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An Optimal Load Frequency Control in a Two-Area Power System Using a Fractional Order Proportional-Integral-Derivative-Based Zebra Optimization Algorithm

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ABSTRACT- Load frequency control systems are crucial for maintaining the stability and reliability of power grids. They help ensure that the power supply matches the demand, preventing fluctuations in grid frequency. However, Load frequency control systems have inherent limitations, such as the potential for instability and oscillation if not properly controlled. In this work, A fractional order proportional integral derivative controller is proposed to address this issue, which exhibits strong capabilities in managing parameter uncertainties, rejecting disturbances, and handling non-linear systems controllers. The novel approach in this search is the application of the zebra optimization algorithm to fine-tune controller parameters, a technique not previously used in load frequency control systems. In this Study the two-area power system with a reheat turbine is used a test case for fractional order proportional integral derivative controller, and the system is simulated using MATLAB/SIMULINK. The objective function integral time of square error is used that acts as a bridge of communication between the system's behavior and the control strategy. The performance of this controller is evaluated under disturbance 0.04. The results of the analysis demonstrated that the fractional order proportional integral derivative based zebra optimization algorithm controller outperformed the traditional fractional order proportional integral derivative controller in terms of three essential criteria: overshoot, settling time, and steady-state error. This research contributes to the advancement of load frequency control systems, ensuring reliable and stable power system operation.

Keywords: Fractional order PID (FOPID), Integral time square error (ITSE), Load Frequency Control (LFC), MATLAB Environment, and Zebra Optimization Algorithm (ZOA).

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1. INTRODUCTION

Due to rising demand and increased environmental consciousness, the relevance of energy generation has recently increased. Therefore, it is a natural expectation of both manufacturers and consumers to utilize electricity as efficiently as possible. Hence, in order to satisfy the energy requirements of both energy providers and customers, linked electrical power networks have been created [1].The automated voltage Regulator (AVR) and load frequency controller (LFC), which are installed on every generator in a power system with both frequency and voltage regulation, are thus required to perform specific control operations [2]. Primary control and supplemental control are the two main control methods used to implement LFC. The main speed control performs the first re-adjustment of the frequency with tie-power by the operation of the governor if the load changes. By adjusting the inputs to the turbine, the governor will make an effort to reduce the frequency and tie line power variation to zero. If the frequency deviation does not go away after the current controller, an integral operation is utilized to decrease it to zero. It is vital to construct load frequency control (LFC) systems that regulate actual power and power production to increase the reliability of power networks [3]. Most of the techniques available in the literature do not have a good ability to deal with uncertainties in system parameters as well as good perturbation rejection, so work has been done on a controller (FOPID), and this control unit has a good ability to deal with uncertainty in the parameters and also has excellent characteristics for turbulence rejection and robustness to high-frequency noise. In addition to that, it deals with non-linear systems and also senses small and large changes. To select the optimal settings for the controller to alter its parameters and provide a better response, a tuning procedure is required for this controller. Historically, the tuning procedure was manually performed, requiring human skill, but this approach consumes time and is inaccurate (Ziegler-Nichols). Modern techniques have recently emerged that take less time, produce precise findings, and respond to the system satisfactorily. These techniques, often known as soft computing, use a variety of optimization techniques, including ant colony optimization (ACO), genetic algorithms, and particle swarm optimization (PSO). It is an optimization procedure used to change the controller's settings. Objective functions are used because they serve as the language of communication between the technology and the system [4]. They consist of a set of standards that determine the improvement of the system. These standards take the error from the system and calculate it with one of their equations, then send it to the technology to inject the system with the best parameters for the best performance. The most famous of these standards are (IAE), (ITAE), (ISE), and (ITSE). ITSE was used as it reduces error and overshoot, and this is what is required. This research paper focuses on the development and application of an optimal load frequency control strategy in multiple power systems using FOPID controllers based on the ZOA algorithm. The utilization of FOPID controllers with ZOA optimization is expected to improve the dynamic response and robustness of LFC in the context of interconnected power systems. The proposed approach aims to achieve optimal frequency regulation, minimize deviations, and enhance the overall stability of multi-area power systems. In the subsequent sections of this paper, we will delve into the mathematical modelling, design, and simulation of the FOPID-based ZOA algorithm for load frequency control in multiple power systems [5]. Additionally, comprehensive analysis and comparative studies will be presented to highlight the effectiveness and advantages of the proposed approach. By addressing the critical issue of load frequency control in a more advanced and optimized manner, this research contributes to the ongoing efforts to enhance the stability and efficiency of power systems in a modern, interconnected world.

2. MODELING OF A TWO-AREA POWER SYSTEM

The transfer function approach and the state variable approach are the two favoured techniques for mathematically describing a control system at the initial stage of its study and design [6]. A two-area power system model is used to simulate and analyse the dynamic behaviour of interconnected power systems. *Figure 1,* illustrates the investigation of the two-area power system's overall power system, which includes the LFC model and controller unit.

ΔPd_1 and ΔPd_2 are the disturbance load changes; Δf_1 and Δf_2 represent the frequency deviation in each power system. The whole power system's standard parameters are provided in [7]. The area control errors of both areas are defined in *equation 1* and *equation 2*.

$$ACE_1 = B_1\,\Delta F_1 + \Delta P_{12} \tag{1}$$

$$ACE_2 = B_2 \Delta F_2 + \Delta P_{12} \tag{2}$$

Where the frequency variations for each region are expressed by ΔF_1 and ΔF_2, the frequency bias constants for each area are B_1 and B2, and the change in the tie-line power plant is expressed by ΔP_{12}.

In *equation 1*, ΔP_{12} represent the Change in The Tie-Line Power, B1, B2 represent the Frequency Bias Constants, ΔF_1, ΔF2 represent the Frequency Deviations. MATLAB/Simulink is used to simulate a power system spanning two areas. Using parameter values obtained from a reliable source [7][8]. The evaluation of proposed controllers under various scenarios will help assess their effectiveness in regulating the power system. *Figure 2,* explain the power system for two area using MATLAB.

Figure 1 Block Structure of Two Area Load Frequency control [9].

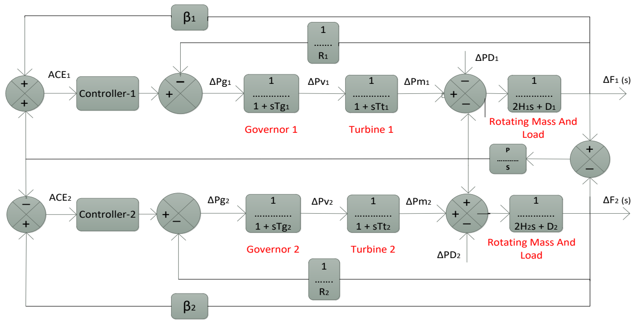


Figure 1. Block Structure of Two Area Load Frequency control [9][10]

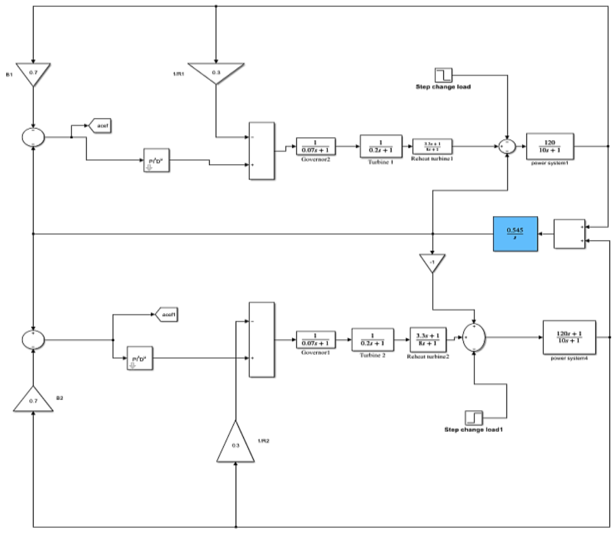


Figure 2. MATLAB Simulink of Two Area Load Frequency Control

3. PROPOSED CONTROLLERS

This study used various controllers in a two-area power system to manage system frequency and sustain power flow across areas during disturbances. It additionally looked at these controllers' ability to endure disturbances. Control systems are subject to various sources of error, including sensor inaccuracies, modeling errors, disturbances, etc. To minimize these errors, control engineers employ precise scientific methods to optimize controller parameters, utilizing optimization algorithms, feedback control, adaptive control, and robust control techniques to enhance the system's performance and reduce error to a minimum. The choice of approach and specific algorithms depends on the nature of the control system and the specific control objectives. *Figure 3*, shows how the optimization algorithm works.

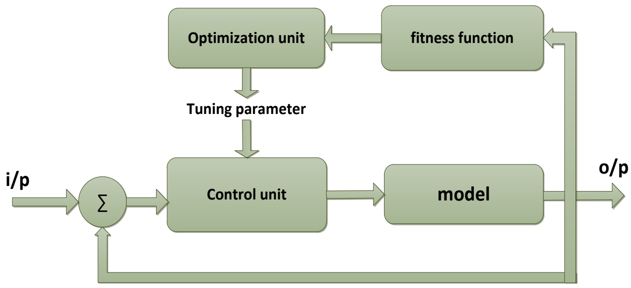


Figure 3. A proposed Scheme for Improving Controller Parameters via the Algorithm

3.1 Fractional Order Proportional Integral Derivative Controller

A typical Fractional Order Proportional Integral Derivative (FOPID) controller may be seen as a logical extension of a fractional order Proportional Integral Derivative. In comparison to an integer-order Proportional Integral Derivative (PID) controller, a FOPID raises the level of liberty by 2. For many closed-loop control systems, it performs better than the conventional PID. It contains five parameters, as shown in *figure 4*, KP, KI, and KD that represent gains of the proportional, integral, and derivative sections; the integrator order is defined by (λ), and the derivative order is specified by (μ) [11]. It also has an excellent ability to handle uncertainty in parameters, excellent disturbance rejection properties, robustness to high-frequency noise, elimination of steady-state errors, and better stability in the case of nonlinear systems. All these characteristics make FOPID highly adaptable and desirable, unlike other controllers.

Figure 4, shows a schematic representation of the proposed controller. The mathematical structure of FOPID is shown in *equation 3.*

$$C_{(S)} = K_P + \frac{K_I}{S^{\lambda}} + K_D S^{\mu} \qquad \lambda, \mu > 0 \ [12] \tag{3}$$

In *equation 1*, λ, μ represent Support Parameters.

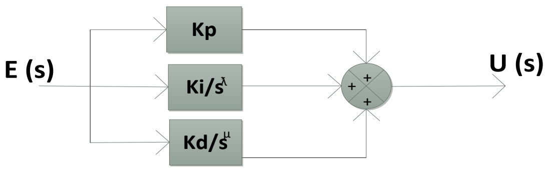


Figure 4. Block Structure of FOPID Controller [13]

4. OBJECTIVE FUNCTION

Each controller requires setting its parameters appropriately to respond well. In each system, the objective function is crucial for calculating errors; it is a responsive language between the optimization technique and the system. A set of criteria is employed in the control method, and when comparing the system efficiency with these criteria, it is seen that the system is improved. Integral Absolute Error (IAE), Integral Time Absolute Error (ITAE), Integral Square Error (ISE), and Integral Time Square Error (ITSE) are some of the most well-known of these criteria, and they are all significant criteria for estimating error in accordance with formulas for every kind. *Equation 4* is shows Integral of time weighted square error.

$$ITSE = \int t \, e_{(t)^2} \ dt \tag{4}$$

The ITSE indices are good criteria for developing control systems because they produce lower vibrations and overshoots, maintain durability, and are also the most sentient, comparison with other standards [13]. In power systems, changes in frequency and tie-line power will occur when a specific disturbance occurs; The choice of the ITSE (Integral of Time-weighted Squared Error) objective function in load frequency control systems, is based on several advantages. ITSE emphasizes error values that persist over time by multiplying the squared error by time. This makes it particularly effective for reducing overshoot and settling time, as it prioritizes correcting errors that last longer, which in turn contributes to system robustness. ITSE's time-weighting component allows it to handle systems where time-related dynamics are critical, ensuring better performance in terms of both stability and transient response, which aligns well with the characteristics of two-area power system thus, the error will be (ΔF, ΔPtie), hence the equation of the ITSE criterion for computing the error will be as follows;

$$\mathrm{ITSE} = \int_0^{T} t \,\{ \Delta_{F1^2} + \Delta_{F2^2} + \Delta_{Ptie\ 12^2} \}dt \tag{5}$$

5. Zebra Optimization Algorithm

Is a brand-new bio-inspired meta-heuristic algorithm known as the Zebra Optimization Algorithm (ZOA), which draws its main inspiration from zebra behaviour in its natural environment. ZOA replicates zebras' feeding habits and their defensive mechanisms against assaults from predators. To solve optimization issues, meta-heuristic algorithms that combine the two ideas of discovering and exploiting are used. The idea of discovering refers to the algorithm's capacity to thoroughly explore the search region and pinpoint the ideal location. The capacity of the algorithm to domestically search within a search area and gravitate toward the best solutions is represented by the idea of exploitation. ZOA members are updated using two of the zebras' in-the-wild steps. First On the basis of simulated zebra feeding behaviour, individuals in the community are updated. The pioneer zebra is the most effective member of the group and directs other animals to where it is in the feeding area. Second: To update the position of the ZOA individuals in the community in the search area, a model of zebra defensive versus predator assaults is utilized. Every zebra represents a potential fix for an issue [14]. The flowchart in *figure 4*, illustrates this algorithm's specifics.

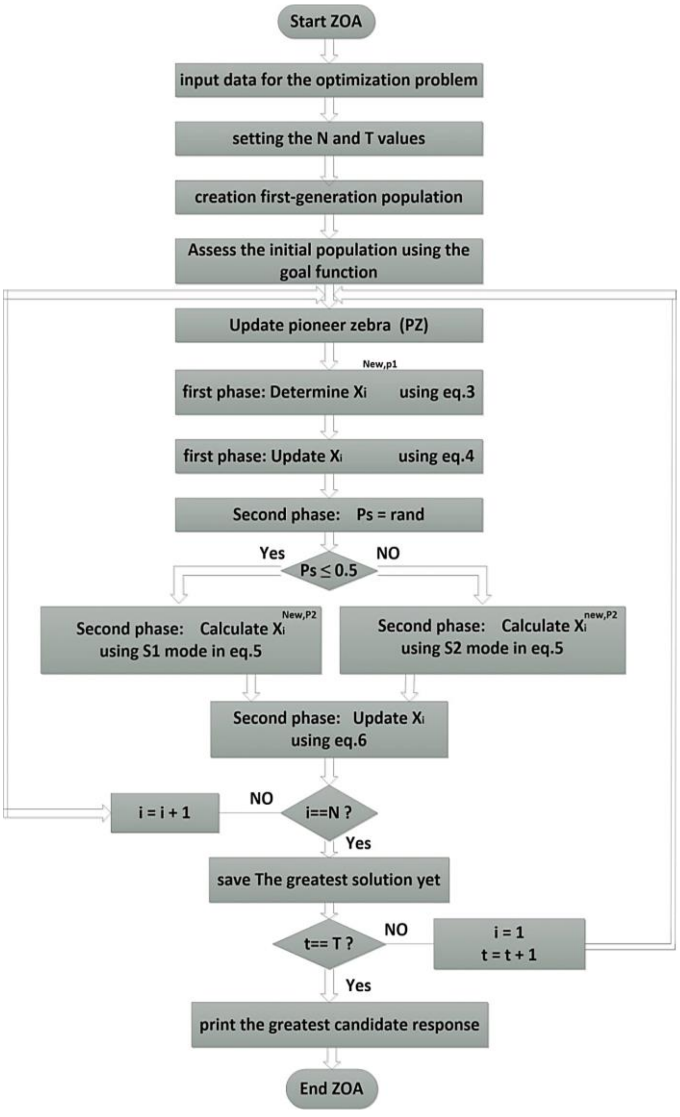


Figure 4. Zebra Optimization Algorithm Flowchart [14]

Equations (6), (7), (8), (9) represent the zebra optimization algorithm found in the flow chart.

$$X_{i,j}^{new,PI} = X_{i,j} + r.\left(PZ_j - I.X_{i,j}\right) \tag{6}$$

$$X_i = \begin{cases} X_i^{new,PI}, & F_i^{new,PI} < Fi\,; \\ X_{i,} & else, \end{cases} \tag{7}$$

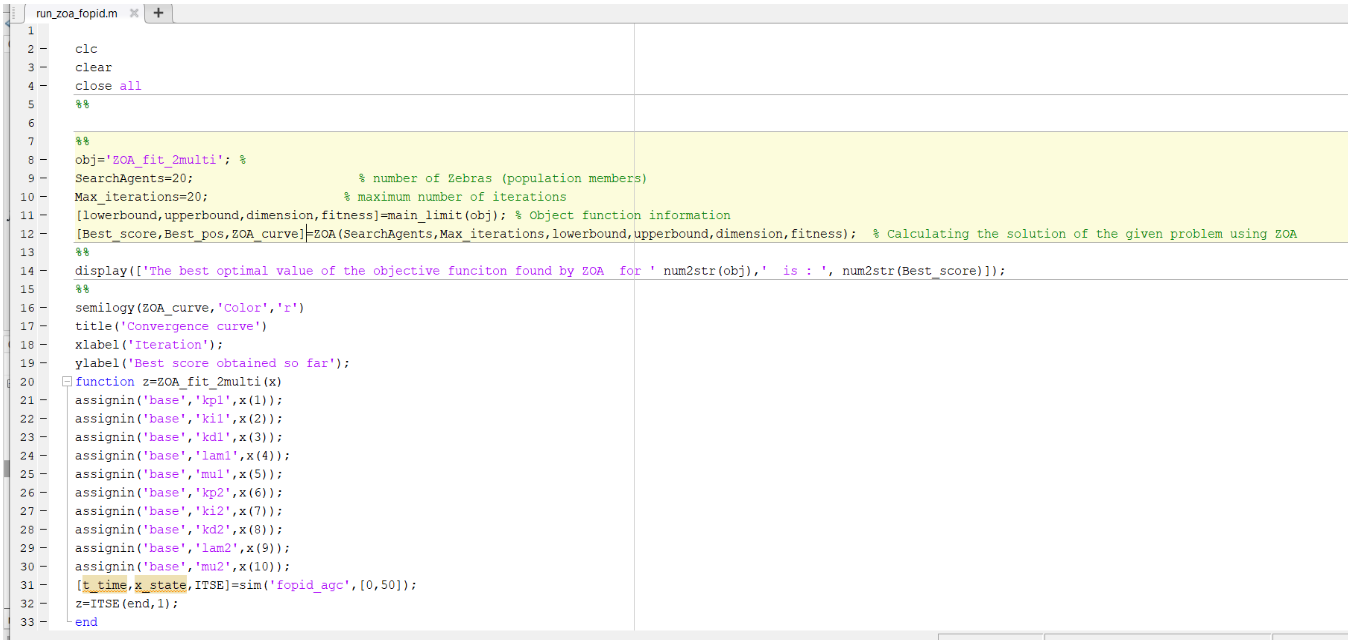
$$x_{i,j}^{new,P2} \begin{cases} S_1 : \; x_{i,j} + R\,.(2r-1) \\ \quad .\left(1-\frac{t}{T}\right).x_{i,j}, \quad P_s \; \le 0.5; \\ S_2 : x_{i,j} + r\,.\left(AZ_j - I.X_{i,j}\;\right), \quad else, \end{cases} \tag{8}$$

$$X_i = \begin{cases} X_i^{new,P2}, & F_i^{new,P2} < F_i\,; \\ X_i, & else, \end{cases} \tag{9}$$

In these equations, the $X_i^{new,PI}$ represent the new status of the ith zebra, $X_{i,j}^{new,PI}$ represent the jth dimension value, $F_i^{new,PI}$ represent the objective function value, PZ represent the pioneer zebra which is the best member, PZ_j represent the jth dimension, r represent the random number in the interval [0,1] And *I* = round (1+rand), where rand is a random number in the interval [0, 1].

6. FRACTIONAL ORDER PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER WITH ZEBRA OPTIMIZATION ALGORITHM

In this search, the integration of the Fractional-Order Proportional-Integral-Derivative (FOPID) controller with the Zebra Optimization Algorithm (ZOA), as shown in *figure 6*, is studied with the goal of maximizing system efficiency via parameters tweaking. When tackling challenging optimization challenges, ZOA is renowned for flexibility and effectiveness. The combination of ZOA with the FOPID controller allows the control system to modify and optimize its settings, resulting in optimal performance. Also, the goal of the study is to show that, in comparison to traditional approaches, this strategy can result in improved control performance, increased system stability, and decreased control error. The ZOA algorithm iteratively seeks optimal or nearly optimal values for the settings of the FOPID controller. The Zebra Optimization Algorithm (ZOA) method commences with initializing the integral and derivative gains to zero and iteratively incrementing them until the system exhibits sustained oscillations. The ultimate gain and period are subsequently determined by identifying the critical point at which sustained oscillations occur. These values are then employed to compute the proportional, integral, and derivative gains of the FOPID controller. The FOPID controller, enhanced with the Zebra Optimization optimal tuning algorithm, can effectively regulate a complex dynamic system characterized by nonlinearity and uncertainties, thereby enhancing its control performance and adaptability. The stages of the suggested ZOA method to get the ideal settings for the FOPID controller are shown in *figure 5*.



```
clc
clear
close all
%%

%%
obj='ZOA_fit_2multi'; %
SearchAgents=20;                              % number of Zebras (population members)
Max_iterations=20;                          % maximum number of iterations
[lowerbound,upperbound,dimension,fitness]=main_limit(obj); % Object function information
[Best_score,Best_pos,ZOA_curve]=ZOA(SearchAgents,Max_iterations,lowerbound,upperbound,dimension,fitness);  % Calculating the solution of the given problem using ZOA
%%
display(['The best optimal value of the objective funciton found by ZOA  for ' num2str(obj),'  is : ', num2str(Best_score)]);
%%
semilogy(ZOA_curve,'Color','r')
title('Convergence curve')
xlabel('Iteration');
ylabel('Best score obtained so far');
function z=ZOA_fit_2multi(x)
assignin('base','kp1',x(1));
assignin('base','ki1',x(2));
assignin('base','kd1',x(3));
assignin('base','lam1',x(4));
assignin('base','mu1',x(5));
assignin('base','kp2',x(6));
assignin('base','ki2',x(7));
assignin('base','kd2',x(8));
assignin('base','lam2',x(9));
assignin('base','mu2',x(10));
[t_time,x_state,ITSE]=sim('fopid_agc',[0,50]);
z=ITSE(end,1);
end
```

Figure 5. The steps of the proposed ZOA algorithm to obtain the best values for the FOPID controller

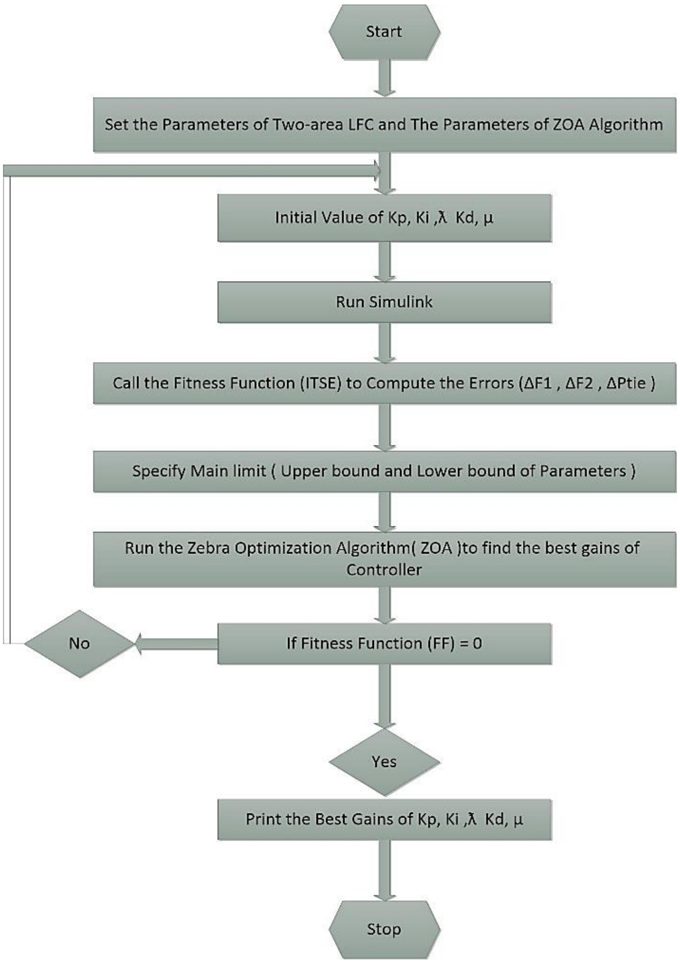


Figure 6. Fractional Order Proportional Integral Derivative with Zebra Optimization Algorithm Flowchart

7. RESULTS AND DISCUSSION

In this section, the results of the study will be presented and discussed, which involved the implementation of the proposed controller in a two-area power system's load frequency control. The two area model parameters are shown in *table 1*, also utilized a novel optimization algorithm to fine-tune the controller's parameters. The comparison is based on three key criteria to assess the controller's performance: overshoot: This metric quantifies the extent to which the control system's response exceeds the desired set point before stabilizing; settling time represents the duration required for the control system's output to settle within a defined range of the set point after a disturbance; and peak time is the time it takes for a dynamic variable in the system (such as voltage or current) to reach its highest value in the dynamic behaviour of the system after a disturbance or change in the steady-state condition. Then the system will be subjected to load disturbance to find out the validity of the proposed controller with the new algorithm. *Figure 7*, shows the fitness function curve.

Table 1. Parameters of Two Area Power System [5].

Characterization	**A1**	**A2**
Frequency	60 Hz	60 Hz
Power System Gain	120 Hz/Pu MW	120 Hz/Pu MW
Power System Time Constant	10 s	10 s
Governor Time Constant	0.07 s	0.07 s
Turbine Time Constant	0.2 s	0.2 s
Reheat Gain	0.33	0.33
Reheat Time Constant	10 s	10 s
Synchronizing Coefficient	0.545 Pu MW/Hz	0.545 Pu MW/Hz
Frequency Bias Constant	0.7 Pu MW/Hz	0.7 Pu MW/Hz
Speed Regulation	0.3	0.3

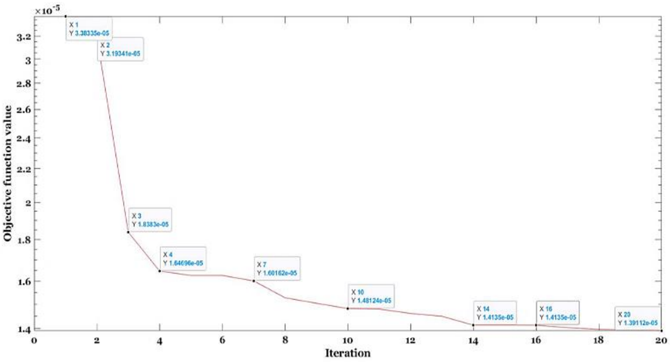


Figure 7. Iteration of the ZOA Algorithm

As the algorithm progresses, the target function curve typically converges towards an optimal point. This convergence indicates that the algorithm is getting closer to a solution that minimizes or maximizes the objective function, depending on the problem's nature. The appearance of the curve provides insights into the values of parameters or variables that yield the best performance. The step load disturbance 0.01 is chosen to test the efficacy and resilience of the proposed control and algorithm. The transient response requirements for (ACEij), (ΔFij), and (ΔPij) in terms of settling time, maximum deviation, and peak time are shown in *tables 2- table 4.*

Figure 8, and *figure 9*, display the area control error for load disturbance. Lower ACE values imply better control system performance. The results, as presented in *table 2,* reveal that the FOPID controller based on the Zebra optimization algorithm surpasses the traditional FOPID controller across three criteria. Notably, it can be observed that the stability time of the system after a disturbance is remarkably fast in the FOPID-ZOA controller. This indicates the proposed ZOA Algorithm ability to restore stability quickly.

░ Table 2. ACE$_{ij}$ Parameters using FOPID and FOPID-ZOA depending on ITSE

Variable		**Settling time (sec)**	**Max. deviation (p.u)**	**Peak time (sec)**
FOPID	ACE1	10	0.011	1
	ACE2	13	0.0045	1.2
FOPID-ZOA	ACE1	3	0.005	0.4
	ACE2	4	0.002	0.7

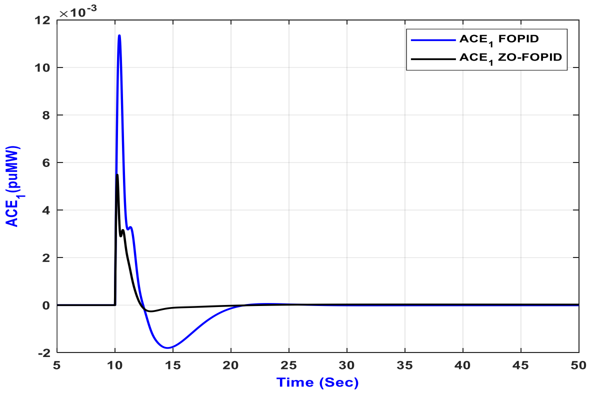


Figure 8. ACE1 Using FOPID Based on ZOA Algorithms

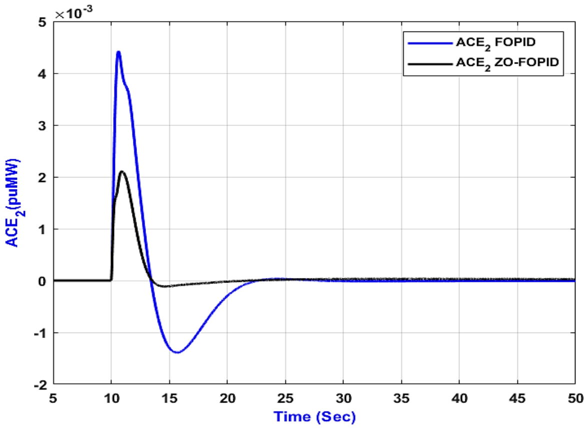


Figure. 9 ACE2 Using FOPID Based on ZOA Algorithms

Figure 10, displays the comparison of changes in tie-line power between the FOPID and FOPID-ZOA controllers for the applied load disturbance. The results, as presented in *table 3*, reveal that the FOPID controller based on the Zebra optimization algorithm surpasses the traditional FOPID controller across three criteria.

░ Table 3. ΔPij Parameters using FOPID and FOPID-ZOA based on ITSE

Variable	**Settling time (sec)**	**Max. deviation (p.u)**	**Peak time (sec)**
FOPID	15	0.0027	1.5
FOPID-ZOA	4	0.0012	1.3

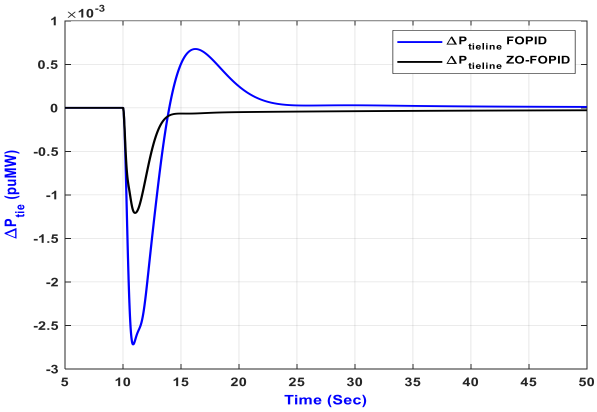


Figure 10. ΔP12 Using FOPID Based on ZOA Algorithm

In this study, *figure 11*, and *figure 12*, display the frequency deviation response for the applied load disturbance. The evaluation reveals that the Fractional Order Proportional-Integral-Derivative (FOPID) controller, based on the Zebra optimization algorithm, exhibits superior performance compared to the conventional FOPID controller. This superiority is demonstrated across three main criteria, as documented in *table 4*, settling time, overshoot, and peak time. These results emphasize the enhanced control capabilities of the ZOA algorithm for FOPID controller in regulating frequency deviations in the system.

Table 4. ΔFij Parameters using FOPID and FOPID-ZOA Based on ITSE

Variable		Settling time (sec)	Max. deviation (p.u)	Peak time (sec)
FOPID	ΔF1	10	0.012	0.8
	ΔF2	12	0.0028	1
FOPID-ZOA	ΔF1	4	0.006	0.4
	ΔF2	6	0.001	0.3

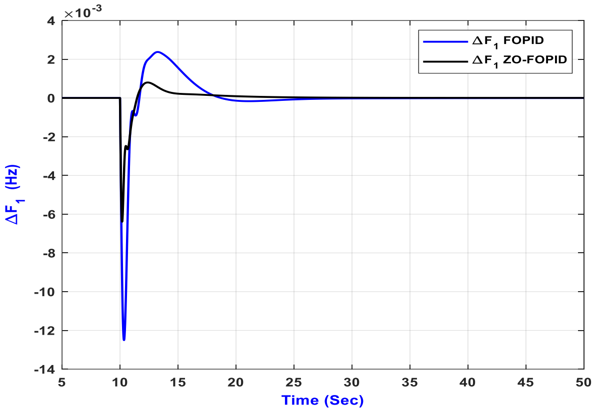


Figure 11. ΔF1 Using FOPID Based on ZOA Algorithm

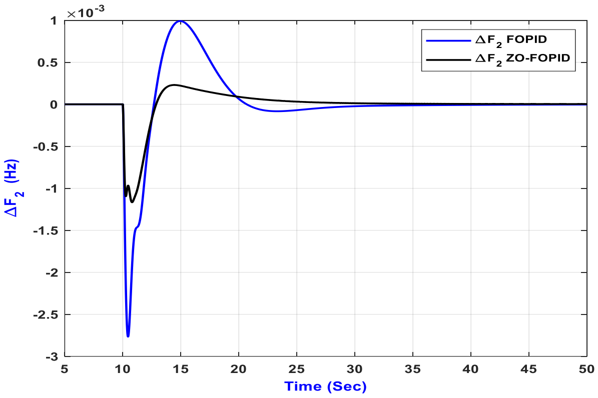


Figure 12. ΔF2 Using FOPID Based on ZOA Algorithm

8. CHANGING OF TWO DISTURBANCES

Here, two load disturbances in values of 0.01 and 0.02 in 20 and 60 sec are chosen to test the efficacy and resilience of the FOPID controller with and without the algorithm and to see the validity of this algorithm in rejecting disturbances. The transient response requirements for (ACE12), (ΔP12), and (ΔF12) are shown in the next paragraphs.

Figure 13 and *figure 14* shows how well the FOPID controller treats the system and gets it back to normal functioning in 3 seconds by applying the ZOA algorithm. Comparing this to the FOPID controller alone, there is a significant improvement, which suggests that the algorithm selected the controller's optimal values in a way that renders the power system resilient to disturbances. It is also quite good at overshooting, having a minimum peak time of 0.4 and a minimum value of 0.005 in it.

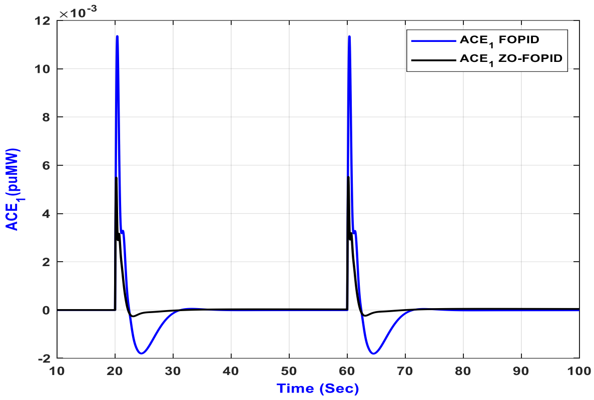


Figure 13. Comparison of Area Control Errors One with Two Disturbance Using FOPID and FOPID-ZOA Controllers.

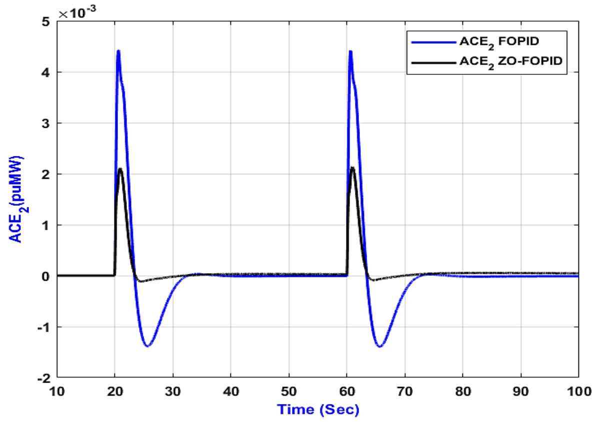


Figure 14. Comparison of Area Control Errors One with Two Disturbance Using FOPID and FOPID-ZOA Controllers

Figure 15 demonstrates how the FOPID controller responded to the change in tie line power when it included the ZOA algorithm and when it did not well the FOPID controller can manage disturbances in a 4-second time frame by using the Zebra Optimization Algorithm (ZOA). This demonstrates its competence in minimizing disruption and returning system reliability in the shortest amount of time.

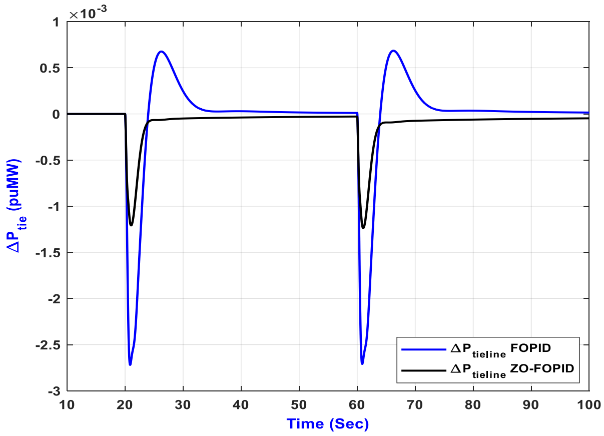


Figure 15. Comparison of Tie-line Power with Two Disturbance Using FOPID and FOPID-ZOA Controllers

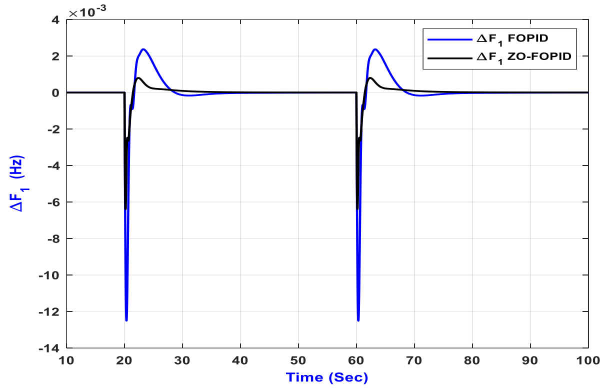


Figure 16. Comparison of Frequency Deviation One with Two Disturbance Using FOPID and FOPID-ZOA Controllers

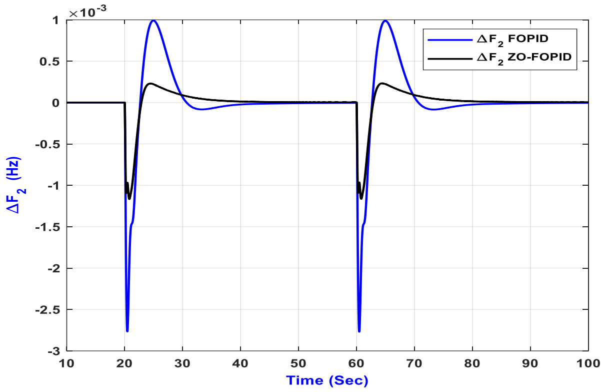


Figure 17. Comparison of Frequency Deviation Two with Two Disturbance Using FOPID and FOPID-ZOA Controllers

The frequency deviation response for two load disturbances is shown in *figure 16* and *figure 17*. According to the evaluation, the Zebra optimization algorithm-based FOPID controller works better than the FOPID controller. With the greatest value for the system's recovery to equilibrium after 4 seconds, the FOPID-ZOA controller performed well. The improvement in the system's recovery to stability is uncommon among other controllers utilized in the same field, demonstrating the controller's strength and efficiency in addressing disturbances in the least amount of time by applying the ZOA algorithm.

9. COMPARISON OF PROPOSED CONTROLLER WITH DIFFERENT CONTROL ALGORITHMS

In this section, the proposed control algorithm of the FOPID controller with the ZOA optimization algorithm was compared with different algorithms for validation. The validity of this controller will be evaluated by comparing its combination with different algorithms. The main goal of this study is to show the reliability of the suggested optimizer by analysing the response of the linked system utilizing the optimal FOPID controller settings that were acquired using the methodologies used. This algorithm will be compared with seven other algorithms [11]. A perturbation of 0.1 and a simulation time of 100 seconds were introduced as implemented with the seven algorithms. Comparison is based on quality standards (setting time, peak time, overshoot). Studying the interconnected system response using the optimal FOPID controller parameters obtained via the implemented techniques is at the core of this work to demonstrate the proposed optimizer's robustness. Therefore, the time responses of the frequencies and tie-line powers' deviations are exhibited in *table 4* and *table 5*.

Table 5. ΔF1, ΔF2, ΔP12 Parameters using Multi-Algorithms with a FOPID Controller

Controller	Settling Time			Rise Time			Peak Time		
	ΔF_1	ΔF_2	ΔP_{12}	ΔF_1	ΔF_2	ΔP_{12}	ΔF_1	ΔF_2	ΔP_{12}
MPA – FOPID	12.48	13.60	13.12	0.1757	0.0028	0.1201	2.0614	0.870	2.765
AEO – FOPID	15.71	14.35	15.31	0.1172	0.0027	0.1079	2.8230	1	2.867
EO – FOPID	12.47	13.6	13.17	0.1757	0.0028	0.1209	2.0614	0.870	2.762
RUN – FOPID	12.55	13.56	13.09	0.1759	0.0028	0.1201	2.0517	0.870	2.762
DMV – FOPID	14.87	14.42	14.86	0.1162	0.0026	0.1047	2.7289	1	2.828
HGs – FOPID	12.83	13.37	13.05	0.1752	0.0028	0.1214	2.0245	0.882	2.734
MHGs–FOPID	12.37	12.25	13.05	0.1215	0.0019	0.0971	2.0477	0.849	2.193
ZOA – FOPID	3	3	3	0.0013	0.0003	0.0043	0.5	0.8	1.5

The plotted curves in *figures 18*, *figure 19*, and *figure 20* confirm that the FOPID controller-based ZOA algorithm is the best in steady-state responses as compared with the other algorithms. Moreover, the ZOA-based system reaches a steady deviation nearly at zero. In contrast, other algorithm-based systems show high values in the overshoot and take a long time to reach stability. Table 4.5 shows that the ZOA-based system is the fastest in reaching stability. It has the shortest settling time and is well-constructed as it has the lowest peak, overshoots at early times, and then becomes steady. It is also clear from the table that FOPID-ZOA returns the system to stability after 3 seconds, which makes it qualified to handle disturbances in electrical power systems.

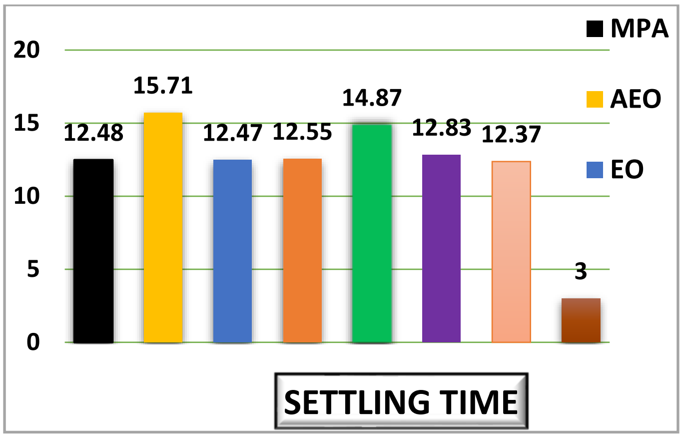


Figure 18. Stability standard of Algorithms through ΔF1

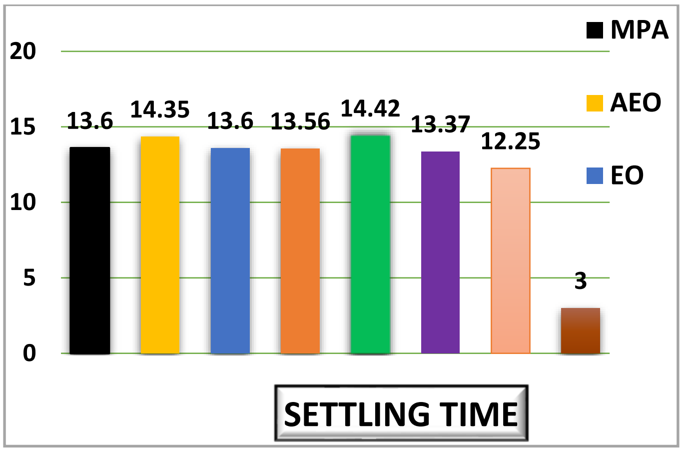


Figure 19. Stability standard of Algorithms through ΔF2

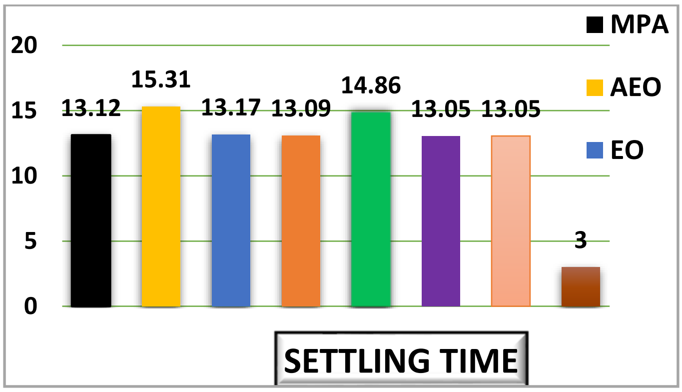


Figure 20. Stability standard of Algorithms through ΔP12

10. CONCLUSIONS

Due to the complexity of modern power systems, load frequency control is crucial because it regulates power between generation and demand, which maintains the stability of the power system. In this work, to maintain frequency deviations and changes in tie-line power controller are FOPID-ZOA proposed, and the results are compared based on three criteria: overshoot, settling time, and peak time, and two load disturbances are applied to evaluate the suitability of the controllers. The objective function ITSE is used to calculate the error. In this paper, a MATLAB Simulink is used to simulate a two-area power system. The simulation results indicate that the FOPID-ZOA controller is superior to the traditional FOPID controller. The FOPID-ZOA controller reduces frequency deviation and changes in tie-line power; it also gives lower overshoot, greater stability, and zero steady-state error. Furthermore, the FOPID controller demonstrated exceptional ability to handle uncertainties in system parameters, excellent disturbance rejection characteristics, and robustness against high-frequency noise. These attributes collectively underscore the adaptability and desirability of the FOPID controller, making it a promising option for effective load frequency control in power systems.

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