

Optimization of Hybrid 1+ Proportional-Integral and Proportional-Integral-Derivative Controller for Load Frequency Regulation in Nonlinear Two-Area Power Systems Using Catch Fish Techniques

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Abstract This investigation investigates the evolution of a hybrid frequency controller that is specifically engineered for nonlinear two-area power systems. The controller ensures reliable frequency regulation by incorporating the most efficient components of both 1+PI and PID control methodologies, particularly when faced with complex issues such as GRC and GDB. In order to achieve the optimal calibration of the control parameters, the CFOA is implemented. This algorithm effectively traverses the search space and avoids suboptimal local optima by utilizing established fishing techniques. The performance criterion for the proposed method is ITAE, and simulations are conducted on a two-area power system model with 0.2 per unit load variations. The results suggest that the hybrid controller significantly reduces overshoot, undershoot, and settling time, while simultaneously guaranteeing a continuous tie-line power flow. The controller's efficacy is extraordinary, with an ITAE of approximately 0.0336. These results emphasize its suitability for complex multi-area power networks and suggest potential applications in future systems, such as renewable energy or fluctuating demands.

Keywords: Catch Fish Optimization, Hybrid 1+PI and PID Controller, Load Frequency Control, Metaheuristic Optimization, Nonlinear Power System

1 Introduction

Interconnected power systems including two areas constitute a crucial framework in contemporary power generation and delivery. These systems are intrinsically complex and acutely sensitive to load-generation discrepancies, frequently resulting in frequency variations that could jeopardize overall system stability [1–3]. Load Frequency Control (LFC) is an essential method for sustaining homeostasis amid constantly fluctuating operational conditions [4]. Despite the popularity of proportional-integral (PI) and proportional-integral-derivative (PID) controllers due to their simplicity and ease of use, they perform inadequately in systems exhibiting nonlinear characteristics such as generation rate constraints (GRC) and governor dead band (GDB) [5]. These constraints frequently result in adverse system reactions, such as overshoot, oscillations, and diminished frequency stability, especially during sudden or erratic load fluctuations [6].

Recent advancements have led to the development of many intricate control methodologies aimed at enhancing control precision. These include sliding mode control [7], fuzzy-PID [8] and [9], fractional order PID (FOPID) [10] and [11], and model predictive control [12–14]. These methodologies include specific limitations, including complex model architectures, prolonged response times, and the necessity for meticulous parameter adjustments, all of which might escalate computational expenses. Moreover, none of these approaches can sufficiently address the intricacies of GRC and GDB.

This paper introduces a hybrid controller that combines a conventional PID controller with a 1+PI structure to get around these restrictions. This approach makes use of well-established control techniques, improving accuracy and adaptability at the same time. The Catch Fish Optimization Algorithm (CFOA) effectively optimizes all controller parameters. CFOA introduces an innovative methodology inspired by human fishing practices. This method substantially reduces the likelihood of hitting a local minimum during the optimization process by combining extensive exploration with targeted exploitation.

2 Methodology

This study primarily compares the performance of traditional controllers with an innovative control method in a nonlinear two-area power system. Four different controller types are covered in the analysis: the basic PI controller, the 1+PI controller, the PID controller, and the recently developed hybrid controller that combines the 1+PI and PID techniques [17–19]. This work primarily focuses on the GDB and GRC, two essential nonlinear constraints that precisely represent the operating characteristics of modern power systems.

A. Nonlinear Two-Area Power Systems

In extensive power systems, the network is typically divided into several control regions, where preserving frequency stability within each area is essential for guaranteeing the overall reliability of the system. A two-area LFC model, which has become a key framework in the research of LFC, is exemplified by the arrangement shown in the accompanying image [20]. This setup illustrates the relationships between control regions and emphasizes the dynamic interactions arising from power exchange along the tie-line [21–23].

A controller, governor, turbine, and power system model are only a few of the various functional parts that make up each area. These components respond to changes caused by oscillations in load and frequency within their specified areas. Figure 1 shows the complex system in detail.

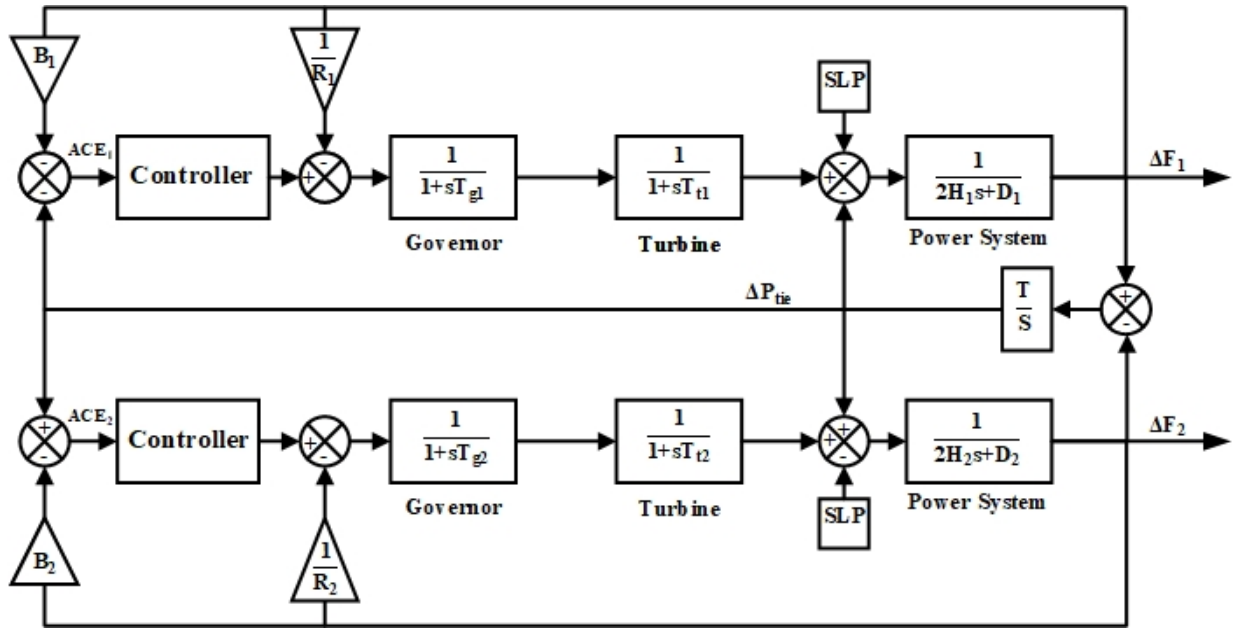


Figure 1: Nonlinear Two-Area Power Systems are under study.

The essence of the load frequency control mechanism is found in the calculation of the Area Control Error (ACE), which indicates the overall deviation within each control area. This error metric accounts for both the local frequency deviation and the net power transfer across the tie-line connecting to the neighboring area. The computed ACE is then fed into the controller to generate appropriate control signals, which are subsequently sent to the power generation units to restore the system frequency to its nominal value [24–26].

The formulation of ACE differs slightly for each area to reflect the direction of power flow. For instance, in Area 1, a change in ACE occurs when the local frequency decreases or when power flows out to Area 2. The ACE for Area 1 can be calculated using Equation (1):

$$ACE_1 = B_1 \Delta f_1 + \Delta P_{tie} \quad (1)$$

In contrast, Area 2—being the receiving side of the power transfer—has its ACE calculated with an opposite convention, as shown in Equation (2):

$$ACE_2 = B_2 \Delta f_2 - \Delta P_{tie} \quad (2)$$

These equations facilitate the design of control mechanisms that effectively respond to both internal disturbances within each area and external influences arising from inter-area power exchanges. The detailed system parameters used in the model are provided in Appendix A.

B. Hybrid 1+PI and PID Controller

In this study, a hybrid controller structure is designed by integrating the 1+PI controller with the conventional PID controller to enhance frequency regulation performance in multi-area power systems exhibiting nonlinear characteristics.

The structure of the proposed hybrid controller, as shown in Figure 2, comprises two main components. This integrated structure enables the controller to tackle system errors thoroughly by providing both swift corrective measures and efficient long-term error prevention strategies [28].

The control signal produced in the initial stage is then routed to the second component—the PID controller—which follows a traditional structure comprising proportional, integral, and derivative elements. To reduce the effects of high-frequency noise,

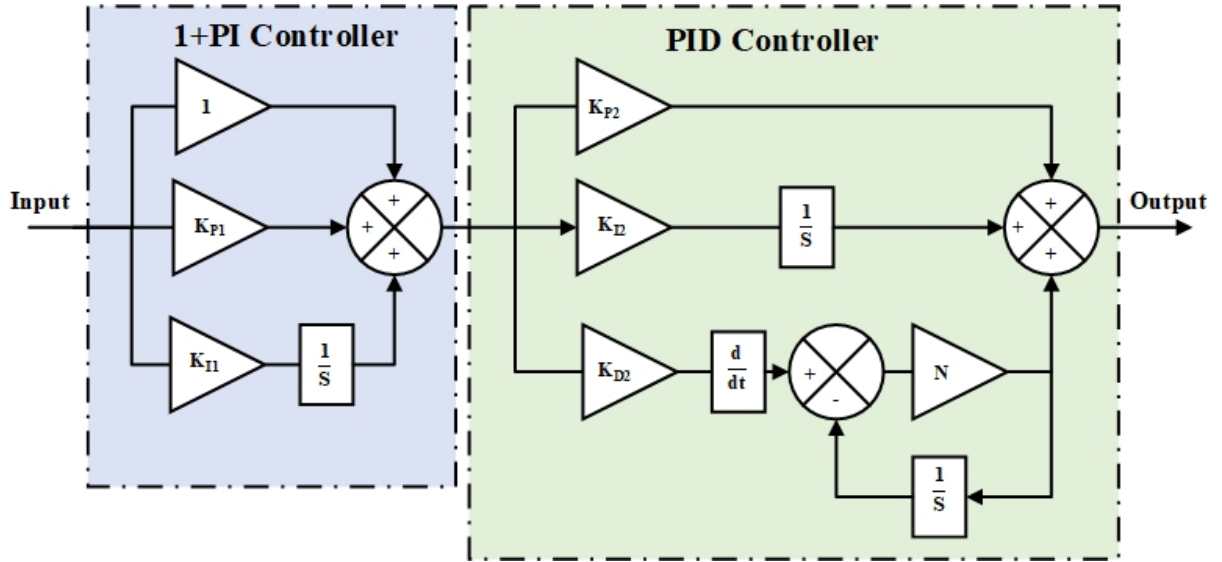


Figure 2: Hybrid 1+PI and PID Controller are under study.

especially during swift load changes, the derivative term is subjected to a low-pass filter characterized by a specific coefficient N . The proposed hybrid controller integrates the advantages of both control strategies, resulting in improved performance in managing system dynamics during both transient and steady-state conditions. The dual-layer configuration enhances the overall quality of control and achieves more effective error suppression compared to using a single controller alone [29–31].

C. Catch Fish Optimization

This study uses the CFOA to determine the best parameters for a hybrid controller that integrates the frameworks of 1+PI and PID controllers, with the goal of effectively managing LFC in a nonlinear two-area power system.

CFOA represents a metaheuristic optimization technique that draws inspiration from the conventional fish-catching methods utilized in rural communities. The core idea—“stirring the water to catch fish”—encapsulates the equilibrium between exploratory inquiry and cooperative problem-solving in unpredictable contexts. This dual-phase mechanism allows CFOA to alternate efficiently between exploration (Equations 3–6) and exploitation (Equations 7–8), thereby improving the algorithm’s ability to converge towards a global optimum solution [32–34].

$$\text{Exp} = \frac{\text{fit}_i - \text{fit}_p}{\text{fit}_{\max} - \text{fit}_{\min}} \quad (3)$$

$$R = \text{Dis} \times \sqrt{|\text{Exp}| \times \left(1 - \frac{\text{EF}_s}{\text{MaxEF}_s}\right)} \quad (4)$$

$$\text{Fisher}_{ij}^{T+1} = \text{Fisher}_{ij}^T + (\text{Fisher}_{\text{pos},j}^T - \text{Fisher}_{ij}^T) \times \text{Exp} + r_s \times s \times R \quad (5)$$

$$\text{Fisher}_{c_i,j}^{T+1} = \text{Fisher}_{c_i,j}^T + r_2 \times (\text{Centre}_c - \text{Fisher}_{c_i,j}^T) + \left(1 - \left(\frac{2 \times \text{EF}_s}{\text{MaxEF}_s}\right)^2\right) \times r_3 \quad (6)$$

$$\sigma = \sqrt{\frac{2(1 - \frac{\text{EF}_s}{\text{MaxEF}_s})}{\left(1 - \frac{\text{EF}_s}{\text{MaxEF}_s}\right)^2 + 1}} \quad (7)$$

$$\text{Fisher}_i^{T+1} = \text{Gbest} + \text{GD} \left(0, \frac{r_4 \times \sigma \times |\text{mean}(\text{Fisher}) - \text{Gbest}|}{3}\right) \quad (8)$$

The operational structure of CFOA is summarized in the flowchart shown in Figure 3

D. Application of Catch Fish Optimization for Hybrid 1+PI and PID Controller in Load Frequency Regulation

In this research, the CFOA is employed to tune the parameters of the hybrid 1+PI and PID controllers for load frequency control in a nonlinear two-area power system. The parameter search space is defined within the range of 0 to 2, which sufficiently covers the values that influence the dynamic behavior of the system without inducing undesirable oscillations or instability.

During each iteration of the optimization process (up to a maximum of 100 evaluations, i.e., $\text{MaxEFs} = 100$), the algorithm

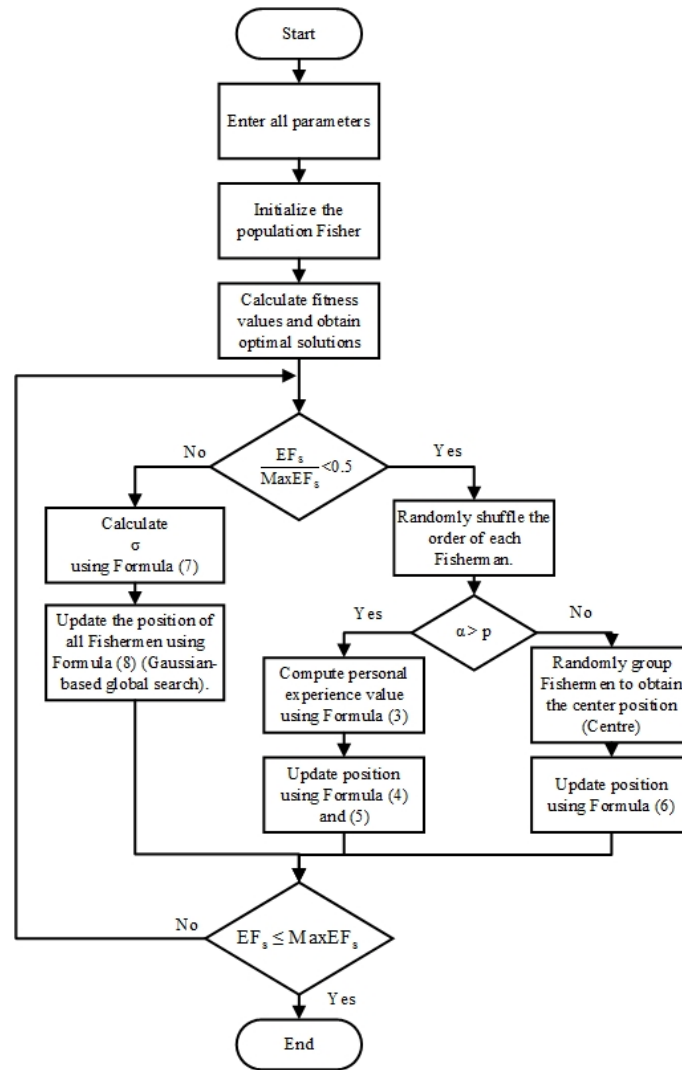


Figure 3: The flowchart of Catch Fish Optimization.

assesses the fitness of each parameter set using the Integral of Time-weighted Absolute Error (ITAE) as the objective function, as described in Equation (9). The ITAE metric considers the frequency deviations in both areas and the variations in tie-line power flow between them [35].

$$\text{ITAE} = \int_0^{30} (t \cdot (|\Delta f_1(t)| + |\Delta f_2(t)| + |\Delta P_{\text{tie}}(t)|)) dt \quad (9)$$

When the ratio $EF_s/\text{Max}EF_s$ is less than 0.5, the algorithm emphasizes global exploration by employing Gaussian distribution to scatter the agents around the global best position (Gbest), thereby reducing the likelihood of premature convergence to suboptimal solutions. As EF_s approach $\text{Max}EF_s$, the algorithm transitions into a collective encirclement phase, leveraging swarm intelligence and agent-based experience to achieve more accurate position updates.

3 Results and Discussion

In this study, the dynamic performance of a nonlinear two-area power system is evaluated under a step load disturbance of 0.2 per unit applied to Area 1, based on the system configuration illustrated in Figure 1. This study aims to evaluate the system response under four distinct control strategies:

- A standard PI controller
- A 1+PI controller with an added feedforward term
- A conventional PID controller

- A hybrid controller that systematically integrates the functionalities of both the 1+PI and PID controllers

To ensure an equitable and consistent basis for comparison, all controllers are tuned using the Catch Fish Optimization Algorithm (CFOA). As a metaheuristic technique, CFOA offers notable advantages in escaping local minimum and effectively balancing global exploration with local exploitation.

Parameter tuning is performed within a predefined range of 0 to 2, using a maximum of 100 evaluation iterations. The resulting optimized parameters for each controller are summarized in Table 1. These values are then used in subsequent simulations to assess and compare the system responses across the four control strategies.

This study used the MATLAB/Simulink platform for conducting numerical simulations. A custom-developed .m script implementing the CFOA was integrated with the power system model and controller architecture, and a step-load disturbance was applied to Area 1.

Simulink was selected as the main simulation tool because of its exceptional fidelity, consistent repeatability, and appropriateness for real-time control applications. The simulation model presents a detailed framework, including components for generators, control systems, transmission line delays, and nonlinear constraints like GRC and GDB, all seamlessly integrated within a cohesive simulation environment.

The simulation results shown in Figure 4 through 6 indicate that the CFOA-optimized Hybrid 1+PI and PID controllers demon-

Table 1: The optimum values of the Controller

Areas	Controllers	Parameters				
		K_{P1}	K_{I1}	K_{P2}	K_{I2}	K_{D2}
Area one	PI	0.5539	0.7518	-	-	-
	1+PI	0.0513	0.7387	-	-	-
	PID	-	-	0.6931	1.9999	0.8630
	1+PI and PID	1.9999	1.9999	1.6068	1.9999	0.6017
Area two	PI	0.0852	0.4023	-	-	-
	1+PI	0.0005	0.0052	-	-	-
	PID	-	-	1.9317	1.1121	1.7343
	1+PI and PID	1.9974	1.9969	1.0383	1.5405	1.9907

strate superior performance compared to traditional controllers across various metrics. It provides exceptional performance in mitigating delays, minimizing overshoot and undershoot, and decreasing settling times in both domains. Furthermore, the proposed controller exhibits enhanced regulation of tie-line power deviations, thereby improving inter-area coordination.

The frequency response in Area 1, shown in Figure 4, indicates that the CFOA-optimized Hybrid 1+PI and PID Controller achieves the lowest undershoot when compared to all other controllers evaluated. The system demonstrates a more rapid and stable convergence to steady-state conditions when compared to the standard PI, 1+PI, and traditional PID controllers. The frequency response transitions seamlessly back to the nominal value, exhibiting minimal long-term fluctuation or steady-state error. The distinctive dynamic characteristics highlight the effectiveness of CFOA in pinpointing globally optimal control parameters. The resulting controller demonstrates impressive adaptability to load variations while maintaining system stability throughout both the transient and steady-state phases of the response.

From the simulation results shown in Figure 5, which illustrate the frequency deviation response in Area 2 under a load disturbance applied to Area 1, it can be observed that the Hybrid 1+PI and PID Controller maintain stable control performance, despite Area 2 not being directly affected by the disturbance.

In the initial transient phase, the hybrid controller shows a significant benefit in reducing overshoot and oscillations relative to the other controllers. The response curve demonstrates impressive smoothness and efficient damping, unlike the significant oscillatory behavior observed in PI and PID controllers, which frequently exhibit notable underdamping.

Moreover, the hybrid controller reaches the steady-state condition more quickly than its alternatives and maintains a remarkably low steady-state error. The frequency deviation in Area 2 gradually approaches zero in a consistent and reliable way. A key component in the context of multi-area LFC systems, the results highlight the controller's capacity to efficiently coordinate control activities across interconnected regions.

As demonstrated by the tie-line power variance between Areas 1 and 2, the Hybrid 1+PI and PID Controller continuously provides outstanding performance (Figure 6). This outcome aligns with previous findings in frequency regulation, affirming its overall de-pendability.

During the early stages of the disturbance, the hybrid controller shows a notable capacity to mitigate variations in tie-line power flow. Comparing it to conventional PI, 1+PI, and PID controllers, it consistently shows little variance over all time intervals. With little overshoot and undershoot, the controller's reaction is smooth and on time, showing how well it can accurately control power distribution across interconnected areas.

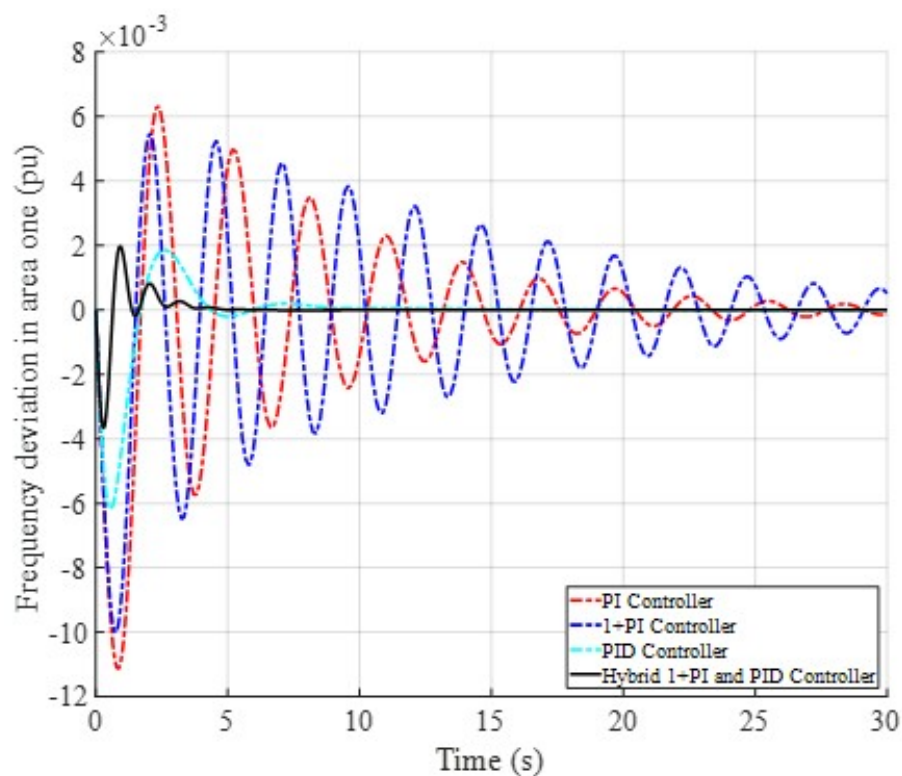


Figure 4: Frequency deviation in area one.

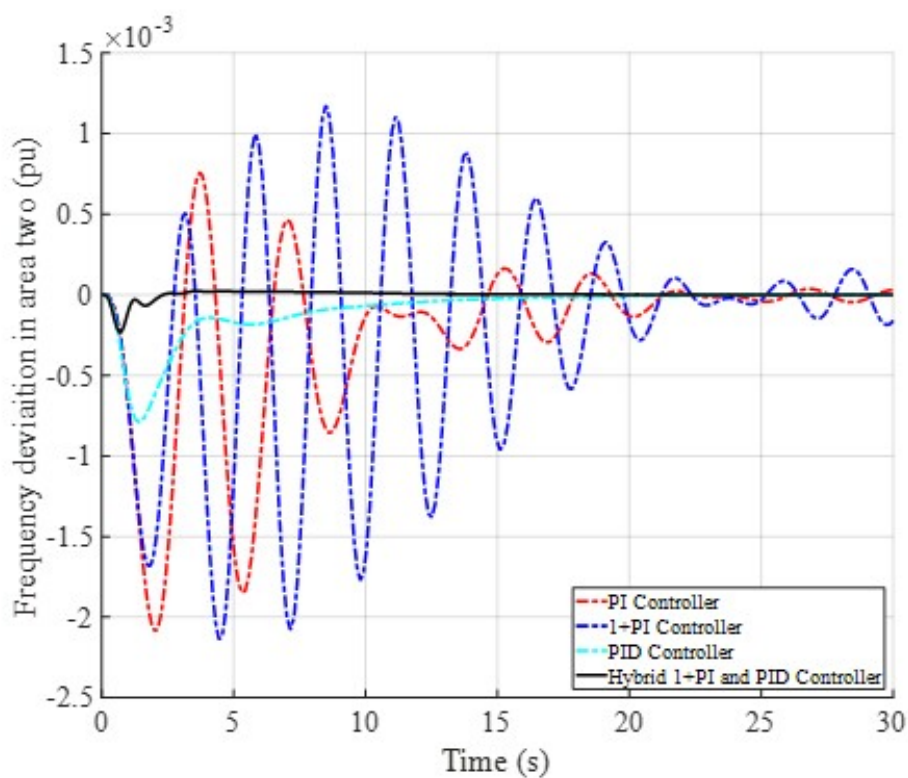


Figure 5: Frequency deviation in area two.

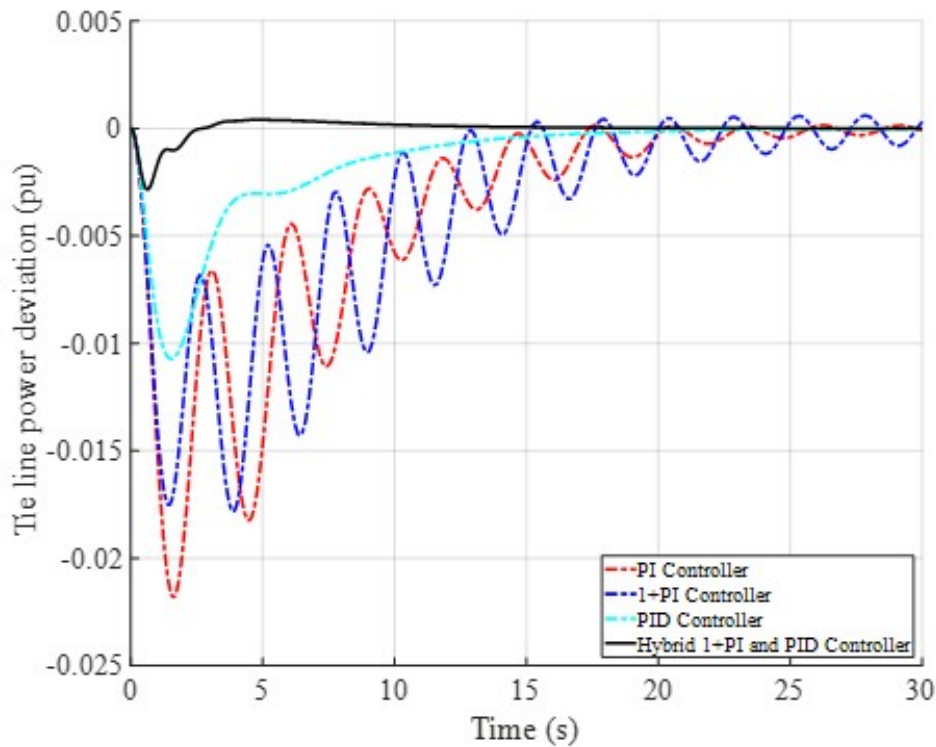


Figure 6: Tie line power deviation.

The hybrid controller demonstrates the quickest convergence to a steady state while effectively reducing oscillations, which is essential for ensuring dependable power transfer among interconnected regions. In multi-area systems, where transmission lines serve as channels linking different control zones, this feature is essential. In these situations, maintaining a balanced tie-line power flow is essential for the reliability and efficacy of multi-area load frequency regulation.

Table 2: Particulars of examinations using various controls.

Controller	Δf_1			Δf_2			ΔP_{tie}			ITAE
	OS	US	ST	OS	US	ST	OS	US	ST	
PI	0.0063	-0.0111	15.393	0.0007	-0.0020	5.9446	0.0001	-0.0217	19.477	1.0920
1+PI	0.0054	-0.0100	24.803	0.0011	-0.0021	12.762	0.0006	-0.0178	24.296	1.5983
PID	0.0018	-0.0061	3.4336	0.0001	-0.0007	0.0001	0.0001	-0.0107	10.635	0.2465
1+PI and PID	0.0019	-0.0036	1.1314	2.2e-05	-0.0002	0.0001	0.0004	-0.0028	1.6428	0.0336

The system response behaviors observed from the simulations clearly demonstrate the effectiveness of the CFOA in tuning the controller parameters. The CFOA-optimized Hybrid 1+PI and PID Controller exhibits superior stability across both transient and steady-state dynamics.

Its fast, smooth response and the ability to significantly suppress tie-line power deviations are strongly aligned with the lowest achieved value of the numerical performance index, ITAE, which was recorded at 0.0336 as shown in Table 2. This indicates that the system can effectively minimize time-weighted accumulated errors under dynamic conditions.

In contrast, the other controllers—PI, 1+PI, and conventional PID—while capable of reducing deviations to some extent, exhibit pronounced oscillatory behavior and significantly higher overshoot and tie-line deviation. These characteristics could compromise long-term system stability, particularly in interconnected multi-area networks.

These findings clearly validate that the combination of a hybrid control structure with an efficient tuning mechanism such as CFOA not only enhances the performance of multi-area LFC but also provides a balanced, reliable, and dynamically superior solution when compared to conventional controllers across all major performance metrics.

4 Conclusion

This paper proposes a solution for load frequency management in nonlinear two-area power systems by designing a hybrid control scheme that combines the advantages of both 1+PI and PID controllers. The CFOA, a metaheuristic approach modeled by traditional fishing methods seen in nature, was used to optimize the controller parameters. This method provides a strong framework for parameter optimization in intricate control systems, successfully mitigating local minimums while maintaining a balance between exploration and exploitation.

The study's conclusions show how well the CFOA-based hybrid design works to enhance frequency regulation in linked power areas, particularly in systems that incorporate renewable energy sources and quickly fluctuate load. Flexible design provides a scalable solution that meets the requirements of modern power networks by supporting various operational scenarios.

Future progress may be achieved by incorporating CFOA with sophisticated intelligent control systems, including fuzzy-FOPID or neuro-PID techniques. The practical feasibility would be illustrated by conducting tests in real-time modeling situations or in environments with stochastic load fluctuations.

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Appendix A

The nominal parameters adopted for the two-area power system are as follows: $F = 60$ Hz; $R_1 = 0.05$ MW/Hz; $R_2 = 0.0625$ MW/Hz; $B_1 = 20.6$ Hz/MW; $B_2 = 16.9$ Hz/MW; $SLP = 0.2$ pu; $T_{g1} = 0.2$ s; $T_{g2} = 0.3$ s; $T_{t1} = 0.5$ s; $T_{t2} = 0.6$ s; $H_1 = 5$; $H_2 = 4$; $D_1 = 0.6$; $D_2 = 0.9$; $T = 2$.

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