuzzy logic-PID; Load Frequency Control (LFC); MATLAB Environment; ITSE function.

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1. INTRODUCTION

The importance of power production has lately grown due to increasing environmental concerns and demand. As a result, using power as effectively as possible is something that both suppliers and consumers naturally demand. Thus, interconnected electrical power systems have been developed to meet the power needs of energy suppliers and consumers [1]. Producing and delivering electricity to consumers at the standard system frequency and voltage range as required by a certain power quality standard is the aim of a power plant. Real and reactive electricity must be created in the electrical systems in such a way that the power generated and demand for load balance each other until consumers utilize the electrical power. Reactive and real power, which are related to both frequency and voltage balance, determine powerful quality. A system's real frequency is set by the balance between the load request and the real electrical power supplied. When the amount of electricity produced is lower than required to meet the load, generating units start to decrease in speed and frequency. In contrast, resource waste occurs when the electricity supplied exceeds the quantity required to run the load. Both frequency and voltage in the electrical system are affected by the frequent random fluctuations in load requirements caused by consumer demands. In order to carry out certain control tasks, an electrical system that regulates both frequency and voltage has to have both an automated voltage regulator (AVR) and a load frequency controller (LFC) [2]. Two major control strategies employed for operating LFC are primary control and supplementary control. If there is an alteration in the load, the governor operates to modify the frequency first through the primary speed control. The governor will attempt to lower the frequency deviation and change the tie line power to zero by modifying the turbine's supplies. An integral operation is used to reduce the frequency variation to zero if the existing controller is unable to eliminate it. To improve the dependability of power networks, load frequency control (LFC) systems that manage real power and power output must be built

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[3]. The frequency stays stable for the following reasons: Variations in system frequency would instantly influence motor efficiency since they directly influence the speed at which three-phase (AC) motors operate. Because both steam turbines and water turbines' blades are designed to operate at a particular speed, variations in frequency will result in an alteration in speed. The resultant excessive vibration will lead to damage to the blades [4]. Suppliers lose money when operating the network at an unpredictable frequency and voltage due to the ensuing drop in load demand. Conventional PID controllers, which are affordable, easy to understand, and easy to operate, have been used in several studies to manage tie-line power and frequency variation. For certain working conditions, their nature has been judged reliable and robust [5]. Power systems demand the creation of sophisticated control schemes capable of efficiently directing and coordinating control operations over several domains. A possible solution to power system complexity is to include fuzzy logic-proportional integral derivative (FL-PID) controllers in LFC systems. Fuzzy logic controllers (FLCs) are an excellent choice for simulating the intricate and dynamic nature of electrical systems because of their superior ability to handle imprecise and uncertain data. Combining the FL-PID controller with the well-known, reliable, and straightforward proportional integral derivative (PID) control makes it an effective instrument for controlling load frequency in multi-system electrical networks. A viable method for adjusting PID controller power system settings is to use fuzzy logic (FL). The integration of different control methodologies presents a promising avenue for delivering resilient, flexible, and effective control, guaranteeing the seamless functioning and dependability of linked power networks. Moreover, PID controllers have the limitation that their settings cannot be changed to account for variations in the load. The PID controller is therefore unable to provide the best possible response for each load variation. Furthermore, this controller only responds to large variations. A study is currently being conducted on a controller (FOPID), and this control structure has excellent features for fluctuations rejection and reliability to high-frequency noise. The majority of methods accessible in the scientific literature do not have a strong capacity to deal with unpredictability in system values in addition to disturbance rejection. Furthermore, it senses both little and big changes and works with non-linear systems. This controller was tuned in order to determine the best settings for changing its characteristics and offering a better response. In the past, the tuning process was carried out by hand, requiring human talent; however, this method is time-consuming and imprecise (Ziegler-Nichols). More recently, sophisticated methods have been developed that are faster, yield more accurate results, and provide a satisfactory response of the system. These methods, often known as "soft computing," include ant colony optimization (ACO), genetic algorithms, and particle swarm optimization (PSO). It is an optimization process that modifies the controller's parameters. On the other hand, objective functions are employed which acts as a language between the system and proposed algorithm to improve the performance. The most well-known functions are (IAE), (ITAE), (ISE), and (ITSE). These standards use one of their equations to determine the inaccuracy in the system for optimal performance. Since ITSE lowers error and overshoot, it was employed since it is necessary. Additionally, the creation and implementation of an ideal load frequency management strategy in various energy systems utilizing FOPID controllers based on the ZOA algorithm it is also an important focus of this research. In the context of linked energy systems, it is anticipated that the use of ZOA optimization in conjunction with FOPID controllers will enhance the resilience and dynamic response of LFC. Additionally, the goal of this suggested method is to maximize frequency control, reduce variations, and improve multi-area power systems' overall stability. The suggested method is then compared to both the standard PID and fuzzy-PID controllers in the study to see which is superior. The following sections of this study will discuss the FOPID-based ZOA algorithm and the fuzzy-PID controller for load frequency management in multiple electrical systems, including their mathematical modeling, design, and simulations. This study adds to the continuing efforts to improve the reliability and effectiveness of power networks in a contemporary, interconnected world by tackling the crucial problem of load frequency regulation in a more sophisticated and optimal manner. This article is divided into multiple sections: *Section 2* depict the modeling of power system; *Section 3* depict the modelling of controllers; Section 4 depict the criteria evaluation function; *Section 5* depict Implementation of the ZOA algorithm; *Section 6* depict results and discussion; *Section 7* depict the conclusion.

2. MODELLING OF A POWER SYSTEM

Simulation and analysis of the dynamic action of linked power networks are performed using a two-area power system model. This configuration in *fig. 1* makes up two generating areas, each having its own collection of governors, turbines, generators, and loads. For balancing power generation and load demand, these parts operate together to provide steady system performance. As seen in *fig. 1*, a two-area network has two frequency deviations: Δf1 for area 1 and Δf2 for area 2. Both areas' control errors (ACE) are sent to the controller [6],[7]. A study of the power system in two areas, comprising the controller unit and LFC approach, is shown in *fig. 1*.

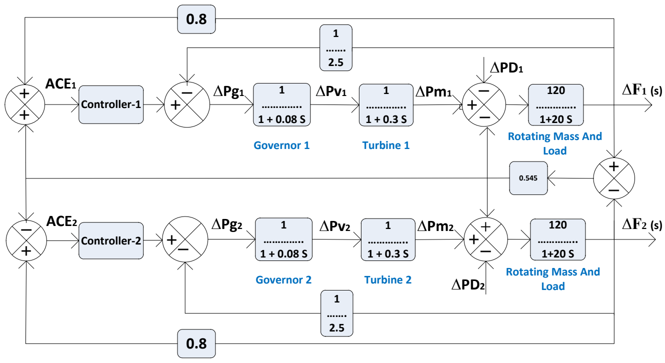

Figure. 1 Block Scheme of a Two-Area LFC [8]

The disturbance variations in load are denoted by ΔPd1 and ΔPd2. Ref.[8] Contains the standard values for all parts of the

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power system. The definition of area control errors for the two areas is as follows:

$$ACE_1 = B_1\,\Delta F_1 + \Delta P_{12} \quad (1)$$

$$ACE_2 = B_2\Delta F_2 + \Delta P_{12} \quad (2)$$

Where the frequency variations for each region are expressed by ΔF_1 and ΔF_2, the frequency bias constants for each area are B1 and B2, and the change in the tie-line power plant is expressed by ΔP_{12}.

3. MODELLING OF CONTROLLERS

In order to maintain power flow between areas throughout disturbances and control system frequency, this research employed a variety of controllers in a two-area power grid. It also examined the robustness of these controllers against disruptions. Errors in control systems can come from a variety of causes, such as inaccurate sensors, faulty modeling, disruptions, etc. Control engineers use exact computational techniques to improve controller settings in order to eliminate these errors. They do this by improving system efficiency and minimizing error to the lowest possible level through the use of optimization strategies, feedback control, adaptive control, and resilient control approaches. The kind of control system and the particular control objectives determine which technique and which algorithms to use.

3.1. Proportional Integral Derivative (PID) Controller

An essential part of control systems is a PID controller, a conventional control device that adjusts a system's output—like a power grid's frequency—in accordance with shifting loads. Its capacity to maintain a stable frequency by modifying control inputs in response to the system's present error, integral of error, and rate of variation in error is its key relevance in LFC. This guarantees a dependable and effective power supply by allowing it to mitigate the impacts of load disruptions and preserve grid stability. The PID controller has three basic parameters (KP, Ki, Kd). KP is utilized to reduce the rise time, Kd is utilized to reduce overshoot and setting time, Ki is utilized to remove the steady-state error [8].

3.2 Fractional Order Proportional Integral Derivative (FOPID) Controller

An improved version of the conventional PID controller is the Fractional Order Proportional-Integral-Derivative (FOPID) controller. The degree of freedom is increased by two using a FOPID compared to an integer-order PID controller. It has five variables as shown in *fig. 2* (KP, KI, and KD) that reflect gains of the derivative, integral, and proportional sections; (λ) specifies the integrator ordering, and (μ) defines the derivative ordering [9]. Additionally, it offers superior stability in nonlinear systems, resilience to high-frequency noise, the capacity to deal with parameter uncertainty, and the capability to eliminate steady-state error [10, 11].

$$C_{(S)} = K_P + \frac{K_I}{S^{\lambda}} + K_D S^{\mu} \qquad \lambda, \mu > 0 \ \ [11] \qquad (3)$$

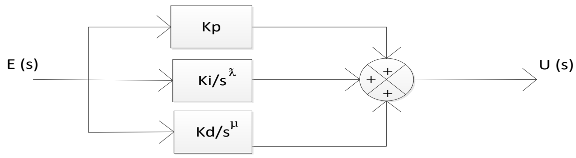

Figure 2. Block Diagram of the FOPID Controller with the System

3.3 Fuzzy Logic Controller (FLC)

Several professional systems and artificial intelligence techniques use a type of logic called a fuzzy logic controller. This kind of analysis of data was developed in 1965 by the Azerbaijani scientist "Lutfi Zadeh" with the intention of using it more effectively. The fuzzy logic controller depends on fuzzy notions and provides a way to convert language control techniques that rely on human experience into intelligent control methods. Fuzzy logic controllers work best when there is uncertainty or incomplete data [5]. Two distinct classes of inference techniques are the Mamdani and Sugeno inference systems. FIS-based mamdani is widely used by most researchers and various experts because it allows specialists to present the model in a more typical and human-like manner than sugeno. The fuzzy logic controller consists of different components as shown in the *figure 3*.

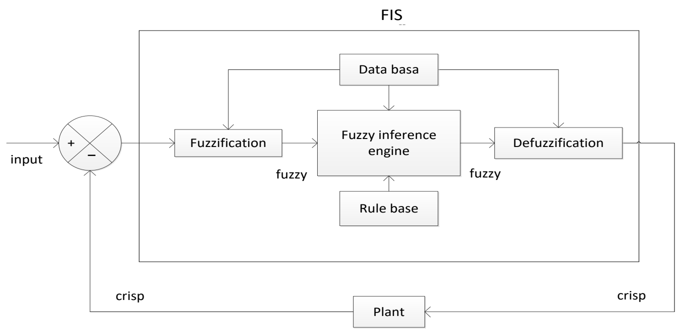

Figure 3. Block Structure of Fuzzy Controller.

In this research, a fuzzy logic controller is used to tune the parameters of a PID controller as shown in *figure. 4*, and after that, it will be compared with PID-ZOA and FOPID-ZOA.

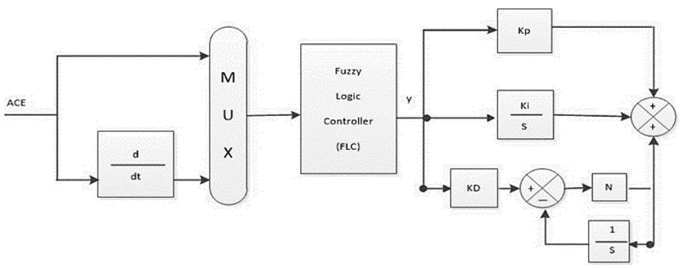

Figure 4. Block Structure of Fuzzy-PID Controller [12]

The area control error (ACE) and the change in area control error (ACE) are utilized as the fuzzy controller's input parameters. A fuzzy controller uses linguistic variables as inputs to handle the area control error. Each of the input values was divided into seven membership functions using combinations of trapezoidal and triangular membership

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functions, as shown in *figures. 5 and 6*. NB (negative big), NM (negative medium), NS (negative small), ZO (zero), PS (positive small), PM (positive medium), PB (positive big).

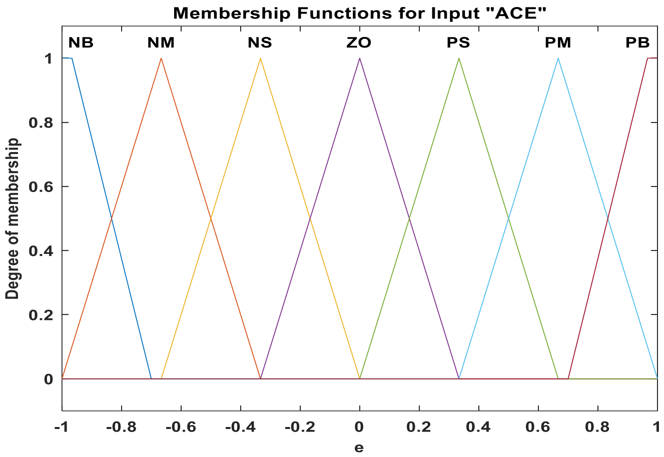

Figure 5. Membership Function for ACE

Each aspect of the membership functions is represented by a membership degree in the input space, which is called the Universe of Discourse.

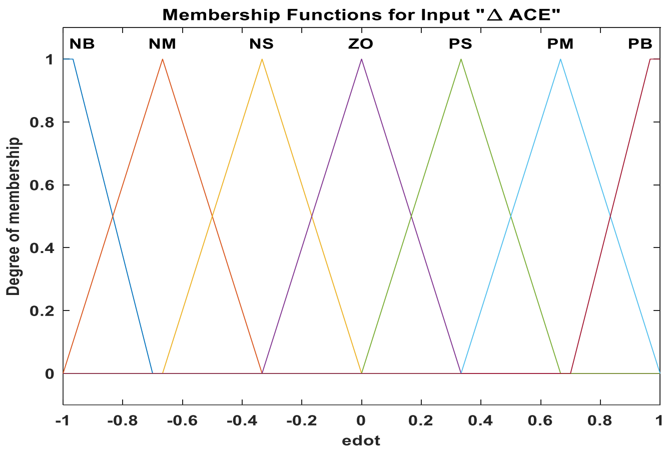

Figure 6. Membership Function for ∆ ACE

4. CRITERIA EVALUATION FUNCTION

The goal of the evaluation function is essential for determining errors in any system. It acts as a communicative bridge between the system and the process of optimization. Among these standards, some of the most famous are IAE, ITAE, ISE, and ITSE; all of these are essential criteria for assessing errors according to formulae of all kinds. Compared to other standards, the ITSE metrics are highly sensitive, preserve durability, and generate fewer disturbances and overshoots, making them useful criteria for control system development [13]. The following is the equation for the ITSE criteria that will be used to compute the error:

$$ITSE = \int_0^T t \,\{ \Delta_{F1}{}^2 + \Delta_{F2}{}^2 + \Delta_{Ptie\,12}{}^2 \}\, dt \qquad (4)$$

5. IMPLEMENTATION OF ZEBRA OPTIMIZATION ALGORITHM (ZOA)

The Zebra Optimization Algorithm (ZOA) is a novel bio-inspired meta-heuristic technique that takes its primary motivation from zebra behaviour in its native habitat. ZOA mimics the eating patterns and defense techniques used by zebras to fend off predator attacks. Meta-heuristic algorithms, which integrate the concepts of discovery and exploitation, are employed to address optimization problems. The algorithm's ability to fully search the search area and identify the optimal place is referred to as "discovering." The concept of exploitation represents the algorithm's ability to locally search inside a search region and drift to the most suitable solution. Two of the zebras' in-wild behaviours are used to update ZOA individuals. In the beginning, members of the neighbourhood are updated based on a zebra feeding pattern. As the most useful leader of the group, the pioneer zebra signals to other individuals where it is in the eating area. Secondly, a zebra defensive vs. predator assault model is used to update the position of the ZOA people within the neighbourhood in the search region. Every zebra is a potential solution to a problem.

The details of this technique are shown in the flowchart in *figure. 7*. The equations of the zebra optimization algorithm found in the flowchart are depicted in Ref. [14].

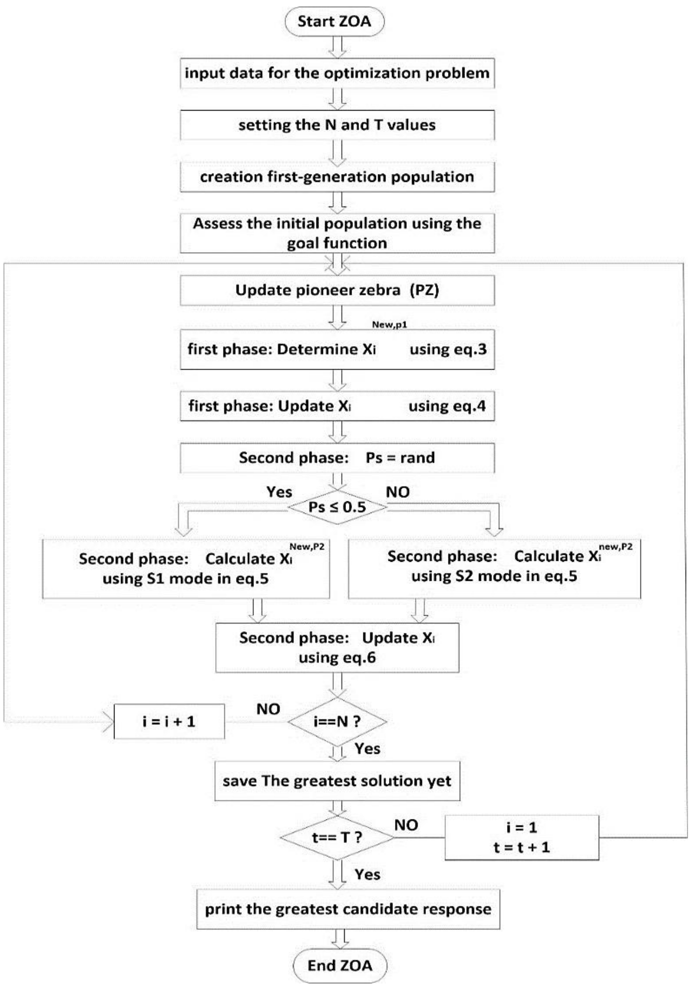

Figure 7. flowchart of Zebra optimization algorithm

6. RESULTS AND DISCUSSION

This part covers and analyses the results of the research, which included setting up a conventional PID controller with a fuzzy logic controller to control load frequency in a two-area power grid. The controller was then contrasted to a fractional-order proportional integral derivative controller to determine which was superior. Also was adjusted the settings of the FOPID controller using a unique optimization technique called the Zebra optimization algorithm. Three main factors were compared in order to evaluate the controller's performance: overshoot: This metric measures how much the control system's response goes beyond the intended set point before stabilizing; peak time is the amount of time it needs for a system dynamic (like voltage or current) to reach its maximum value in the dynamic nature of the system following a disturbance or change in the steady-state condition; and settling time is the amount of time needed for the control system's output to settle within a specified range of the set point following a disturbance. After that, load fluctuations will be applied to the system to determine the correctness of the controllers. *Table 1* shows the parameter values of the controllers designed in the two-area power system. *Figure. 8* shows the objective function curve.

Table 1. Controllers Parameters of PID and FOPID for Two Area

Variable	Area 1	Variable	Area 2
PID	$P_1 = 0.7$ $I_1 = 1.8$ $D_1 = 0.758$	PID	$P_2 = 1.9$ $I_2 = 0.014$ $D_2 = 0.68$
FOPID	$P_1 = 1.2$ $I_1 = 1.9$ $\lambda_1 = 1.2$ $D_1 = 1.8$ $\mu_1 = 0.54$	FOPID	$P_2 = 0.95$ $I_2 = 0.014$ $\lambda_2 = 0.4$ $D_2 = 0.6$ $\mu_2 = 0.5$

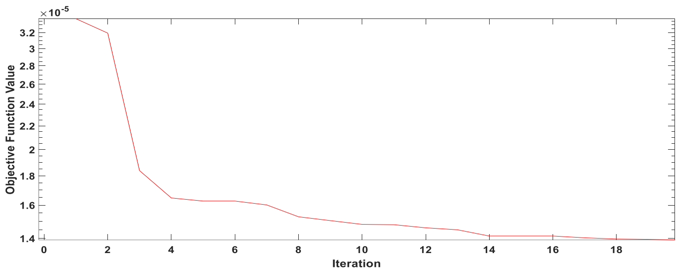

Figure 8. Iteration of the ZOA Algorithm

Generally, the goal function shape converges to an ideal position as the algorithm advances. According to the nature of the issue, this point of convergence means that the algorithm is coming closer to an approach that decreases or increases the goal function. The way the curve appears gives information about what values of the parameters or factors lead to the greatest results. The selected two-step load perturbation (0.01 and 0.02) is used to evaluate the robustness and effectiveness of the fuzzy-PID and FOPID-ZOA controllers. *Tables 2–4* display the transient response characteristics in the context of peak time, maximum deviation, and settling time for (ACEij), (ΔFij), and (ΔPij). *Table 5* displays the two area model variables.

Table 2. ACEij Parameters using PID, FUZZY-PID, FOPID and ZOA depending on ITSE

Variable		Settling time (sec)	Overshoot (p.u)	Peak time (sec)
PID	ACE1	20	0.013	2
	ACE2	20	0.0063	2.2
FOPID	ACE1	12	0.0114	1.8
	ACE2	13	0.0045	1.7
PID-ZOA	ACE1	18	0.0108	1.9
	ACE2	18	0.006	2
FUZZY-PID	ACE1	8	0.0085	1
	ACE2	8	0.0027	1.5
FOPID-ZOA	ACE1	3	0.0082	0.5
	ACE2	5	0.0031	1

The area control error for two load disruptions is shown in *figures. 9 and 10*.

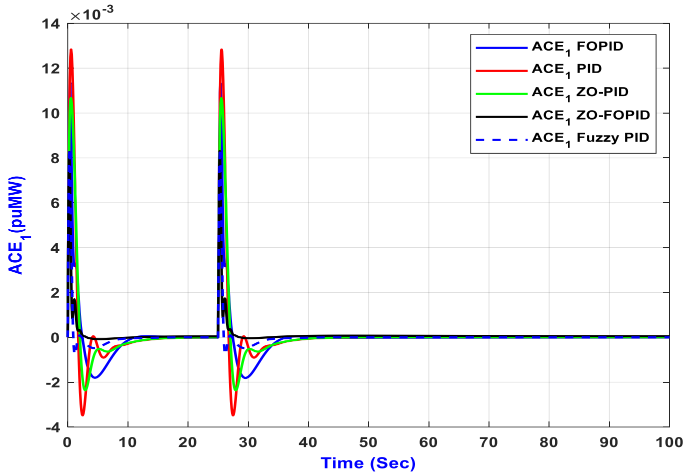

Figure 9. ACE1 Using PID, FOPID, Fuzzy-PID Based on ZOA Algorithms

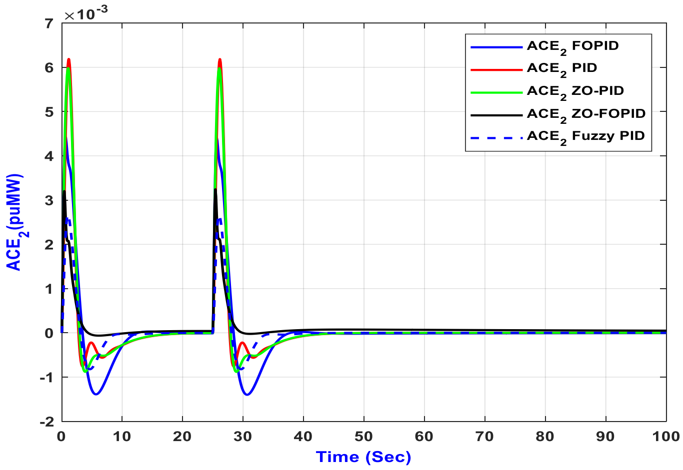

Figure 10. ACE2 Using PID, FOPID, Fuzzy-PID Based on ZOA Algorithm

A lower ACE value indicates improved control system efficiency. The findings, which are shown in *table 1*, show that

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the FOPID controller, which uses the Zebra optimization algorithm, outperforms the fuzzy-PID controller and PID-ZOA in three areas. Interestingly, it is noted that with the FOPID controller, the system's stability period following a disturbance is very short. This shows the FOPID controller can promptly bring stability back and is effective in manipulating the system during disruptions.

Figure. 11 compares the variations in tie-line power for two disruptions in load between the Fuzzy-PID, FOPID-ZOA, and PID-ZOA controllers. The research results, which are shown in *table 3*, show that the FOPID controller, which depends on the Zebra optimization algorithm, outperforms the fuzzy-PID controller in three categories.

Table 3. ΔPij Parameters using PID, FUZZY-PID, FOPID and ZOA depending on ITSE

Variable	Settling time (sec)	Overshoot (p.u)	Peak time (sec)
PID	17	0.005	2
FOPID	13	0.0027	1.5
PID-ZOA	15	0.0037	1.7
FUZZY-PID	8	0.0022	0.8
FOPID-ZOA	5	0.0013	0.5

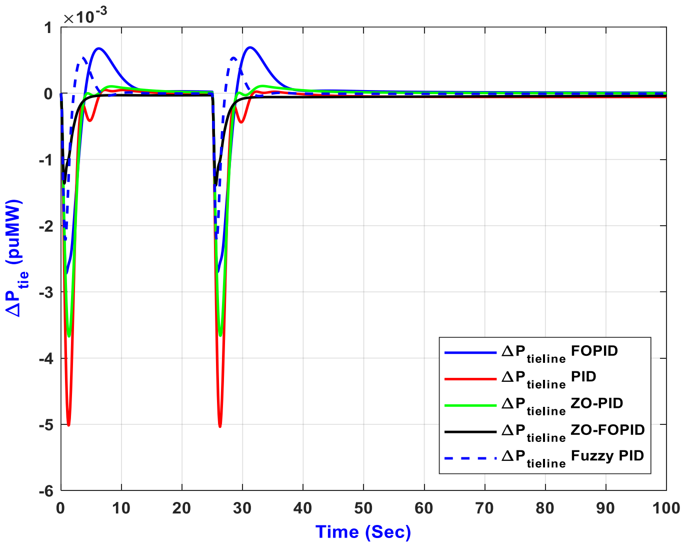

Figure 11. ΔP12 Using PID, FOPID, Fuzzy-PID Based on ZOA Algorithm

Figures. 12 and 13 in this research show the frequency variation response for two disruptions to the load. The analysis shows that the Zebra optimization algorithm-based Fractional Order Proportional-Integral-Derivative (FOPID) controller performs better than the fuzzy-PID controller. *Table 4* documents the three primary criteria that show this superiority: peak time, overshoot, and settling time. The results presented here highlight the FOPID controller's improved control ability in managing frequency variances within the system.

Table 4. ΔFij Parameters using PID, FUZZY-PID, FOPID and ZOA depending on ITSE

Variable		Settling time (sec)	Overshoot (p.u)	Peak time (sec)
PID	ΔF1	18	0.013	1.9
	ΔF2	22	0.0017	1
FOPID	ΔF1	16	0.012	1.4
	ΔF2	19	0.0027	0.8
PID-ZOA	ΔF1	13	0.011	1.6
	ΔF2	17	0.0034	1.3
FUZZY-PID	ΔF1	9	0.009	1
	ΔF2	13	0.0019	1.5
FOPID-ZOA	ΔF1	5	0.008	0.5
	ΔF2	10	0.0025	0.5

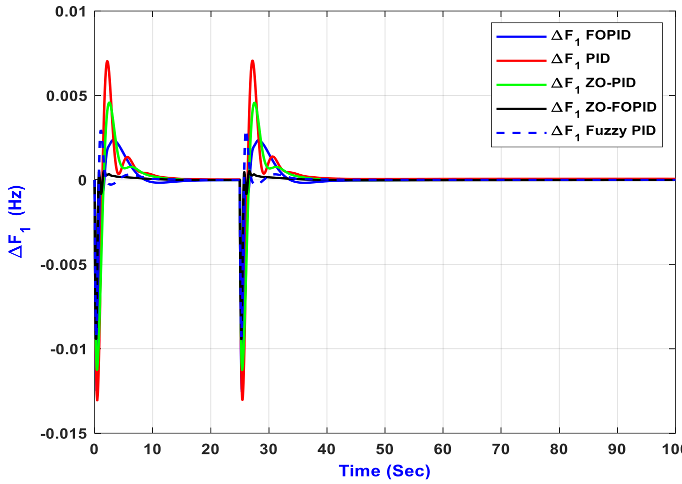

Figure 12. ΔF1 Using PID, FOPID, Fuzzy-PID Based on ZOA Algorithm

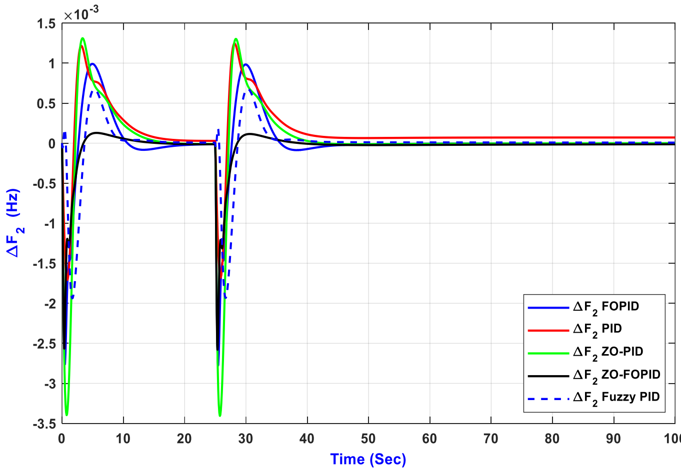

Figure 13. ΔF2 Using PID, FOPID, Fuzzy-PID Based on ZOA Algorithm

It can be shown from the figures that in load frequency control systems, the Fractional Order Proportional-Integral-Derivative (FOPID) controller performs better than a Fuzzy-PID controller and conventional PID. FOPID controllers can be helpful in load frequency control (LFC) systems for the following primary reasons:

- Non-Integer Order Control: The ability of FOPID controllers to use non-integer (fractional) orders for the derivative, integral, and proportional terms is by far their greatest benefit. A greater variety of control actions are therefore made possible.
- The FOPID controller gives the power system more stability at the price of increasing the level of freedom over the PID controller by two factors (λ, μ).
- Enhanced resilience is provided by FOPID controllers, particularly when there are ambiguities and fluctuations in the system values. The controller may be tuned to manage certain system features thanks to the fractional orders, which also increase its adaptability to variations in the load or generation.
- Addresses both non-linear and linear systems.

Table 5. The Two-Area Power System Elements

Characterization	A1	A2
F	60 Hz	60 Hz
K_{PS}	120 Hz/Pu MW	120 Hz/Pu MW
T_{PS}	20 s	20 s
T_G	0.08 s	0.08 s
T_T	0.3 s	0.3 s
K_R	0.33	0.33
T_R	10 s	10 s
2ЛЬT12	0.545 Pu MW/Hz	0.545 Pu MW/Hz
β	0.8 Pu MW/Hz	0.8 Pu MW/Hz
R	2.5 Hz/Pu MW	2.5 Hz/Pu MW

7. CONCLUSIONS

Load frequency management is essential as it preserves the reliability of the power system by regulating electricity between supply and demand, which is made necessary by the complexity of contemporary power systems. A two-area power system was employed in this work. MATLAB Simulink was utilized in this work to model the power system. A comparison was done among the controllers, which included the classic PID and fuzzy-PID controllers as well as the suggested FOPID controller, in order to sustain frequency variances and variations in tie-line power. Three factors are compared: overshoot, settling time, and peak time. Two load disruptions, 0.01 and 0.02, respectively, were used to assess the controllers' appropriateness. To compute the error, the goal function ITSE was employed. Research results showed that by lowering variance in frequency and tie-line power fluctuations, the FOPID controller outperformed the conventional PID controller system and fuzzy-PID controller. The Zebra Optimization technique is a novel method whose primary motivation was to modify the system variables. It is also used in research to optimize the LFC system. Depending on each controller's ZOA algorithm, the controllers' operational performance was also contrasted. The FOPID-ZOA controller outperforms the conventional PID_ZOA controller and Fuzzy-PID controller, according to the simulation findings, The FOPID-ZOA controller provides reduced overshoot, better stability, and decreased variation in frequency and tie-line power fluctuations. Additionally, the FOPID controller showed remarkable robustness versus high-frequency noise, outstanding rejection of disruption properties, and remarkable capacity to handle uncertainty in system variables. Together, these characteristics highlight the FOPID controller's versatility and appeal, making it a viable choice for efficient load frequency management in power systems.

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