Adaptive Load Frequency Control for Interconnected Grids Using Ant Lion Optimization

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Received: 25 July 2025 | Revised: 17 September 2025, 26 October 2025, and 20 November 2025 | Accepted: 5 December 2025

DOI: https://doi.org/10.48084/etasr.13641

ABSTRACT

This paper presents an Ant Lion Optimization (ALO) algorithm for Load Frequency Control (LFC) of a three-area interconnected power system, which utilizes a Proportional–Integral–Derivative (PID) controller. The LFC problem is essential for maintaining system stability and dependability by balancing power generation and load demand. The study determines the optimal PID controller settings to reduce frequency oscillations and improve dynamic performance using sophisticated metaheuristic optimization techniques, such as the ALO algorithm. MATLAB/Simulink simulations are used to assess the controller's performance and implementation. The simulation is run under a step load disturbance to demonstrate the efficacy of the suggested model. The robustness of the suggested scenario is confirmed by the fact that the control target can still be accomplished even when governor and turbine parameters alter. The Integral of Time-weighted Absolute Error (ITAE) is used to compare the simulation results obtained by different optimization strategies. The study demonstrates that ALO significantly improves the dynamic performance of LFC in interconnected power systems. It achieves faster settling time, reduced frequency deviations, and enhanced system stability compared to traditional methods. ALO-based controllers also show robust adaptability to load variations and parameter uncertainties.

Keywords-Load Frequency Control (LFC); Ant Lion Optimization (ALO); Proportional–Integral–Derivative (PID); energy consumption; Integral of Time-weighted Absolute Error (ITAE)

I. INTRODUCTION

To prevent negative impacts on power plant equipment, which could eventually result in power outages, frequency in electric power systems must be kept at around a nominal value. Maintaining the stability and reliability of interconnected power systems while frequently fluctuating load conditions occur is a critical challenge, especially in large-scale power networks with multiple control areas [1]. Additionally, the power system network has become more adaptable in managing supply and demand fluctuations [2]. Various aspects of power and frequency control are discussed in [3]. One of the key elements to ensure this stability is Load Frequency Control (LFC), which ensures that generator power output is adjusted to reduce frequency variations and match load demand [4]. Any imbalance between generation and load in power systems leads to frequency fluctuations, which can affect the system's performance and cause outages if not properly controlled [5]. Numerous control techniques have therefore been implemented over the years to address the LFC problem effectively in multi-area power systems [6-8].

Classical control approaches like Proportional–Integral–Derivative (PID) controllers have been widely adopted for LFC due to their simplicity and ease of implementation [9]. However, the performance of conventional PID controllers depends heavily on the proper tuning of control parameters, which becomes increasingly complex in multi-area power systems with nonlinearities and uncertainties [10]. To address this issue, various optimization algorithms have been employed to enhance PID controller performance by determining optimal control parameters. Techniques such as Particle Swarm Optimization (PSO) [11, 12], Genetic Algorithm (GA) [13], and Jaya algorithm (JA) [14] have shown promising results in optimizing LFC controllers in recent years. Despite these advances, there remains a need for more robust and efficient algorithms [15] to improve the dynamic response and reduce the frequency deviations in interconnected systems.

Among newer metaheuristic optimization algorithms, the Ant Lion Optimization (ALO) algorithm has gained significant attention due to its strong balance between exploration and exploitation, both of which are essential for optimizing control parameters in complex, nonlinear systems [16]. ALO has been successfully implemented to solve various optimization problems, such as renewable energy management [17] and automatic voltage regulation [18], demonstrating its robustness and effectiveness. In the context of LFC, where achieving fast, stable, and coordinated frequency regulation across interconnected areas is critical, ALO offers a promising alternative to traditional optimization algorithms by providing more accurate and reliable solutions for PID parameter tuning in multi-area power systems.

Several studies have focused on applying artificial intelligence and optimization techniques to improve LFC performance in interconnected systems. In particular, various metaheuristic optimization algorithms, including the sine cosine algorithm [19], teaching–learning-based optimization [20], grey wolf optimization [21], and firefly algorithm [22], have been employed for LFC, achieving varying levels of success in enhancing controller performance. To address economic considerations, the authors in [23] propose a cost-optimization model for the biomass supply network. In addition, to improve power system frequency stability, an LFC can be integrated with a Battery Energy Storage System (BESS) and a PID controller [24]. The main performance metrics used in this paper are those typically employed to reduce frequency deviations.

The ALO control algorithm proposed in this study utilizes a PID controller, which is simple to implement and reliable compared to conventional control methods. The simulation results demonstrate the reliability and validity of the proposed control strategy. Furthermore, the suggested approach outperforms the two benchmark control schemes in terms of control performance and frequency regulation. The structure of this work is as follows: (i) the reachable and bounded conditions of the proposed method are mathematically confirmed; (ii) the ALO algorithm is applied to the LFC problem and compared to two alternative control strategies through simulation; (iii) the resilience of the suggested method to parameter changes is verified.

II. SYSTEM UNDER STUDY

A simplified model of linked electrical grids, specifically a three-area power system configuration, is frequently employed in the study of LFC. To ensure frequency stability and efficient energy consumption, each region consists of its own collection of power generation units, load demands, and control mechanisms. Typically, PID controllers, governors, turbines, and power generators are used, as depicted in Figure 1.

The mathematical modeling of each area is as follows:

- Governor: $G_{TG}(s) = \frac{1}{1+sT_g}$
- Turbine: $G_T(s) = \frac{1}{1+sT_t}$
- Power system: $G_{ps}(s) = \frac{K_{ps}}{1+sT_{ps}}$

Here, T_g, T_t, and T_{ps} denote the time constants of the governor, turbine, and power system, respectively, whereas K_{ps} is the gain of the power system.

The basic configuration of a PID controller is given in Figure 2 and can be expressed as:

$$y(t) = K_p m(t) + K_i \int_0^t m(t)dt + K_d \frac{dm(t)}{dt} \qquad (1)$$

where m represents the control error and $y(t)$ is the control signal. The three controller parameters are the proportional gain K_p, integral gain K_i, and derivative gain K_d.

The objective function for this test system is defined using the Integral of Time-weighted Absolute Error (ITAE). The ITAE for the LFC is given by:

$$J = \text{ITAE} = \int_0^{t_{sim}} \left(|\Delta f_i| + |\Delta P_{tie_{12}}|\right) t dt \qquad (2)$$

where $\Delta P_{tie_{12}}$ is the tie-line power deviation, Δf_i is the frequency deviation in each area, and t_{sim} is the simulation time period. The controller parameters must satisfy the following constraints:

$$\text{Minimize } J$$
$$K_{p_{min}} \le K_p \le K_{p_{max}};\ K_{i_{min}} \le K_i \le K_{i_{max}};$$
$$K_{d_{min}} \le K_d \le K_{d_{max}} \qquad (3)$$

The minimum and maximum values of the controller gains were chosen as 0 and 5, respectively ($K_p, K_i, K_d \in [0,5]$). These limits provide a practical search interval that prevents unrealistically large gains while allowing sufficient freedom for the optimizer to find effective tuning solutions.

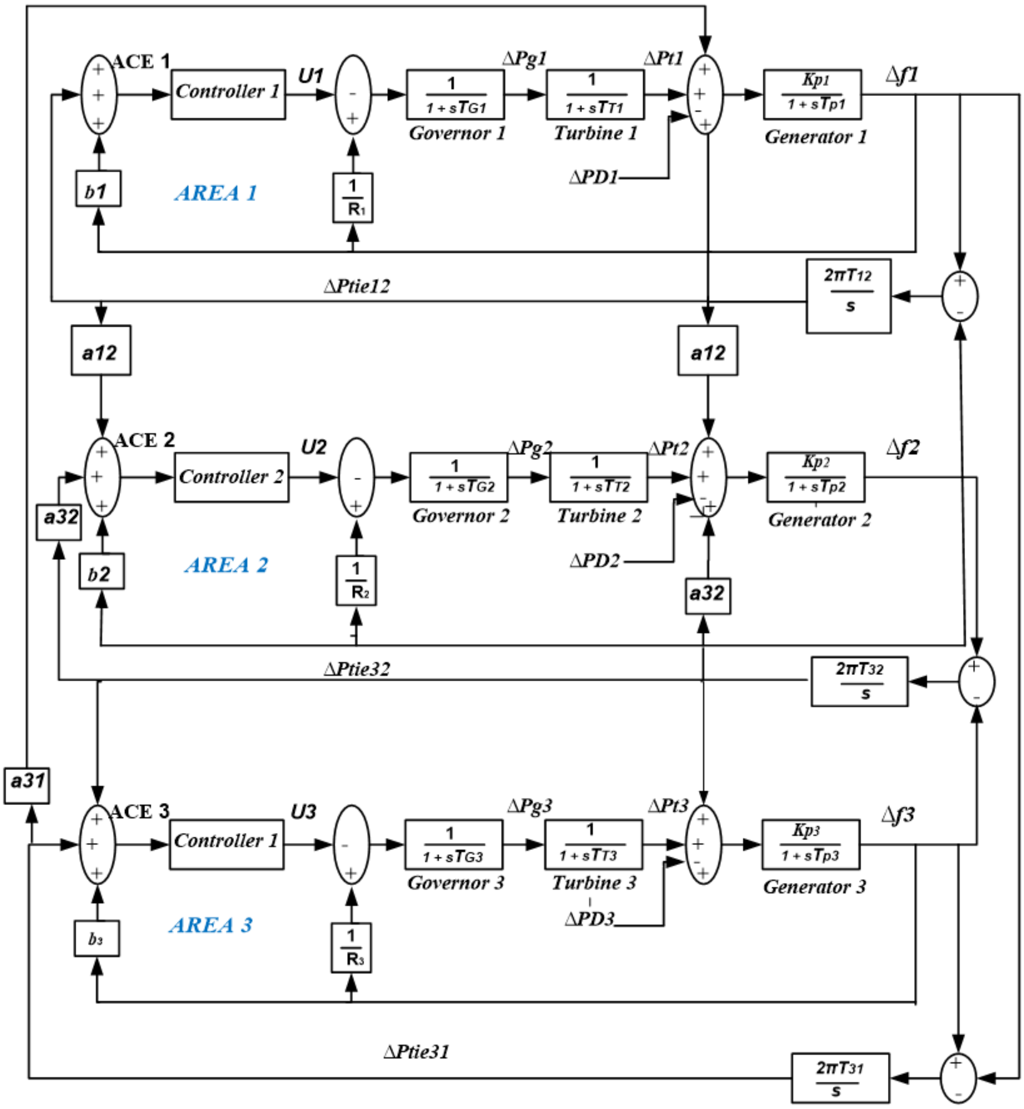


Fig. 1. Block diagram of a three-area LFC system.

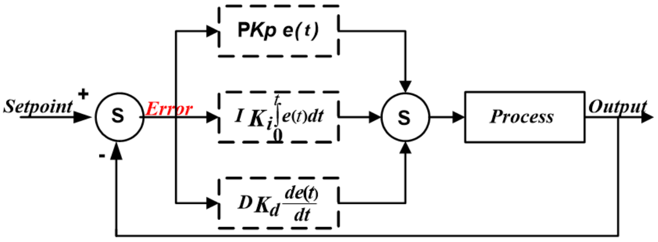


Fig. 2. Configuration of the PID controller.

III. ANT LION OPTIMIZATION

The ALO algorithm is a metaheuristic method inspired by nature that mimics how antlions hunt in the wild. Because of its ability to balance exploration and exploitation, ALO, proposed by authors in [16], is very useful for solving complicated optimization problems. ALO demonstrates superiority over other metaheuristic algorithms due to its effective balance between exploration and exploitation, Conventional methods, in contrast, often suffer from premature convergence. The algorithm requires fewer parameters, reducing implementation complexity and sensitivity to parameter tuning. In a stochastic search space, the method simulates the interaction between ants, representing potential solutions, and antlions, which serve as adaptive traps. The following stages are part of ALO's operational mechanism.

A. Search Space and Population

Within the specified search space, a population of ants and antlions is initiated randomly. A position vector that corresponds to a possible solution to the optimization problem is used to represent each ant and antlion.

B. Random Walk

Using a roulette wheel selection system, each ant walks at random while being influenced by a chosen antlion. Stochastic yet bounded exploration is ensured by mathematically modeling the walk as a cumulative sum of a sequence of random steps. Since ants move at random when searching for food in the wild, the random walk is used to mimic ant movement:

$$Y(t) = [0, \text{cumsum}(2g(t_1) - 1), \text{cumsum}(2g(t_2) - 1), \ldots, \text{cumsum}(2g(t_n) - 1)] \quad (4)$$

where n is the maximum number of iterations, t is the step of the random walk (in this case, an iteration), cumsum calculates the cumulative sum, and $g(t)$ is a stochastic function defined as:

$$g(t) = \begin{cases} 1, & \text{if } rand > 0.5 \\ 0, & \text{if } rand \leq 0.5 \end{cases} \quad (5)$$

where $rand$ is a random number generated with a uniform distribution in the interval [0,1]. To keep the random walks within the search space, they are normalized using min-max normalization:

$$Y_i^t = \frac{(Y_i^t - l_i)(m_i - n_i)}{(p_i^t - l_i)} + n_i \quad (6)$$

where n_i and m_i are the variable's current minimum and maximum, whereas l_i and p_i^t are the minimum and maximum of the random walk for the i-th ant at iteration t.

C. *Mechanism of the Trap*

Figure 3 shows the flow chart. Antlions "trap" ants by attracting them to their area. Concentrating the search on potential regions of the search space corresponds to exploitation in optimization:

$$n_i^t = antlion_k^t + n^{t-1}$$

$$m_i^t = antlion_k^t + m^{t-1} \quad (7)$$

where n_i^t and m_i^t are the minimum and maximum bounds for the selected j-th antlion at iteration t, and n^t and m^t are the minimum and maximum bounds for the i-th ant and antlion.

D. *Elite Solution*

In addition to the selected antlion, ants are guided by the elite antlion, the best solution found so far. This dual guidance mechanism integrates local and global search trends, improving convergence. Each ant performs a random walk (H_A^t) around the elite antlion (H_E^t) and the antlions selected by the roulette wheel. This can be modeled as:

$$ant_i^t = \frac{H_A^t + H_E^t}{2} \quad (8)$$

ALO is appropriate for a wide range of engineering, machine learning, and combinatorial optimization problems due to its capacity to strike a balance between intensification and diversification.

IV. SIMULATION RESULTS

In a three-area LFC system, the ALO algorithm tunes controller gains by simulating system dynamics, evaluating frequency and tie-line deviations using a fitness function, and guiding ants through random walks influenced by elite antlions. By iteratively updating solutions, ALO converges to optimal parameters, ensuring faster, stable, and robust frequency control.

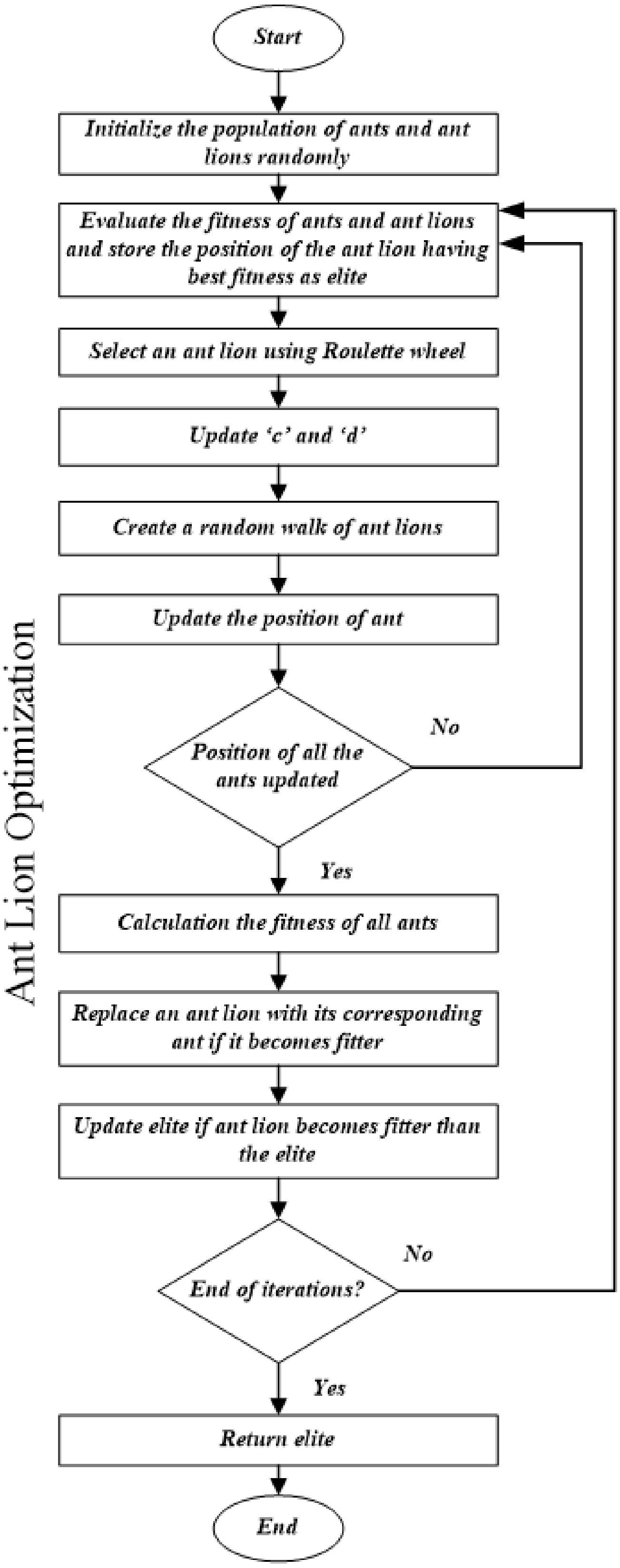


Fig. 3. Flow chart of the ALO algorithm.

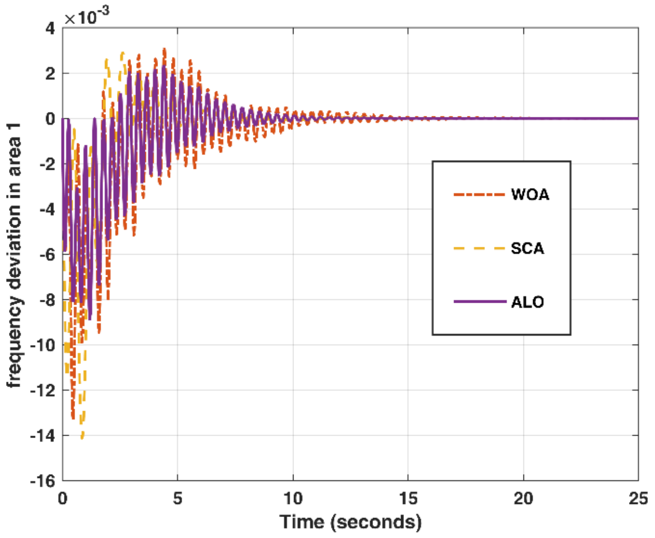
This section presents a comparative evaluation of the ALO algorithm against two widely used metaheuristic techniques: the Whale Optimization Algorithm (WOA) and the Sine Cosine Algorithm (SCA). All algorithms were implemented under identical simulation conditions in MATLAB/Simulink. A total of 25 iterations were selected for the optimization process, based on preliminary convergence studies. These initial tests indicated that ALO consistently achieved a high-quality solution well before the 25-th iteration for this specific optimization problem.

A. Case 1: Step Load Perturbation in Both Areas

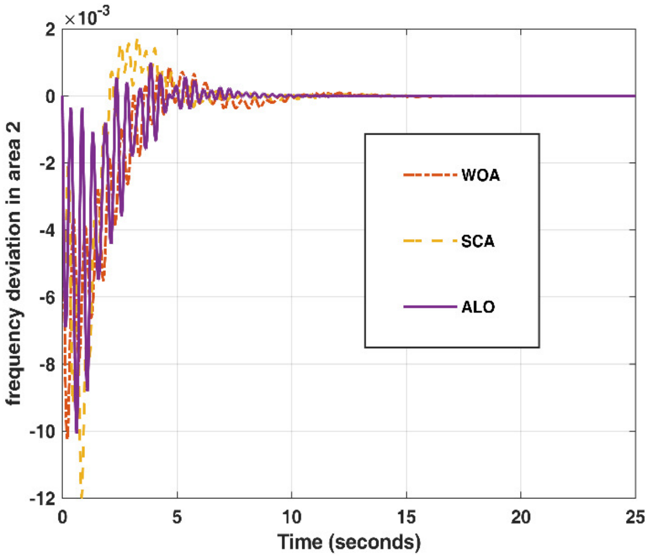
Simulation results are used to evaluate how different optimization methods influence tie-line power behavior and frequency deviations across the interconnected system. For a fair comparison, the optimal PID gain values for all three controllers are obtained through their respective optimization processes. The analysis is conducted on a three-area LFC system, which provides a realistic representation of interconnected grids. Table I presents the optimal controller parameters derived from each technique. Figures 4(a)-(c) display the frequency deviations for the three areas, whereas Figures 4(d)-(f) display the tie-line power deviations between the interconnected areas. All frequency and tie-line power deviations are reported in per-unit (pu) for consistency with standard conventions.

TABLE I. OPTIMAL PARAMETERS OF PID CONTROLLERS

Parameter	WOA	SCA	ALO
ITAE	0.15301	0.1013	0.09884
K_{p1}	2.9832	0.9975	4.9975
K_{p2}	2.5173	3.2137	2.8327
K_{p3}	0	0	0.34208
K_{i1}	5	3.2126	3.0111
K_{i2}	1.5671	4.2409	3.2958
K_{i3}	0.1847	1.9469	3.3834
K_{d1}	5	1.298	4.998
K_{d2}	1.058	4.636	2.608
K_{d3}	1.092	0	0.360



(a)



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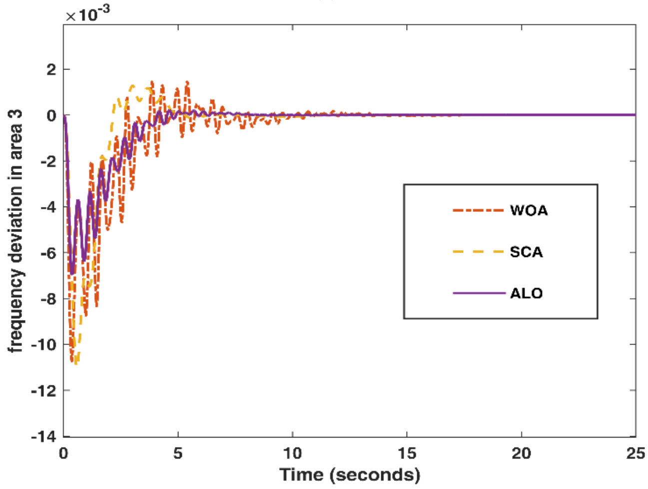

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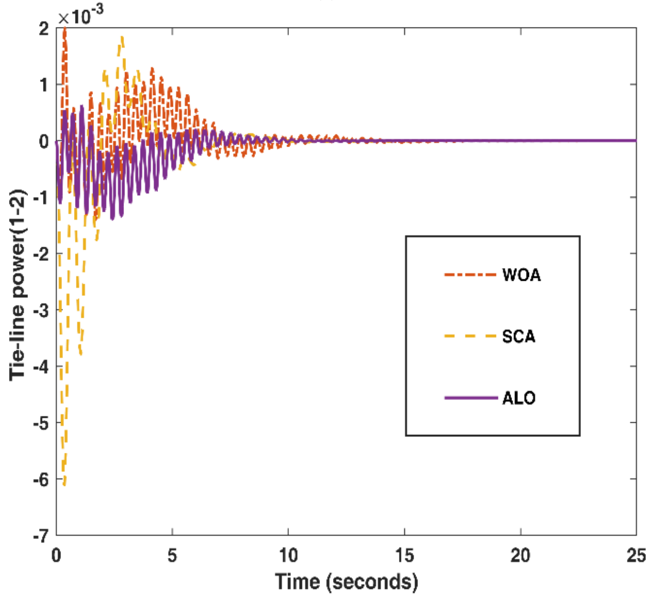
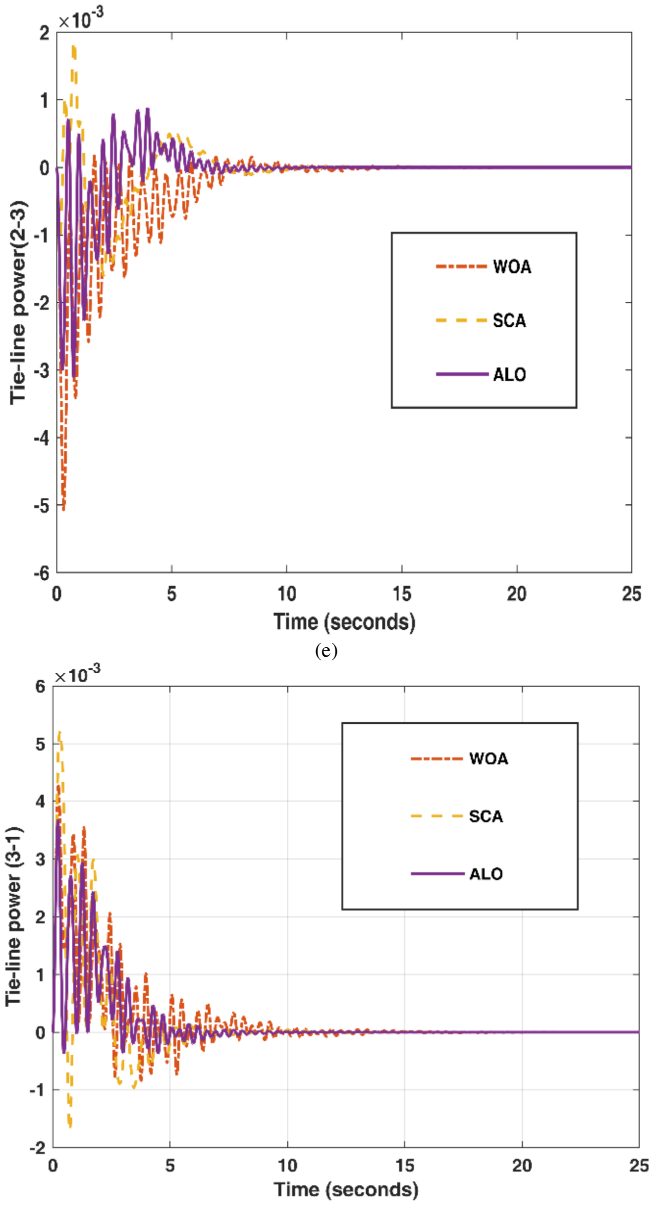


(d)



(e)

(f)

Fig. 4. Responses of the three-area system: (a) frequency deviation in area 1, (b) frequency deviation in area 2, (c) frequency deviation in area 3, (d) tie-line power between areas 1 & 2, (e) tie-line power between area 2 & 3, (f) tie-line power between areas 3 & 1.

The ITAE, used as the main performance index in this study, further demonstrates the effectiveness of ALO. ALO achieves an ITAE value of 0.098844, outperforming both the SCA and WOA methods, which yield 0.1013 and 0.15301, respectively. The lower ITAE value obtained by ALO indicates faster reduction of frequency oscillations, reduced overshoot, and improved stability. These improvements reflect the algorithm's strong balance between exploration and exploitation when tuning the PID controller parameters. Figure 5 presents the corresponding convergence curve, illustrating how ALO reaches an optimal solution more rapidly.

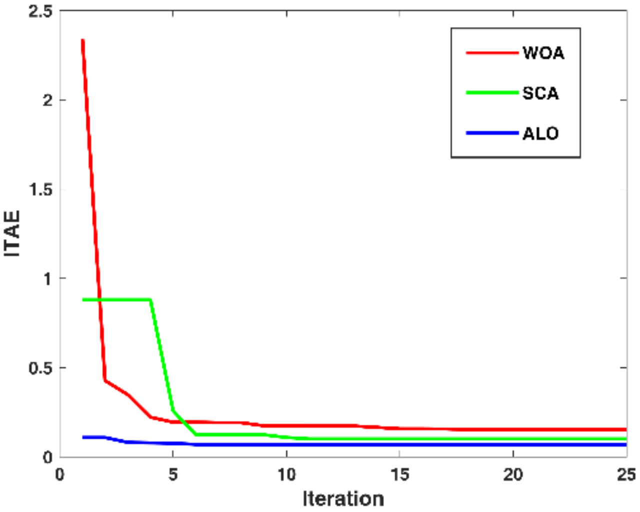


Fig. 5. Convergence curve of the ALO, SCA, and WOA based on the ITAE objective function.

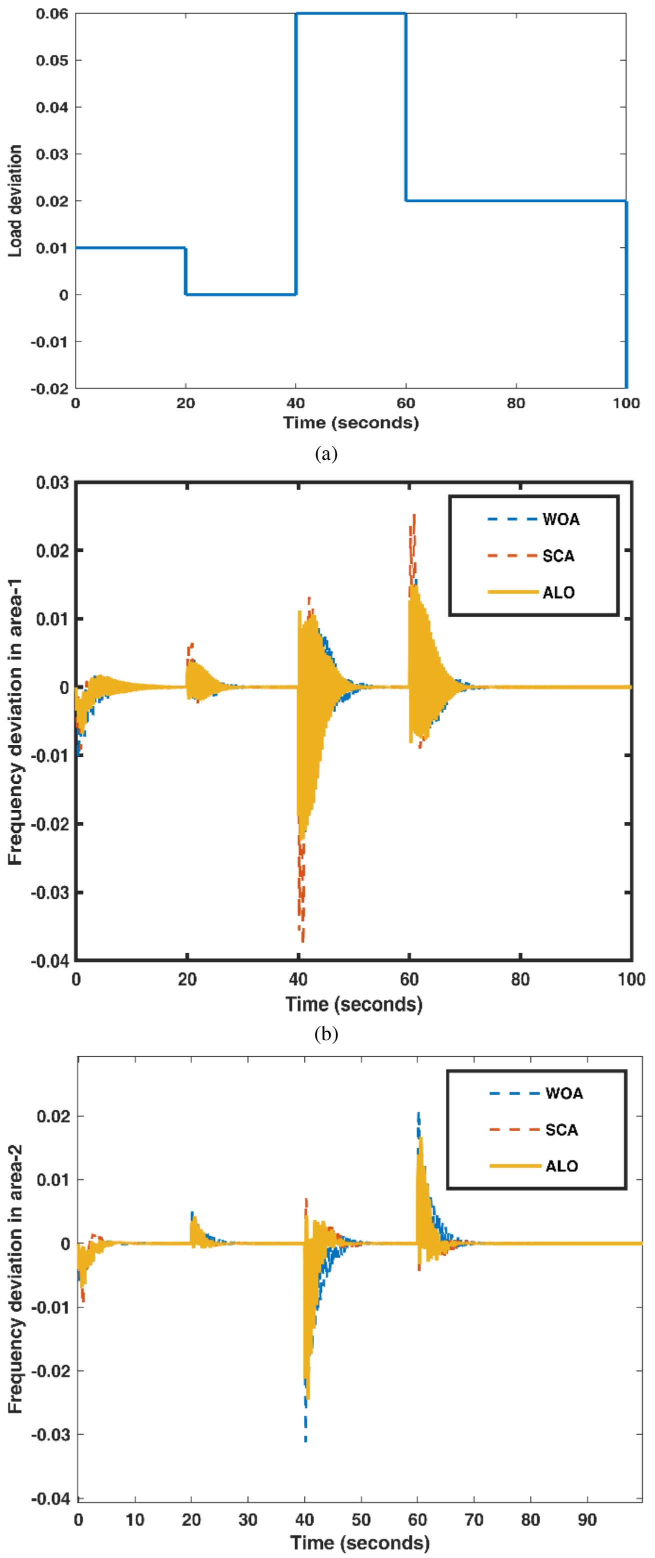
The settling times for ALO occur at 4.194 s, 5.47 s, 5.47 s, 7.75 s, 6.31 s, and 6.27 s for Δf_1, Δf_2, Δf_3, ΔP_{1-2}, ΔP_{2-3}, and ΔP_{1-3} respectively. The overshoot for Δf_1, Δf_2, Δf_3, ΔP_{1-2}, ΔP_{2-3}, and ΔP_{1-3} using ALO are 0.00173, 0.0007, 0.0003, 0.00063, 0.000855, and 0.00368, respectively. The undershoot for Δf_1, Δf_2, Δf_3, ΔP_{1-2}, ΔP_{2-3}, and ΔP_{1-3} using ALO are −0.0087, −0.0099, −0.0065, −0.0013, −0.00311, and −0.000372, respectively. The transient responses under step load perturbation in both areas are presented in Table II.

TABLE II. TRANSIENT RESPONSES USING DIFFERENT ALGORITHMS (CASE 1)

Algorithm	Δf_1	Δf_2	Δf_3	ΔP_{1-2}	ΔP_{2-3}	ΔP_{1-3}
	Settling time (s)					
SCA	4.855	5.99	5.90	8.70	7.05	8.97
WOA	9.60	6.33	8.85	10.54	6.96	9.13
ALO	4.194	5.47	5.47	7.75	6.31	6.27
	Overshoot					
SCA	0.0028	0.00176	0.00117	0.00187	0.001877	0.00518
WOA	0.00312	0.00086	0.00144	0.0019	0.000168	0.00446
ALO	0.00173	0.0007	0.0003	0.00063	0.000855	0.00368
	Undershoot					
SCA	−0.0141	−0.0119	−0.0109	−0.0061	−0.0015	−0.00164
WOA	−0.0132	−0.0102	−0.01068	−0.0008	−0.00506	−0.00083
ALO	−0.0087	−0.0099	−0.0065	−0.0013	−0.00311	−0.00037

B. Case 2: Random Load Perturbation in Both Areas

The frequency response of the three-area system under random load deviations is illustrated in Figure 6. From the simulation results, it is evident that the PID controller tuned using the ALO algorithm outperforms both the GWO and SCA approaches. Specifically, the peak overshoot for frequency deviations in areas 1 and 2 (Δf_1, and Δf_2) using ALO are 0.015 and 0.016, respectively, whereas the corresponding undershoot values are −0.022 and −0.025, respectively. The detailed transient response parameters for all three optimization methods under random load disturbances are presented in Table III.



(a)

(b)

(c)

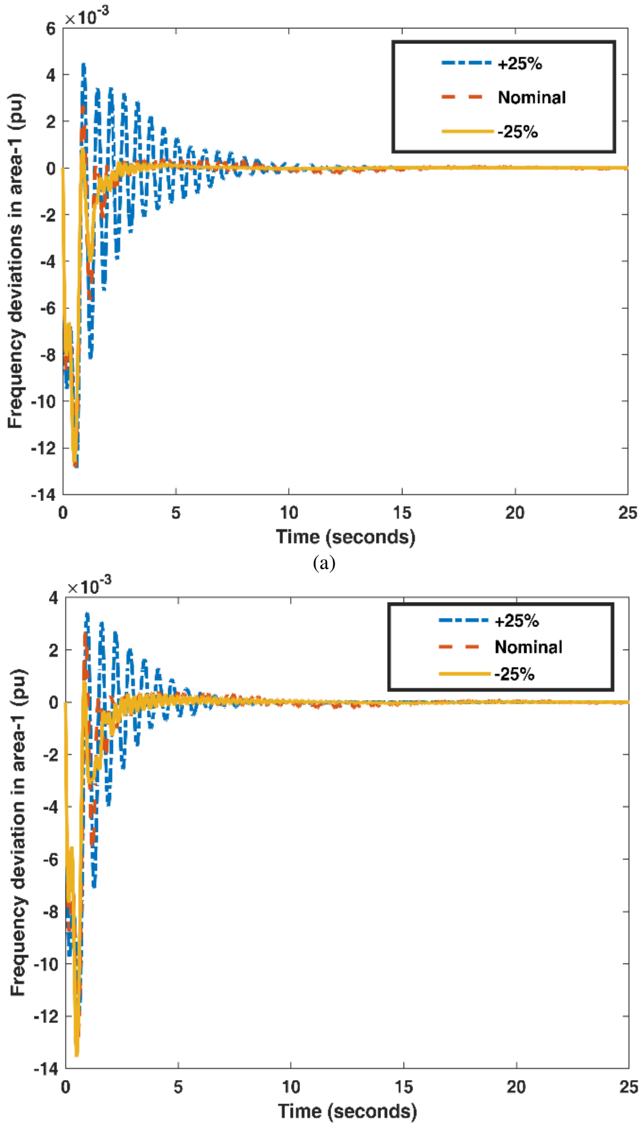
Fig. 6. Responses of the three-area system: (a) random load pattern, (b) frequency deviation in area 1, (c) frequency deviation in area 2.

TABLE III. TRANSIENT RESPONSES UNDER RANDOM LOAD (CASE 2)

Algorithm	Overshoot		Undershoot	
	Δf_1	Δf_2	Δf_1	Δf_2
SCA	0.025	0.02	-0.038	-0.032
WOA	0.018	0.018	-0.025	-0.027
ALO	0.015	0.016	-0.022	-0.025

C. Case 3: Sensitivity Analysis

A thorough sensitivity analysis was conducted by altering the governor and turbine time constants by +25%, nominal, and −25%. Figure 7 shows the resulting frequency deviations in area 1. Despite these parameter variations, the results indicate that the ALO-tuned PID controller maintains stable and robust frequency responses, demonstrating the controller's resilience to system fluctuations.



(a)

(b)

Fig. 7. Sensitivity analysis of frequency deviation in area 1: (a) by varying T_g, (b) by varying T_t.

V. CONCLUSION

To maintain Load Frequency Control (LFC) stability, an Ant Lion Optimization (ALO)-tuned Proportional–Integral–Derivative (PID) controller is proposed. Simulation results under three different cases demonstrate that the control objectives are successfully achieved, confirming the effectiveness of the ALO-based approach. Compared to the Whale Optimization Algorithm (WOA) and Sine Cosine Algorithm (SCA), the ALO-tuned controller exhibits reduced overshoot, faster response time, and decreased chattering, illustrating its superiority. The ALO-tuned PID controller is evaluated using key performance metrics such as the Integral of Time-weighted Absolute Error (ITAE), frequency deviation, and tie-line power deviation. Overall, the proposed scheme features a simple design that is easy to implement in industrial applications compared with other control techniques.

Future scope includes extending the approach to multi-area power grids with high renewable energy penetration, where dynamic uncertainties are more pronounced. Further research will benchmark the ALO-tuned PID controller against more recent and hybrid optimization algorithms to substantiate the findings. Integration with real-time control systems and hybrid artificial intelligence techniques can enhance robustness, scalability, and responsiveness to grid disturbances, ensuring stable operation under evolving energy landscapes.

ACKNOWLEDGMENT

This work is sponsored by INTI International University, Malaysia.

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