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A fuzzy-PID controller for load frequency control of a two-area power system using a hybrid algorithm

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ABSTRACT

This paper presents the use of a new hybrid optimization approach known as particle swarm optimization and grey wolf optimizer (PSO-GWO) for improving frequency stability load frequency control (LFC) in tow-area power systems. The approach consists in optimizing the fuzzy proportional-integral-derivative (fuzzy-PID) controller parameters with meta-heuristic hybrid algorithm: PSO-GWO. This technique allows to have dynamic responses with the least possible frequency deviation in very short response times. The approach proposes to controls the tie-line power and the frequency deviation in the considered two-area power systems under variable perturbation in load and changing of system parameters in order to evaluate its effectiveness. The suggested hybrid algorithm-based fuzzy-PID controller is compared with various widely used control methods in the literature such as PID controller and algorithms such as PSO and GWO in order to evaluate its effectiveness and its robustness. Through the simulations carried out on MATLAB/Simulink, the proposed PSO-GWO fuzzy-PID and the objective function exhibit improved performance, achieving minimal objective values. The proposed technique proved to be quite powerful tool in the resolution of problems related to electrical power systems, particularly in load frequency control.

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1. INTRODUCTION

Electric grids are complex systems composed of multiple generation units, transmission networks, and distribution networks. Quite often, generation units are geographically concentrated, while consumers are dispersed over a vast territory, creating a unique network topology. This geographical aspect of grids makes them intricate and particularly challenging to manage. Indeed, their proper operation relates to instantaneous balances between supply (generation) and demand that are never guaranteed, as well as compliance with countless technical and economic constraints that evolve over time. Furthermore, the loads placed on electric grids are constantly and continuously changing.

Therefore, it is necessary to ensure a continuous power supply capable of immediately responding to load fluctuations while maintaining a level of service quality that meets the expectations of consumers, whether they are industrial or residential. Therefore, the quality of service provided by the grid is the primary concern of the operator. As a result, production units are subject to strict constraints for maintaining frequency and voltage within the contractual limits imposed by the necessary conditions for stable system operation. It is a problem that concerns the entire interconnected electrical system because any imbalance between production and consumption leads to a change in speed and, consequently, in frequency.

Electric systems are organized into control areas interconnected by interconnection lines [1], [2], where generators within the same control area always adjust their speed together to maintain the frequency and power to predefined values under disturbances. If a sudden load change occurs within a control area of an interconnected electrical network, there will be both a frequency variation and a power flow change across the interconnection line. The primary goals of load frequency control (LFC) are: Ensure network stability by keeping the frequency at a level near the nominal value for which the network elements were designed. Control of the power transmitted, via the interconnection lines, between areas.

Recently, numerous control methods have been developed by multiple researchers to manage load frequency control in power grids in order to maintain the primary goals of load frequency control. Conventional proportional-integral (PI) [3] and proportional-integral-derivative (PID) [4] controllers are commonly employed in load frequency control due to their straightforward principles, robustness, and simplicity of execution. While these controllers can bring stability to power systems, they exhibit certain drawbacks, including extended stabilization periods, frequent rebound overshooting, and significant transient frequency deviations.

To enhance dynamic performance, researchers have extensively investigated load frequency control issues in conjunction with advanced control techniques. These include neural network control [5], fractional order PID [6], predictive control [7], fuzzy logic controller [8], and sliding mode control [9], [10]. These approaches have demonstrated superior dynamic responses compared to traditional controllers, offering innovative solutions to LFC challenges. Additionally, these sophisticated techniques are intricate and demand a thorough understanding of their internal structure, thereby limiting their practical applicability.

After years of development, heuristic intelligent algorithms have garnered significant attention and have been applied to fine-tune parameters of LFC controllers, including PI and PID controllers. This utilization is attributed to their effectiveness in addressing optimization problems. For a two area interconnected system, Chorasiya and Suhag [11] uses multi-verse optimizer (MVO) and salp swarm algorithm (SSA) to optimize PID controller. Using a whale optimization algorithm, the PID controller for LFC of multi-area power systems is optimized in [12]. Particle swarm optimization (PSO) [13], craziness-based crow search algorithm (CCSA) [14], [15], genetic algorithm optimizer (GAO) [16], grey wolf optimizer (GWO) [17], hunger games search (HGS) algorithm [18], hybrid gravitational–firefly algorithm (hG-FA) [19], grey wolf optimizer and cuckoo search (GWO-CS) [20], moth flame and water cycle optimization (MFO-WC) [21], genetic algorithm-teaching learning-based optimization (GA-TLBO) [22], [23], bacteria foraging optimization algorithm and particle swarm optimization (hBFOA–PSO) [24], PSO-pattern search (PSO–PS) [25], hybrid Alopex based DECRPSO algorithm (ADECRPSO) [26], A fuzzy based symbiotic organism search (FSOS) [27]. Nevertheless, recent research highlights certain drawbacks associated with these methods. Almost all of these algorithms rely on the accurate initialization of input parameters and exhibit a slow convergence rate towards global solutions. Furthermore, there are instances where they may generate local solutions instead of global ones. Considering the understanding of the aforementioned problems, this article strives to introduce a new hybrid optimization approach known as particle swarm optimization and grey wolf optimizer (PSO-GWO) to address the control challenges of load frequency (LFC) in an interconnected electrical system.

This study focused on the two-area power system. The study employed novel approach in order to adjust the fuzzy-PID controller's parameters with the objective of minimizing the integral time absolute error (ITAE). The analysis of system performance took into account disturbance-induced step load changes and variable load perturbations in both areas. A comparative assessment of the algorithm's performance was conducted against two other optimization methods PSO and GWO based PID and fuzzy-PID controllers, and the results conclusively revealed the efficiency and efficacy of the newly proposed algorithm. The following list shows the significant contributions of the study.

- A fuzzy logic PID controller (fuzzy-PID) is used to achieve robust stability and performance in the two-area power system.
- Furthermore, a new hybrid particle swarm optimization and grey wolf optimizer (PSO-GWO) is used to tune the gains of the proposed the gains of the proposed controller.
- Step load disturbances and variable load disturbances are evaluated on the studied system to confirm the robust performance of the proposed controller.
- The robustness of the fuzzy-PID controller under load variation and parametric changes has been evaluated.

This paper begins with an introduction to the power system model for LFC in a two-area configuration and the controller fuzzy-PID structure in section 2, while section 3 outlines the problem formulation and the proposed optimization hybrid algorithm (PSO-GWO), and for simulation results and discussions, refer section 4. The paper concludes in the final section.

2. THE MODEL OF THE STUDIED POWER SYSTEM AND CONTROLLER STRUCTURE

2.1. The model of the studied power system

A power system with several zones has the advantage of reinforcing continuity of service by giving the different zones the possibility of being interdependent with each other by allowing an exchange of energy between them, when necessary, this exchange being able to be done through interconnection lines. The zones (networks) of the system are connected through transmission lines ensuring the exchange of energy between them as illustrated in Figure 1. Any variation in load without the network is reflected throughout the system and the frequency value in each zone is affected. Due to the interconnection, the frequency of the zones evolves differently in the transient phase to finally take the same value in steady state precisely because of the strong dependence between the zones.

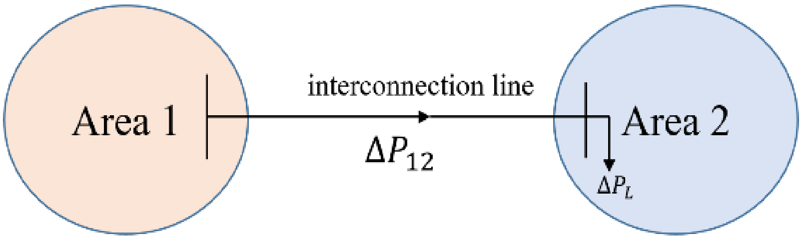


Figure 1. Diagram of an interconnection line

The block diagram of the considered two-area power system of LFC is shown in the Figure 2; where Δf_1 and Δf_2 are the system frequency deviations in *Hz*, and ΔP_{12} is the incremental deviation in tie line power. Each zone within studied system incorporates fuzzy-PID controller, a load, the governor, the turbine and the generator. In order to facilitate the frequency domain analyses, transfer functions are employed to represent each element within the system. The explication and the nominal values of system parameters are illustrated in the Table 1.

- The governor:

$$G_g = \frac{1}{1+sT_g} \tag{1}$$

- The Turbine:

$$G_t = \frac{1}{1+sT_t} \tag{2}$$

- The generator:

$$G_p = \frac{K_p}{1+sT_p} \tag{3}$$

Where: $T_p = 2H/(fD)$ and $K_p = 1/D$.

Table 1. System parameters

Parameter	Explication	Value
f(Hz)	Nominal frequency of the system	50
H (pu/s)	Machine inertia	4.15
D (pu/Hz)	Load damping factor	0.0083
T_{g1} and T_{g2} (s)	Speed governor time constants	0.08
R_1 and R_2 (Hz/pu)	Governor speed regulation parameters	2.4
Tt_1 and T_{t2} (s)	Turbine time constants	0.3
B_1 and B_2	Frequency bias parameters	0.425
T_{12} (pu)	Synchronizing coefficient	0.545

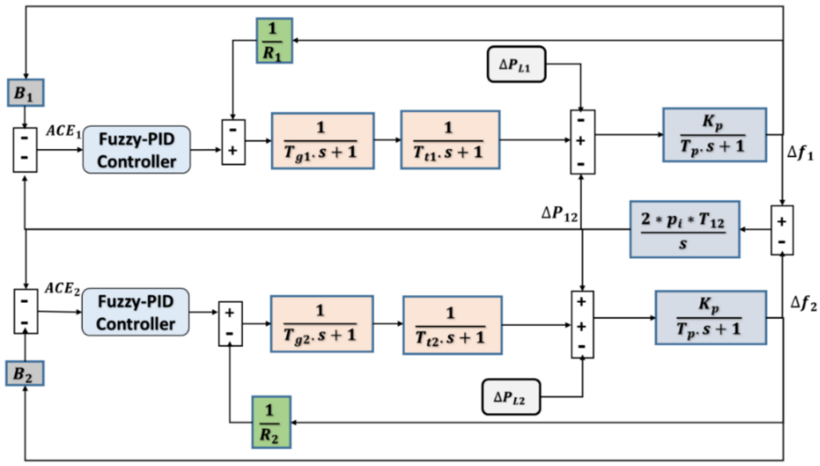


Figure 2. Block diagram of the studied power system for LFC

2.2. Controller structure

In order to maintain the frequency and tie-line power of *b* the two-area power system under consideration, a fuzzy PID controller is proposed for implementation in both areas of the system. The structure of the suggested fuzzy-PID, composed of fuzzy logic controller and PID controller, is shown in Figure 3 [28]. Where K_1 and K_2 are the scaling factors of input and K_p, K_i and K_d are the gains of the PID controller and are considered as the scaling factors of output. These parameters are optimized by proposed hybrid PSOGWO algorithm in this paper. ACE is area control error input to the fuzzy logic controller represented in both area by (4) and (5):

$$ACE_1 = B_1 \Delta f_1 + \Delta P_{12} \quad (4)$$

$$ACE_2 = B_2 \Delta f_2 - \Delta P_{12} \quad (5)$$

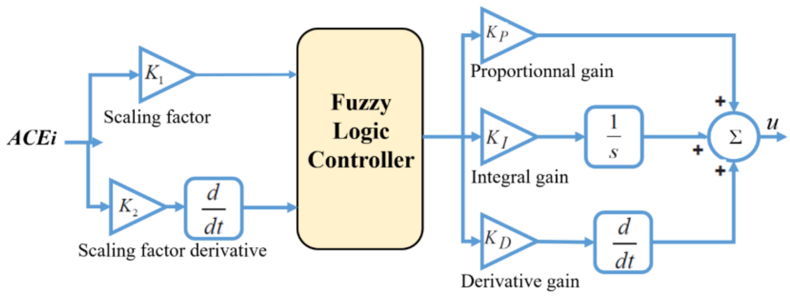


Figure 3. Structure of the fuzzy-PID controller

In detail, FLC or fuzzy logic controller is a system composed from three major steps: fuzzification, fuzzy inference system, and defuzzification. The fuzzification step first involves defining fuzzy sets for the input and output variables. In our case, there are five sets characterized by the following standard labels: (NG) negative large, (NM) negative average, (EZ) around zero, (PM) positive average, and (PG) positive large. Further rule base of the controller is in Table 2.

Table 2. Rule base of the controller

ACE\dotACE	NG	NM	EZ	PM	PG
NG	PG	PG	PM	PM	EZ
NM	PG	PM	PM	EZ	EZ
EZ	PM	PM	EZ	EZ	NM
PM	PM	EZ	EZ	PM	NG
PG	EZ	EZ	NM	PG	NG

3. PROBLEM FORMULATION AND THE PROPOSED HYBRID ALGORITHM
3.1. Problem formulation
In an LFC optimization problem, the objective function is defined as the error which depends on the following two variables: The frequency deviation Δfi and the power exchange deviation on the interconnection lines ΔPij. The error is typically formulated in the form of four main performance criteria in the design of control systems (integral time absolute error (ITAE), integral absolute error (IAE), integral square error (ISE), and integral time square error (ITSE)), ITAE is the most commonly used criterion and it favored as a fitness function because it reduces oscillation, overshoot and settling time. As a result, the objective function used by LFC can be written as (6):

$$mi\,n(ITAE) = \int_0^{t_{sim}} (|\Delta f_1| + |\Delta f_2| + |\Delta P_{12}|).t.dt \tag{6}$$

subject to (7):

$$K_{cpmin} \leq K_{cpi} \leq K_{cpmax} \tag{7}$$

The suggested optimization method for determining the considered controller's parameters minimizes the objective function. K_{cpi} are the controller parameters to be optimized and K_{cpmin}, K_{cpmax} are the controller parameters' lower and upper limits respectively.

3.2. Proposed hybrid algorithm
3.2.1. Particle swarm optimization
PSO is a swarm-intelligence based optimization approach that uses particles to move them about in the search space to find the optimum solution to the problem; it drew inspiration from the social interactions observed in birds. PSO, a meta-heuristic optimization methodology, offers a population-based search approach for global optimization, with the main benefit of being simple to use and requiring few parameters to be adjusted [29].

3.2.2. Grey wolf optimization
A newly created meta-heuristic algorithm called the grey wolf optimizer (GWO) imitates the swarming hunting behavior of wolves. The male and female pack leaders in GWO are referred to as alpha (α) and are the first and best individuals. The second and third top wolf are referred to (β) and (δ). The grey wolf's lowest rank is omega (ω), which is subordinate to all other governed wolves [30].

3.2.3. Hybrid PSO–GWO algorithm
The algorithm PSO-GWO is a recent swarm-based meta-heuristic endowed with several advantages, including simple implementation and low memory utilization. The key idea is to combine the exploration and exploitation capabilities of PSO and GWO to produce variants with strength and memory consumption. They operate simultaneously in various ways. The PSO-GWO algorithm is employed to simultaneously utilize and investigate the positions of the initial three agents within the search space. The equations (8) to (11) show the mathematical expressions:

$$X_1 = X_\alpha - A_1 \cdot |C_1 \cdot X_\alpha - X| \tag{8}$$

$$X_2 = X_\beta - A_2 \cdot |C_2 \cdot X_\beta - X| \tag{9}$$

$$X_3 = X_\delta - A_3 \cdot |C_3 \cdot X_\delta - X| \tag{10}$$

$$X_{123}(t+1) = \frac{X_1(t)+X_2(t)+X_3(t)}{3} \tag{11}$$

where A_1, A_2, A_3, C_1, C_2, and C_3 stand for the top three wolves' coefficient vectors, while X_1, X_2, and X_3 stand for the positions of the top three wolves relative to the corresponding prey. X_{123} designates the location of the current solution.

Equations (12) and (13) show how the PSO technique can be used to update the wolves' positions and speeds, which are denoted by x_i^k and v_i^k:

$$v_i^{k+1} = (v_i^k + r_1c_1(x_1 - x_i^k) + r_2r_2(x_2 - x_i^k) + r_3r_3(x_3 - x_i^k) \tag{12}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (13)$$

where the revised positions and speeds of the top three wolves are indicated by x_i^{k+1} and v_i^{k+1}, respectively. $r_1 \in [0, 1]$, $r_2 \in [0, 1]$ and $r_3 \in [0, 1]$ are random number, besides, the optimization parameters, denoted by C_1, C_2, and C_3 and are set to 0.5.

The objective is to optimize the proposed fuzzy-PID controller in the studied system. It is important to note that the controller's parameters were set utilizing a hybrid PSO-GWO. In order to get the best values depending on the system requirements, the PSO-GWO MATLAB code includes the lowest and highest values of fuzzy-PID gains. For this study, a number of steps were utilized to obtain the best values for the fuzzy-PID controller's parameters, illustrated in Figure 4.

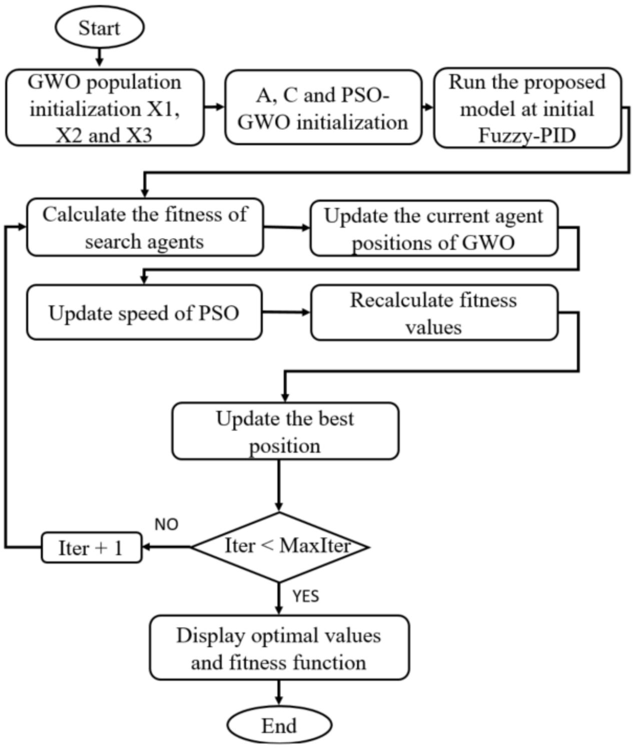


Figure 4. Flowchart for hybrid PSO-GWO algorithm

4. RESULTS AND DISCUSSION

The testing system was established by configuring it as a Simulink model in MATLAB (R2022a) software, running on a computer equipped with an Intel Core i7 processor and 32 GB of RAM. Furthermore, the proposed algorithm PSO-GWO code is executed as an *.m* MATLAB file, connecting with the Simulink model representing the power system under study to facilitate the optimization procedure. Moreover, the various optimization algorithms used to compare with the proposed method, such as GWO and PSO, were also evaluated within MATLAB. In Table 3, you can find the parameters considered in the analyzed system. Through an examination of various case studies, we evaluated the performance of the suggested controller within dynamic system operating scenarios. The suggested hybrid algorithm-based fuzzy-PID controller is compared with various widely used control methods in the literature such as PID controller and algorithms such as PSO and GWO in order to evaluate its effectiveness and its robustness. For the proposed fuzzy-PID controller, we fine-tuned its parameters using tree separate optimization techniques with the aim of minimizing the ITAE. More precisely, these optimization methods were employed to determine the most suitable fuzzy-PID controller parameters for the load frequency control (LFC) of the two-area power system (TAPS). The adjusted PID and proposed fuzzy-PID controller gains are shown in Table 3.

To demonstrate the effectiveness of these optimization techniques, we focused on tree specific cases, as detailed below. In the first case, we studied the response of the system for step load change, in the second case a variable load changes were applied to test system area 1 and area 2, and in the last case, we examined both the frequency and power response when faced with uncertainties in system parameters.

Table 3. Controller parameters

	K_p	K_i	K_d	K_1	K_2
PSO PID	0.112	2.545	1.783	---	---
GWO PID	0.30	3.235	1.923	---	---
PSO-GWO PID	0.615	3.336	1.980	---	---
PSO FPID	3.597	2.114	1.026	0.012	12.545
GWO FPID	4.280	3.577	1.789	0.017	13.487
PSO-GWO FPID	5.458	5.154	1.534	0.009	15.608

4.1. Case 1: system response for step load change

In this case, a load increment of 0.01 per unit was introduced to test system area 1, while test system area 2 experienced a load increase up to 0.03 per unit as shown in Figure 5. For the parametric tuning of the fuzzy-PID controller, the suggested hybrid algorithm PSO-GWO, PSO, and GWO were applied. Their outputs were compared in relation to overshoot and settling time for Δf_1, Δf_2 in both areas 1 and 2, and for the variation in the tie-line power ΔP_{12}. Values of ITAE, the peak overshoot and the settling time for the output variables are reported in Table 4. From the Figure 6(a) frequency deviation of the area 1, Figure 6(b) frequency deviation of the area 2, Figure 6(c) deviation in tie line power and from the Table 4, the proposed optimization technique clearly demonstrated superior performance in settling time compared to the controller PID and to the two widely recognized optimization algorithms (PSO and GWO). Additionally, it exhibited minimal overshoot in the context of tie-line power flow, offering an extra advantage.

Table 4. ITAE, over-shoot and settling time of case 1

	ITAE	Over-Shoot	Settling Time		ITAE	Over-Shoot	Settling Time
PSO PID	0.1576	Δf_1: -0.00198	Δf_1: 30.996	PSO FPID	0.06199	Δf_1: -0.001076	Δf_1: 18.734
		Δf_2: -0.00254	Δf_2: 30.645			Δf_2: -0.002178	Δf_2: 18.302
		ΔP_{12}: 0.0038	ΔP_{12}: 25.836			ΔP_{12}: 0.002008	ΔP_{12}: 19.634
GWO PID	0.1207	Δf_1: -0.00179	Δf_1: 29.529	GWO FPID	0.03289	Δf_1: -0.000911	Δf_1: 15.292
		Δf_2: -0.00249	Δf_2: 29.112			Δf_2: -0.001974	Δf_2: 14.7565
		ΔP_{12}: 0.00339	ΔP_{12}: 23.975			ΔP_{12}: 0.001687	ΔP_{12}: 15.77
PSO-GWO PID	0.0877	Δf_1: -0.00168	Δf_1: 22.456	PSO-GWO FPID	0.02261	Δf_1: -0.000731	Δf_1: 13.613
		Δf_2: -0.00245	Δf_2: 21.836			Δf_2: -0.001741	Δf_2: 13.314
		ΔP_{12}:0.00317	ΔP_{12}: 22.227			ΔP_{12}: 0.001333	ΔP_{12}:13.334

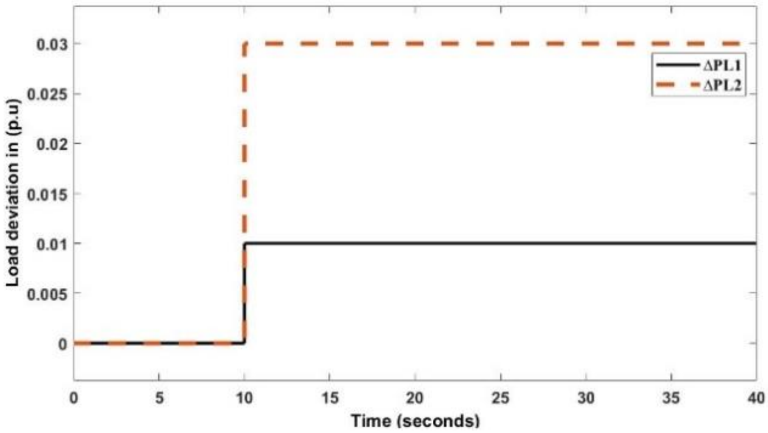


Figure 5. Step load disturbance

4.2. Case 2: system response for variable load change

A variable load changes were applied to test system area 1 and area 2 as depicted in Figure 7. Table 3 displays the applied proposed fuzzy-PID controller coefficients that were determined using he suggested hybrid intelligent optimization algorithms PSO-GWO in contrast to other algorithms PSO, and GWO using PID and fuzzy-PID controllers. Figure 8(a), Figure 8(b) and Figure 8(c) show, respectively, Δf_1, Δf_2 in both areas 1 and 2, and the change in the tie-line power ΔP_{12}. Figure 8 show that this method is far better to other algorithms and that the system can easily dampen any changes in load and will never become unstable. Table 5 demonstrates that the ITAE value of the suggested PSO-GWO is the lowest than other algorithms.

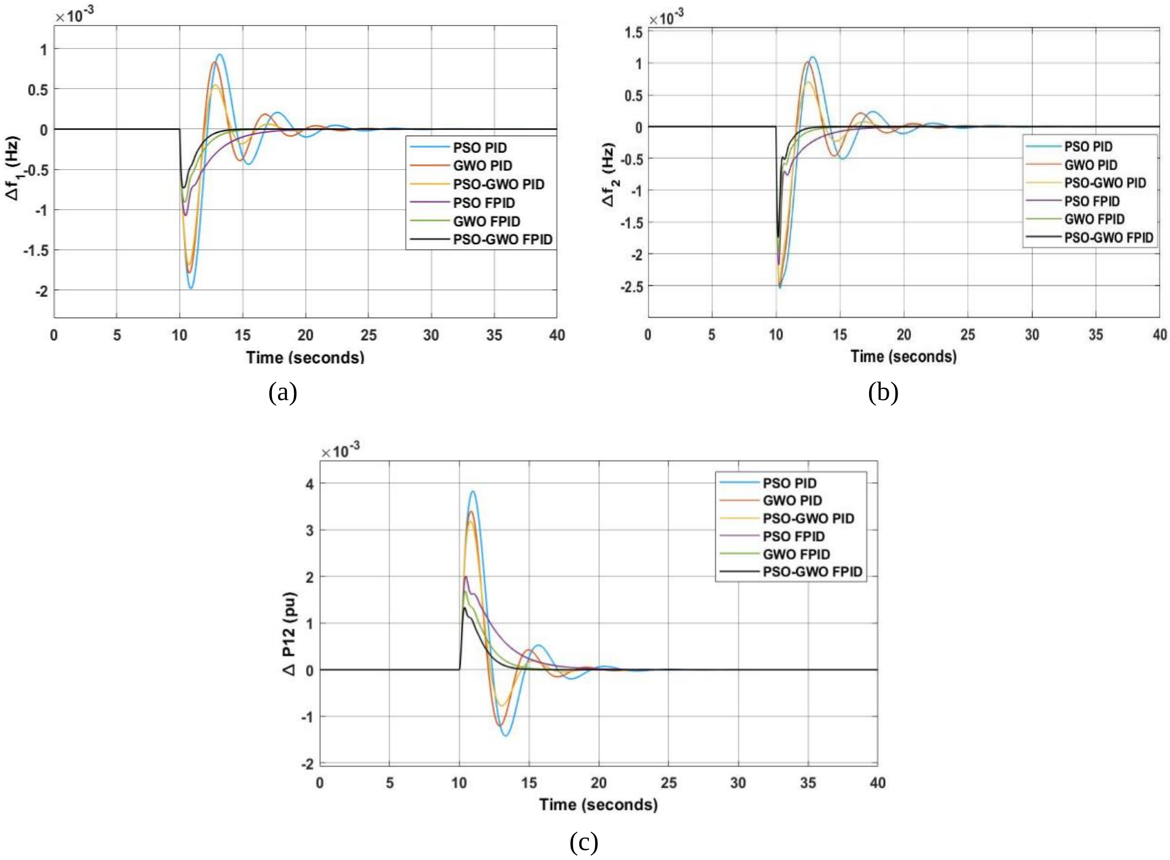


Figure 6. Case 1: Dynamic power system response (a) Δf_1, (b) Δf_2, and (c) ΔP_{12}

Table 5. ITAE of case 2

	ITAE
PSO PID	1.2055
GWO PID	1.1621
PSO-GWO PID	1.0235
PSO FPID	0.9038
GWO FPID	0.5135
PSO-GWO FPID	0.3574

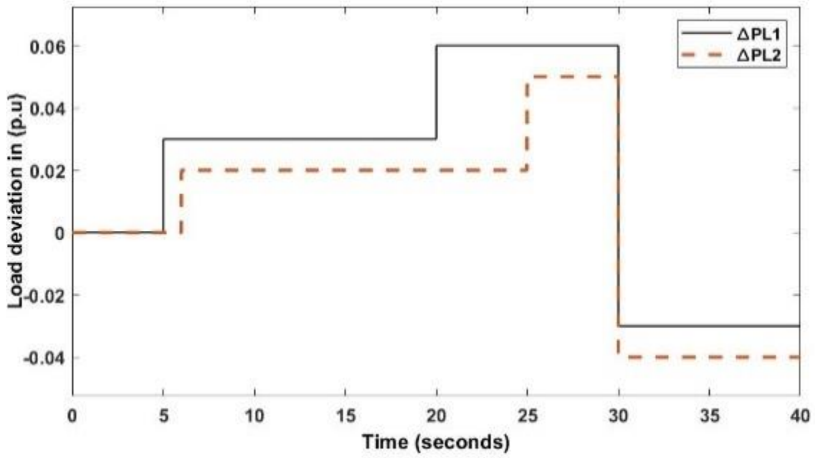
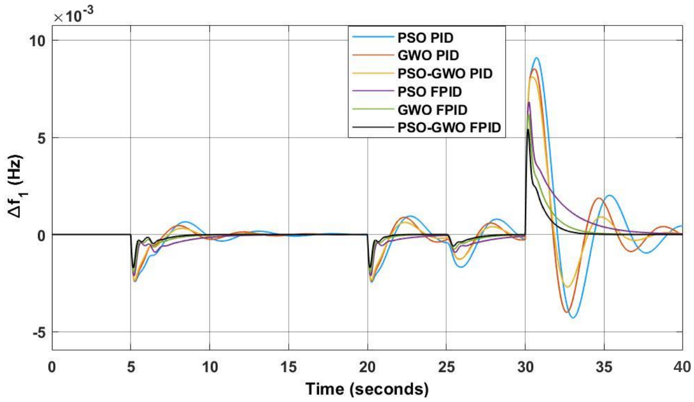
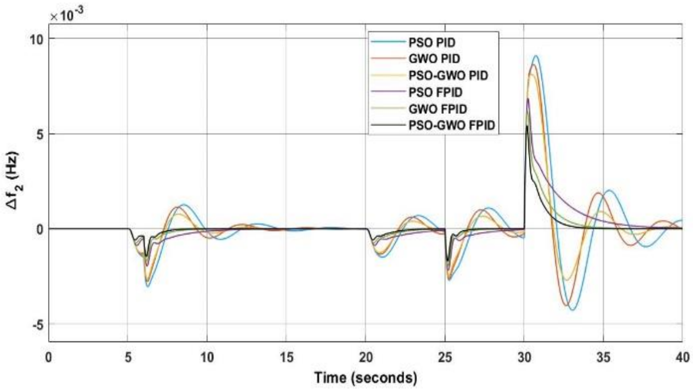


Figure 7. Variable load change



(a)



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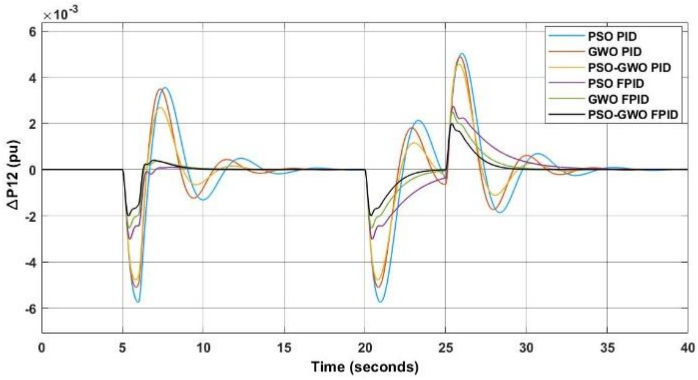


(c)

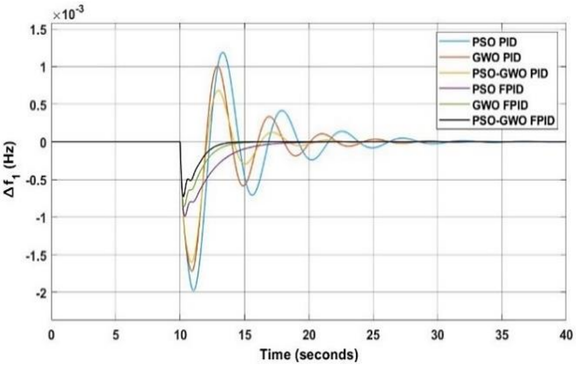
Figure 8. Case 2: dynamic power system response, (a) Δf_1, (b) Δf_2, and (c) ΔP_{12}

4.3. Case 3: step load change with parameter uncertainties

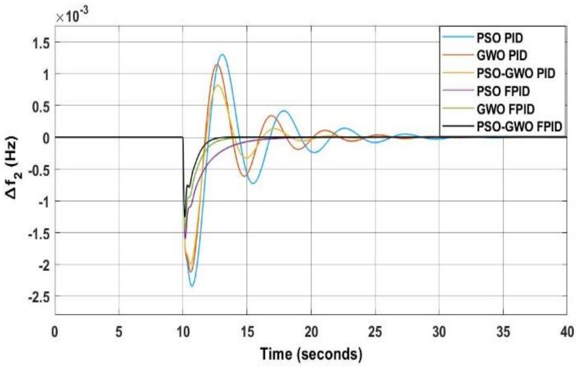
The robustness of any method can be evaluated by examining both the frequency and power response when faced with uncertainties in system parameters. This evaluation is crucial for understanding how well the power system can withstand significant changes in these parameters, as illustrated in Table 6. The primary aim of this study is to assess how well the proposed approach can maintain its performance when subjected to substantial modifications in the studied system settings, particularly in the presence of load perturbations. Figure 9(a) frequency deviation of the area 1, Figure 9(b) frequency deviation of the area 2 and Figure 9(c) deviation in tie line power, show the dynamic behavior of the system using the fuzzy-PID configuration that has been optimized using PSO-GWO for handling step load variations in two specific regions. It is apparent that the suggested technique provides a dependable and stable control strategy, as demonstrated by the results above, indicating that the system under investigation exhibits a high degree of resilience to variations in all parameters.

Table 6. Variation of system parameters

Parameter	Actual value	Variation range	New value
K_p	1/0.0083	-50%	60.23
T_p	20	-45%	11
T_{g1}	0.08	+50%	0.105
R	2.4	+35%	3.24
T_{t2}	0.3	-45%	0.165



(a)



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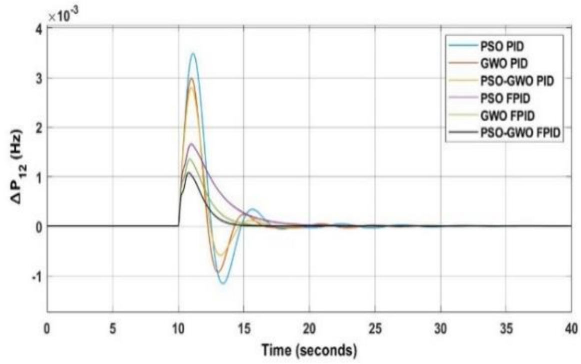

(c)

Figure 9. Case 3: Dynamic power system response, (a) Δf_1, (b) Δf_2, and (c) ΔP_{12}

5. CONCLUSION

This research addresses the issue of load frequency control (LFC) within a power system consisting of two areas. The parameters of the proposed fuzzy-PID controller are adjusted using a novel hybrid technique called PSO-GWO, with a focus on minimizing ITAE performance indices. MATLAB/Simulink was employed to assess system performance, accounting for load changes in both areas. The results clearly demonstrate that the suggested controller, tuned using the suggested algorithm, excels in resolving optimization issues by yielding appropriate gains more rapidly than other algorithms such as PSO and GWO with PID controller and the proposed fuzzy-PID. The proposed PSO-GWO FPID and the objective function exhibit improved performance, achieving minimal objective values (ITAE=0.02261, overshoot area 1= -0.000731 Hz*;* overshoot area 2= -0.001741 Hz*;* settling time=13.613 s). Consequently, this approach effectively maintains the balance between power supply and demand, reducing frequency errors and promptly correcting frequency deviations. In the future, this optimization method can be utilized in various facets of power systems, with a specific focus on voltage regulation.

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