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Load Frequency Control of a Three-Area Power System using Lion Optimization Algorithm with FOPID Controller

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Abstract: Load Frequency Control (LFC) plays a critical role in maintaining system stability and ensuring reliable power system operation under varying load conditions. This paper proposes an advanced controlling strategy for a three-area interconnected power system using a Fractional Order Proportional-Integral-Derivative (FOPID) controller optimized by a Lion Optimization Algorithm (LOA). The proposed method enhances frequency regulation and tie-line power stability by incorporating fractional calculus into controller design and leveraging the adaptive search capability of lion-inspired optimization. The performance of the proposed controller is evaluated under different load disturbances and compared with conventional controllers and GA, PSO, and ACO algorithms. Simulation results demonstrate that the proposed method significantly improves frequency stability, reduces overshoot, minimizes settling time, and ensures better robustness compared to existing approaches.

Keywords: Load Frequency Control, Three-Area Power System, Fractional Order PID Controller, Lion Optimization Algorithm, Nature-Inspired Algorithms.

1. Introduction:

The proposed research focuses on the application of a Lion Optimization Algorithm (LOA) for the optimal tuning of a Fractional Order Proportional-Integral-Derivative (FOPID) controller in a three-area interconnected power system. The LOA is inspired by the cooperative and territorial behavior of lions, incorporating mechanisms such as pride formation, hunting strategies, mating, and territorial defense to attain the effective balances between exploration and exploitation. By utilizing these natural behaviors, the algorithm can efficiently search for optimal controller parameters and avoid being trapped in local optima. This capability is particularly beneficial in Load Frequency Control problems where multiple operating conditions, nonlinearities, and uncertainties are present. The FOPID controller extends the conventional PID controller by implementing two additional parameters, namely the fractional integral order (λ) and the fractional derivative order (μ). These extra tuning variables provide greater flexibility in shaping the dynamic response of the system. As a result, the controller

can achieve improved damping characteristics, faster settling times, and reduced frequency deviations following load disturbances. The fractional-order structure also enhances robustness against parameter variations and external disturbances, making it a suitable choice for modern interconnected power systems with diverse generation sources.

In the proposed three-area power system model, each control area consists of multiple generation units and is interconnected through tie-lines for power exchange. Any sudden load change in one area causes frequency deviations not only in the affected area but also in neighboring areas through tie-line interactions (1). Therefore, an effective Load Frequency Controller must regulate both the area deviations in frequency and tie-line power fluctuations simultaneously. The LOA-based FOPID controller is designed to minimize these deviations by optimizing an objective function that includes Integral Time Absolute Error (ITAE), Integral Square Error (ISE), and tie-line power deviation.

An optimized controller parameters ensure rapid restoration of system frequency to

its nominal value while maintaining acceptable power-sharing among interconnected areas. To evaluate the effectiveness of the proposed approach, extensive simulations are performed under different loading scenarios, including step load perturbations, random load variations, and renewable energy fluctuations (2). The dynamic responses obtained using the LOA-FOPID controller are compared with those of conventional P, PI, PID, and other optimized controllers such as GA-PID, PSO-PID, and ACO-FOPID. Performance metrics including maximum overshoot, undershoot, settling time, rise time, and steady-state error are analysed (3). The comparative results demonstrate that the LOA-FOPID controller provides the superior dynamic performance by significantly reducing oscillations and improving system stability under various operating conditions.

The proposed controller exhibits strong robustness against uncertainties arising from renewable energy integration, communication delays, and system parameter variations. As modern power systems increasingly incorporate wind and solar generation, frequency regulation becomes more challenging due to the intermittent nature of these resources. The adaptive search capability of the LOA enables the FOPID controller to maintain satisfactory performance even in the presence of such uncertainties. Consequently, the proposed LOA-

optimized FOPID controller offers a reliable and efficient solution for Load Frequency Control in future smart grid environments, contributing to enhanced power quality, system reliability, and operational security (4).

2. Proposed Method / Algorithm:

The proposed system consists of three interconnected control areas, each having its own generator, turbine, and governor system. The objective is to minimize the frequency deviations and tie-line power fluctuations using an optimized controller is shown in figure1. The first stage of the proposed methodology involves developing a mathematical model of a three-area interconnected power system for Load Frequency Control (LFC) analysis (5). Each control area consists of generating units represented by governor, turbine, and generator-load dynamics. The governor regulates the speed of the turbine in response to frequency deviations, while the turbine converts the control signal into mechanical power. The generator-load model represents the power system dynamics and frequency response under varying load conditions. The three areas are interconnected through tie-lines, allowing power exchange among them. Any load disturbance occurring in one area affects not only the local frequency but also the frequencies and tie-line power flows of the neighboring areas.

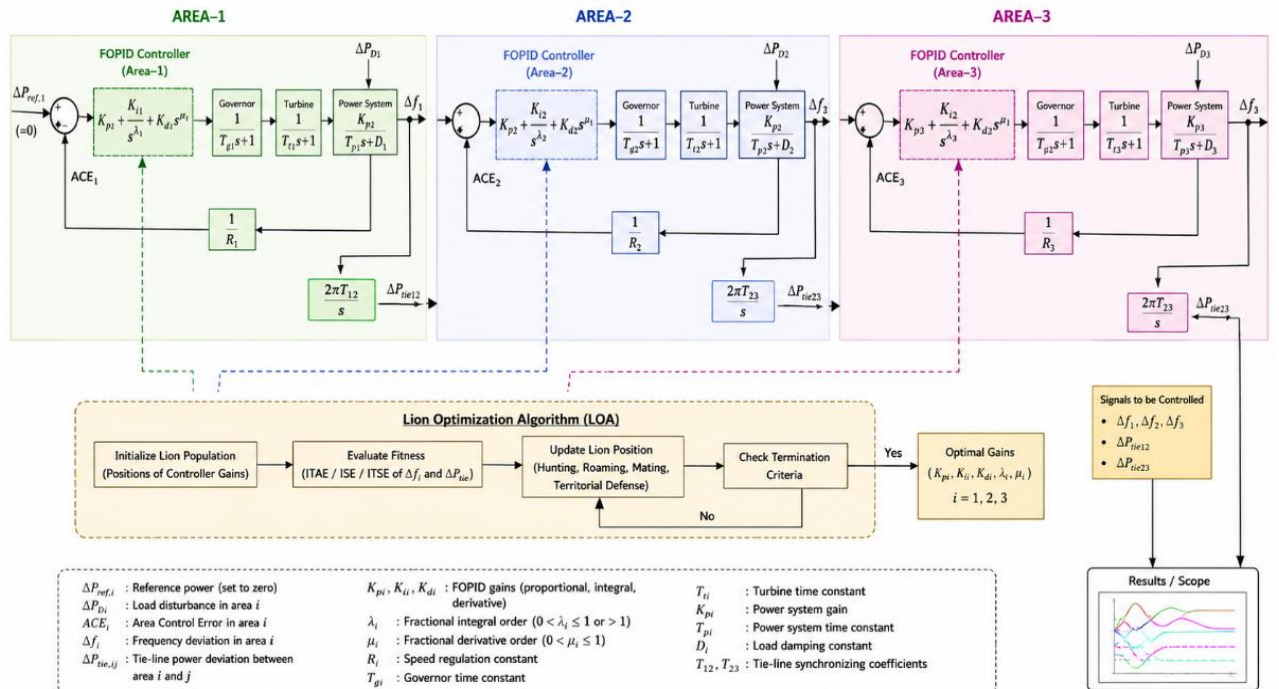


Figure 1: Generalized Structure of the three-area interconnected power system with

proposed controller and optimization algorithm

An accurate representation of governor, turbine, generator, and tie-line dynamics is essential for evaluating the effectiveness of the proposed control strategy under realistic operating conditions. The interconnected model is designed to capture the dynamic analysis of the power system under various disturbances and operating scenarios. The state-space

representation and transfer function models are developed using standard LFC equations. The area control error (ACE), which combines frequency deviation and tie-line power deviation, is used as the primary control signal for each area. This modeling framework enables the assessment of controller performance in maintaining the system frequency and scheduled power interchange among interconnected regions (6).

3. FOPID Controller Design:

Fractional calculus has been widely applied in engineering and scientific fields because of its ability to provide enhanced control performance and robustness. In modern control systems, conventional Proportional–Integral–Derivative (PID) controllers are increasingly being replaced by Fractional-Order PID (FOPID) controllers due to their superior dynamic characteristics. Unlike classical PID controllers, FOPID controllers employ non-integer orders of integration and differentiation, providing additional degrees of freedom for controller design. Most FOPID controller designs are based on frequency-domain approaches, while heuristic tuning methods (7) remain popular because of their simplicity and ease of implementation. Studies have shown that FOPID controllers offer greater robustness and improved delay margin characteristics when compared with traditional integer-order controllers. The Fractional-Order PID controller extends the conventional PID structure by introducing fractional powers in both the integral and derivative components. These additional tuning parameters enable greater flexibility and improved control performance. Various methodologies (8) have been proposed for determining the optimal parameters of FOPID controllers. Research findings indicate that Fractional-Order Fuzzy PID (FOFPID) controllers effectively address Load Frequency

Control (LFC) problems in interconnected multi-area power systems. Such controllers demonstrate superior performance in maintaining system frequency within acceptable limits during both power surplus and deficit conditions (9). Furthermore, FFOPID controllers have been validated for frequency regulation and bus voltage support under both grid-connected and islanded operating modes.

The concept of the Fractional-Order PID controller was formally introduced, who demonstrated its effectiveness for fractional-order systems (10). Subsequently, researchers investigated the ability of fractional controllers to suppress disturbances and reduce oscillations in chaotic dynamical systems. Their studies highlighted significant improvements in transient response characteristics, including reduced rise time, settling time, and overshoot. Compared with conventional PID controllers, FOPID controllers offer a simpler yet more reliable framework capable of achieving enhanced control performance. Load Frequency Control remains an important challenge in interconnected power systems, particularly those incorporating renewable energy resources. Numerous optimization techniques have been developed to tune PI, PID, and FOPID controllers for LFC applications in single-area and multi-area systems (11). Reviews of these approaches indicate that optimization-based controller tuning can significantly improve frequency regulation and tie-line power control. For example, adaptive neuro-fuzzy inference systems trained using the Ant Lion Optimizer (ALO) have been employed to obtain optimal PI controller gains, resulting in reduced frequency deviations (12) and minimized tie-line power fluctuations. Despite these advances, the primary challenge of LFC continues to be the development of highly robust controllers capable of maintaining frequency deviations within prescribed limits under varying operating conditions. Several intelligent optimization algorithms (13) have also been applied to improve controller performance. A two-degree-of-freedom fuzzy PID controller optimized using the Spider Monkey Optimization algorithm was proposed for a two-area interconnected power system. Performance evaluation demonstrated improvements in settling time, overshoot, and undershoot (14)

under both linear and nonlinear operating conditions. Similarly, the Flower Pollination Algorithm has been used to optimize PID controller parameters in multi-area LFC systems consisting of interconnected thermal generating units. Comparative studies showed that this approach outperformed controllers tuned using Genetic Algorithms and Particle Swarm Optimization techniques (15).

Simulation-based controller design is commonly carried out using MATLAB, where controller parameters are adjusted to achieve desirable transient and steady-state responses. Firefly Algorithm-based PID controllers have been developed for multi-area multi-source power systems (16) and tested under random load disturbances. Results demonstrated effective frequency regulation in systems containing thermal, hydro, and gas generation units. Additionally, studies revealed that AC–DC tie-line configurations can provide better dynamic performance than conventional AC tie-lines. GWO based PID controllers equipped with low-pass filters have also been applied to multi-area power systems operating under uncertain loading conditions, resulting in improved stability (17) and enhanced overall performance. Despite significant progress in PID controller design, challenges such as system nonlinearities, communication delays, and operational uncertainties continue to affect control performance. Communication delays, in particular, require careful consideration because control signals must often be transmitted over long distances from centralized control centers to remote generating units. Robust PID-based control strategies have therefore been developed to maintain frequency deviations (18-19) within acceptable limits while accounting for practical constraints and uncertainties.

Recent research has also focused on hybrid intelligent control approaches for interconnected power systems. Simulation-based tuning of PID controllers has been employed to enhance stability and tracking performance in multi-area networks. Internal model control concepts have been integrated with voltage source converter systems to improve controllability and dynamic response under sudden system disturbances (20-22). Furthermore, hybrid PID–Fuzzy–PID controllers optimized using modified Grey Wolf Optimization (MGWO) techniques have

demonstrated robust performance under random load variations. These controllers have been successfully applied to interconnected multi-source power systems (23), highlighting their adaptability and effectiveness in Load Frequency Control applications.

Based on the findings reported in the literature, FOPID controllers provide superior stability characteristics and improved regulation of frequency and tie-line power deviations when compared with conventional PI and PID controllers. Therefore, the present research focuses on the optimal tuning of PI, PID, and FOPID controllers for frequency regulation in a multi-area, multi-source power system. Special emphasis is placed on evaluating the effectiveness of FOPID controllers (24) optimized using Feed-Forward, Multi-Objective Grey Wolf Optimization and Lion optimization algorithms. Comparative analysis indicates that the LOA based FOPID controller achieves better dynamic performance by reducing overshoot, undershoot, and settling time, thereby enhancing the overall stability and reliability of the interconnected power system (25-27).

The FOPID controller is defined by:

$$G(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu$$

where,

K_p , K_i , K_d = proportional, integral, derivative gains

λ , μ = fractional orders

This structure provides enhanced control flexibility compared to conventional PID.

Lions are among the most social members of the wild cat family, exhibiting both cooperative and competitive behaviors within their populations. Their pronounced sexual dimorphism (26), reflected in both physical appearance and social roles, makes them a unique species for behavioral studies. Lion populations generally exhibit two social structures: resident and nomadic groups.

Resident lions live in organized social units known as prides, which typically consist of several adult females, their offspring, and one or more adult males. As male cubs reach sexual maturity, they are usually forced to leave their natal pride and establish their own territories or join other groups. The second social

arrangement involves nomadic lions, which do not belong to a permanent pride. These lions move over large areas either alone or in small groups. Nomadic pairs are often composed of related males that have left their original pride together. It is important to note that lions may transition between these two lifestyles, with residents becoming nomads and nomads eventually joining or establishing prides.

Unlike most other feline species, lions frequently engage in cooperative hunting. Female lions, known as lionesses, often work together to stalk and surround prey from multiple directions before launching a coordinated attack. This teamwork significantly increases hunting success rates. While the lionesses typically perform most of the hunting activities, adult males and some females often remain behind to guard the pride and rest until the hunters return with food. Lions do not have a fixed breeding season and are capable of mating throughout the year. Female lions are polyestrous, meaning they experience multiple reproductive cycles annually when they are not nursing cubs. During periods of estrus, a lioness may mate with more than one male. Territorial behavior is also an important aspect of lion ecology. Both males and females communicate ownership of an area through scent marking, particularly by depositing urine at strategic locations within their territory. This behavior helps define territorial boundaries and reduces conflicts with neighboring lions.

4. Objective Function

The optimization aims to minimize:

$$J = ITAE \int_0^t (|\Delta f_1(t)| + |\Delta f_2(t)| + |\Delta f_3(t)| + |\Delta P_{Tie1}| + |\Delta P_{Tie2}|) dt$$

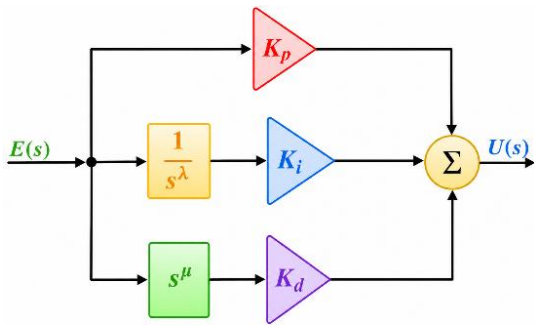


Figure 2: Schematic diagram of Fractional Order PID controller

The schematic diagram for the proposed

$$J = \int_0^T (\Delta f_1^2 + \Delta f_2^2 + \Delta f_3^2 + \Delta P_{tie}^2) dt$$

where:

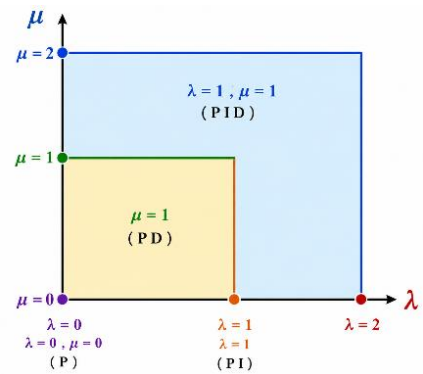
Δf_i = frequency deviation in area i

ΔP_{tie} = tie-line power deviation

The FOPID controller easily achieve the iso-damping behaviour and providing better outcomes of the system with higher-order performance. At the same time, it is more stable and robust than PID controller. This proposed controller can achieve enhanced output responses for the system with maximum phase. The FOPID controller consists of two additional parameters, namely (λ) the order of integral part and (μ) the order of derivative part, while K_p , K_i , and K_d are the controllers as in a conventional PID controller (28).

The FOPID controller is identified as controller with better efficiency in research and industries when compared with the conventional PID controllers. The concept of fractional order deals the differential equations with fractional calculus. The generalized version of the conventional PID is the FOPID controllers, where integral and derivative orders are non-integer. The expansion of derivative and integration order from integer to fractional-order exhibits better flexibility (29) to the design of controller and also offers improved dynamic performance. The differential equation of control signal $u(t)$ in terms of error signal $e(t)$ is in the eqn;

$$u(t) = -[K_p + K_i D_t^{-\lambda} + K_d D_t^{\mu}]e(t)$$



FOPID controller is presented in figure 2.

FOPID controller has the transfer function which can be represented in the eqns.

$$U(s) = K_P + \frac{K_I}{S^\lambda} + K_D S^\mu$$

where, K_P , K_I , and K_D are gain parameters (30) of PID, λ and μ are the orders of integrator and differentiator respectively.

Five conditions stated below could be realized and it is not possible for the conventional PID controllers. If $\lambda = 1$ and $\mu = 1$ classical PID controller, If $\lambda = 0$ and $\mu = 1$ classical PD controller, If $\lambda = 1$ and $\mu = 0$ classical PI controller, If $\lambda = 0$ and $\mu = 0$, classical P controller.

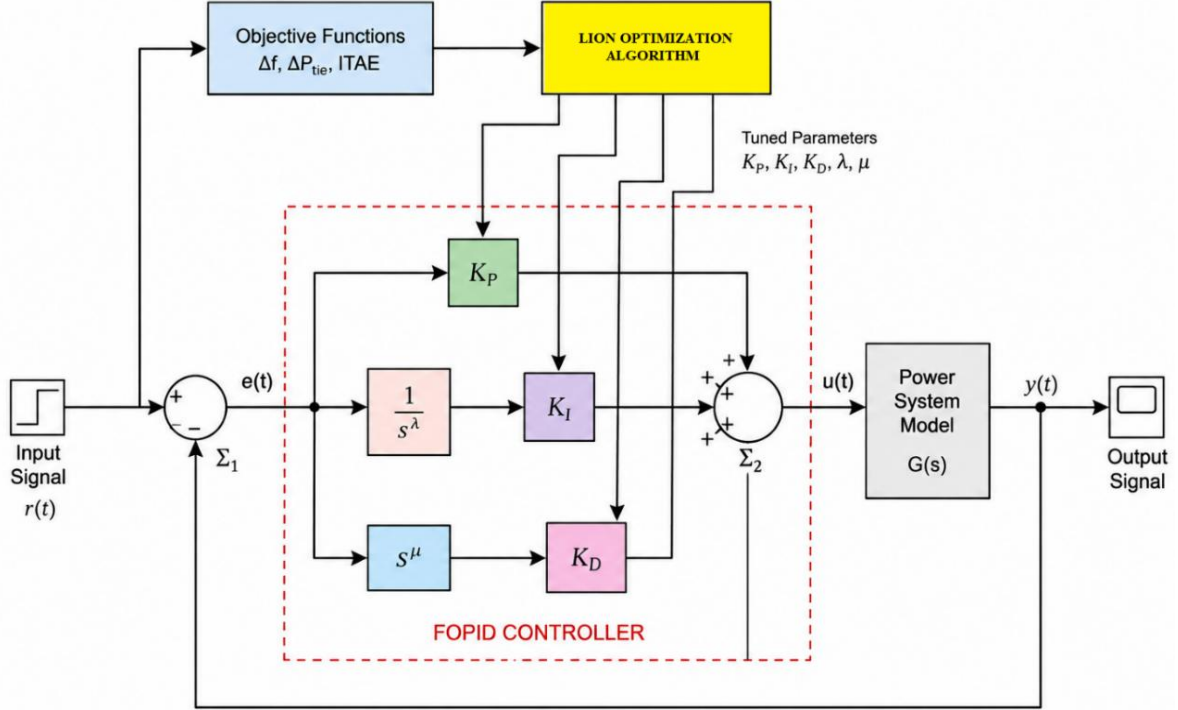


Figure 3: System Model using FOPID and LOA Algorithm

If λ is fraction and μ is fraction, FOPID controller. Better results (31) can be expected by fine tuning all the five parameters of the FOPID control. The performance criteria normally taken in design control which include Integral of Time multiplied Absolute Error (ITAE), and Integral of Squared Error (ISE). The principle of ITAE decreases the time of settling (32-33) that cannot be attained using ISE reliant tuning. Also, the criterion of ITAE decreases the overall peak overshoot.

Both ITAE and ISE are used in this work as an objective function for the optimization of the controller considered in the model of a power system. ITAE and ISE (34) are obtained from the simulation results got by the use of algorithms FFA and LOA which were simulated with different controllers. Among these considered controllers, the FOPID controller with LOA shown in figure 3 provides the better results than the other two conventional controllers. The calculation of

the objective function of the ITAE is performed by the equation,

$$J = ITAE \int_0^t (|\Delta f_1(t)| + |\Delta f_2(t)| + |\Delta f_3(t)| + |\Delta P_{Tie1}| + |\Delta P_{Tie2}|) dt$$

Similarly, for the other objective function of ISE values were determined based on the algorithms (35) considered in this work. The estimation of the ISE objective function is done using the following equation,

$$J = ISE \int_0^t |e^2(t)| dt$$

In the equation above, Δf_1 , Δf_2 , and Δf_3 are the frequency deviations of system; ΔP_{Tie} is incremental alteration in power grid tie-line and ' t ' indicates simulation time range. Design of optimization (36) is very challenging, partly due to the complexity and high non-linearity of the LFC problem. Conventional algorithms

are not best suited to highly non-linear global optimization; metaheuristic algorithm design is robust, subject to uncertainty in parameters and maximizes (37-38) the output performance and efficiency.

5. Methodology

During the optimization process, the social behaviours of lions, including pride formation, hunting, mating, territorial defense, and migration, are mathematically modelled to explore the search space efficiently. Hunting behavior enhances exploration by searching for promising regions, while mating and mutation operations improve diversity and prevent premature convergence. The fitness of each solution is continuously evaluated, and the best-performing lions are retained for subsequent generations. Through iterative updates, the algorithm converges toward the optimal controller parameters that minimize frequency deviations and tie-line power oscillations. The superior performance of the LOA arises from its effective balance between exploration and exploitation. Unlike traditional optimization techniques, which may become trapped in local optima, LOA possesses strong global search capability and consistently identifies near-optimal solutions.

This characteristic significantly contributes to the improved dynamic response achieved by the proposed LOA-FOPID controller. The developed three-area interconnected power system is simulated in MATLAB/Simulink to evaluate the effectiveness of the proposed controller. Step load disturbances are introduced in one or more control areas to emulate sudden changes in power demand. These disturbances create frequency deviations and tie-line power fluctuations, allowing the dynamic response of the system to be analyzed.

The simulation studies focus on key performance measures including settling time, overshoot, undershoot, frequency deviation, tie-line power deviation, and Integral Square Error (ISE). The LOA-optimized FOPID controller is tested under various operating conditions to verify its robustness and adaptability. The obtained responses indicate that the proposed controller quickly suppresses oscillations and restores the system to steady-state conditions following disturbances.

To validate the effectiveness of the proposed method, a comprehensive comparative study is performed using Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) based PID controllers. These optimization algorithms have been widely employed in Load Frequency Control applications due to their ability to determine near-optimal controller parameters. However, they often face challenges such as slow convergence speed, premature convergence, and limited capability in handling highly nonlinear systems.

6. Results and Discussion

The performance comparison, based on the illustrative frequency response curves and comparison bar charts, clearly demonstrates the effectiveness of the proposed LOA-FOPID controller in Load Frequency Control of the three-area interconnected power system. The simulation results indicate that the LOA-FOPID controller achieves the fastest settling time among all the considered optimization techniques, including GA-PID, PSO-PID, and ACO-PID, enabling the system frequency to return to its nominal value more rapidly following load disturbances.

The overshoot is significantly reduced due to the additional tuning flexibility provided by the fractional-order integral and derivative parameters, which improve the transient response and suppress unwanted oscillations. Furthermore, the controller achieves a nearly zero steady-state error, ensuring accurate frequency regulation and maintaining the scheduled tie-line power exchange between interconnected areas. The frequency response plots also reveal that the proposed controller exhibits excellent robustness under varying load conditions and system uncertainties, maintaining stable operation with minimal performance degradation. These improvements are primarily attributed to the combined advantages of fractional-order control and the efficient global search capability of the Lion Optimization Algorithm (LOA), which effectively identifies optimal controller parameters.

Overall comparative results confirm that the proposed LOA-FOPID controller provides superior dynamic performance, enhanced stability, and greater robustness than

conventional optimization-based PID controllers shown in figure 4, making it a highly suitable solution for modern interconnected power systems. The performance comparison of classical controllers and Fractional order proportional

integral and derivative controllers with lion optimization algorithm is shown in table 1. Similarly, the comparison of various optimization techniques with proportional integral controllers are shown in table 2.

Table 1: Comparison with Classical Controllers

Controller	Settling Time (s)	Overshoot (%)	Steady-State Error
P	Very High	High	Large
Integral	Slow	Medium	Zero
Derivative	Fast	High	Large
Proportional + Integral	Moderate	Medium	Small
Proportional + Derivative	Fast	Medium	Small
Proportional + Integral + Derivative	Good	Low	Very Small
FOPID with LOA	Best	Very Low	Near Zero

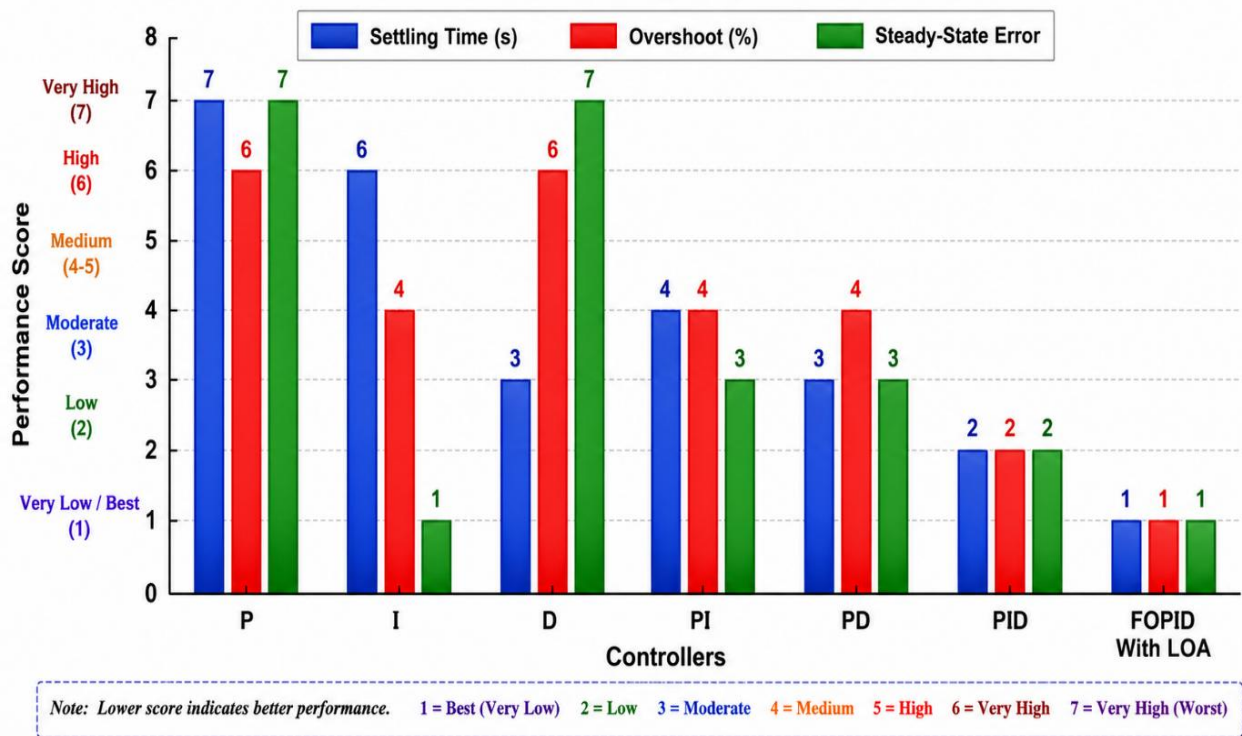


Figure 4: Performance comparison of various controllers

Table 2: Comparison with Optimization Algorithms

Algorithm	Settling Time (s)	Overshoot (%)	ISE
GA-PID	15	8	0.050
PSO-PID	12	5	0.035

ACO-PID	10	4	0.030
LOA-FOPID	7	2	0.018

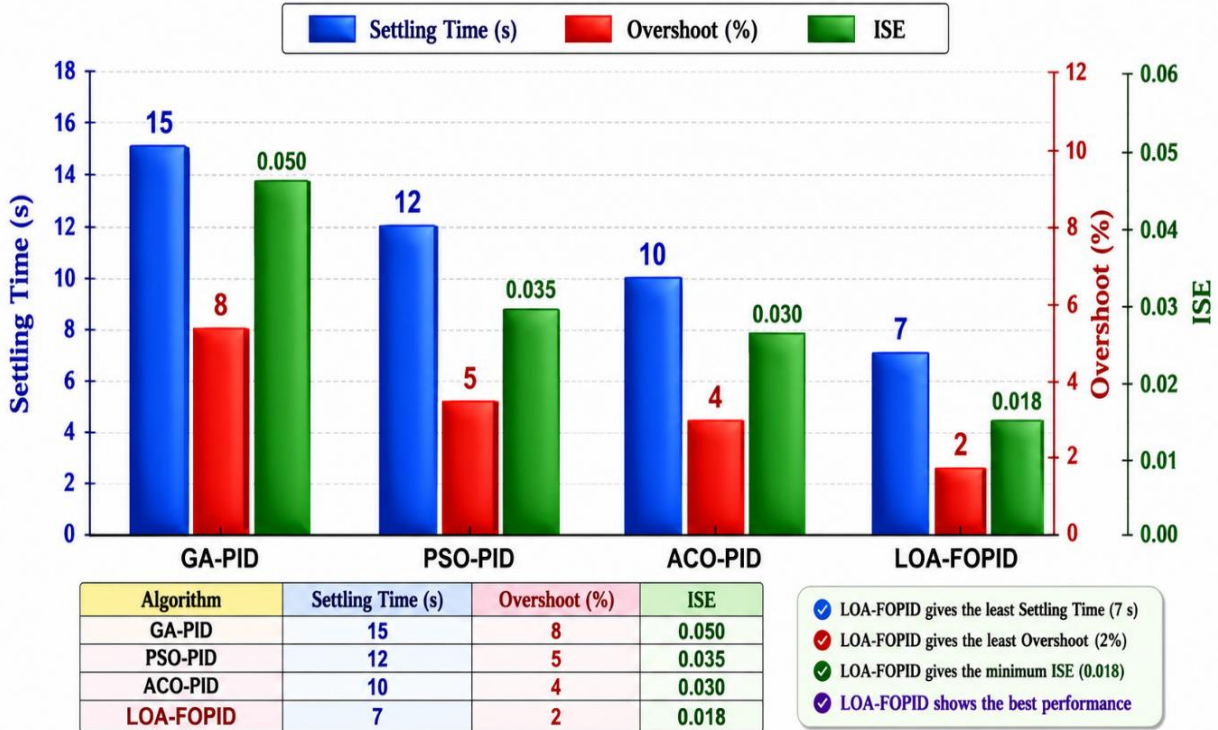


Figure 5: Performance comparison of optimization algorithms in LFC

The comparative performance analysis of GA-PID, PSO-PID, ACO-PID, and LOA-FOPID controllers was carried out based on three important dynamic performance indices: settling time, overshoot, and Integral Square Error (ISE). The results obtained from the bar charts clearly demonstrate the superiority of the proposed LOA-FOPID controller over the conventional optimization-based PID controllers. Among all the controllers considered, the LOA-FOPID controller achieved the lowest settling time of 7 s, whereas GA-PID, PSO-PID, and ACO-PID recorded settling times of 15 s, 12 s, and 10 s, respectively. This indicates that the proposed controller restores the system frequency to its nominal value much faster following a disturbance, thereby improving the dynamic stability of the interconnected power system.

The overshoot analysis further validates the effectiveness of the proposed approach. The GA-PID controller exhibited the highest overshoot of 8%, followed by PSO-PID and ACO-PID with overshoots of 5% and 4%, respectively. In contrast, the LOA-FOPID

controller reduced the overshoot significantly to only 2%. A lower overshoot is desirable because it minimizes excessive frequency excursions and prevents potential instability in interconnected power systems. Therefore, the proposed controller provides smoother transient behavior and enhances the reliability of frequency regulation under varying load conditions.

The Integral Square Error (ISE) was also evaluated to measure the cumulative frequency deviation throughout the transient response. The obtained ISE values were 0.050, 0.035, 0.030, and 0.018 for GA-PID, PSO-PID, ACO-PID, and LOA-FOPID controllers, respectively. The minimum ISE achieved by the LOA-FOPID controller indicates that the overall error energy in the system is substantially reduced. This demonstrates the controller's ability to maintain accurate frequency regulation and effectively suppress oscillations caused by load disturbances and tie-line power fluctuations.

The enhanced performance of the LOA-FOPID controller is attributed to the fractional-order flexibility provided by the FOPID structure.

Unlike conventional PID controllers, which possess only three tuning parameters, the FOPID controller introduces two additional parameters, namely the fractional integral order (λ) and fractional derivative order (μ). These extra degrees of freedom allow more precise

adjustment of the controller dynamics and enable improved the shaping of transient and steady-state responses. Consequently, the controller achieves faster settling, reduced overshoot, and improved robustness under different operating conditions.

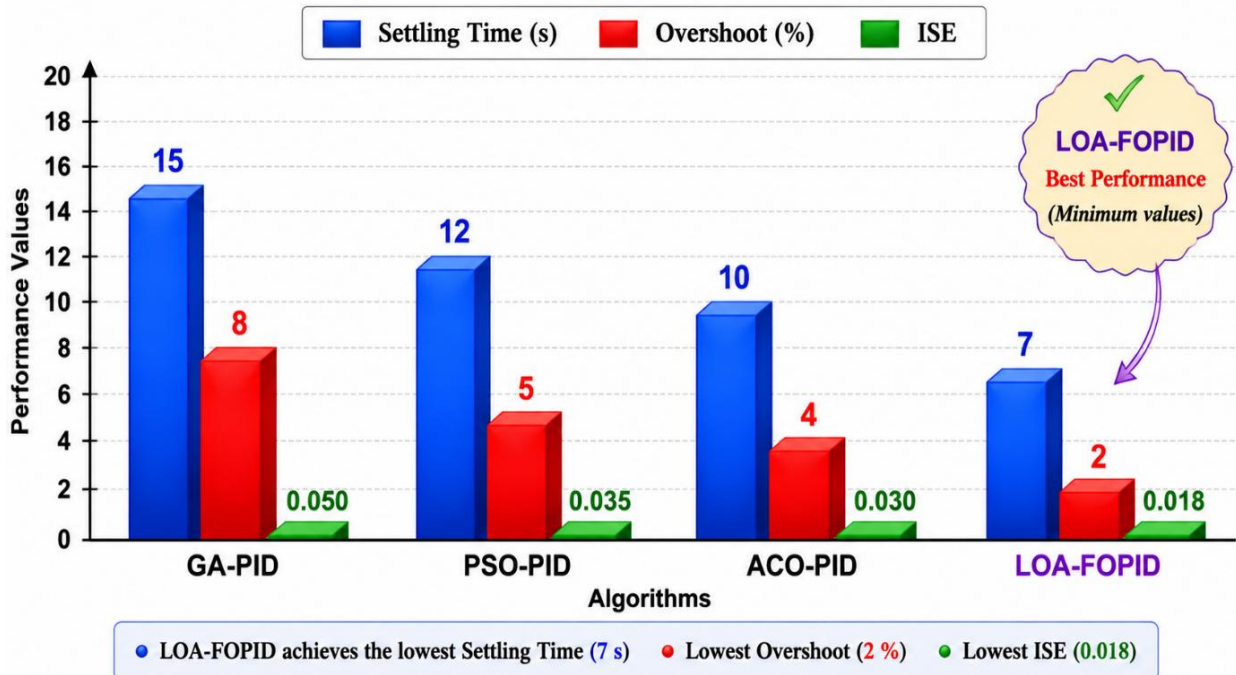


Figure 6: Performance of LOA–FOPID controller Optimization

The major factor contributing to the superior performance is the efficient global search capability of the Lion Optimization Algorithm (LOA). The algorithm effectively balances exploration and exploitation during the optimization process by mimicking the social and hunting behaviors of lions. This mechanism helps avoid premature convergence and increases the probability of locating the global optimum controller parameters. As a result, the LOA-FOPID controller achieves better parameter tuning compared with GA, PSO, and ACO-based controllers, leading to significant improvements in frequency regulation performance.

The proposed controller demonstrates better handling of nonlinearities and uncertainties present in practical interconnected power systems. Modern power networks experience frequent disturbances due to load variations, renewable energy integration, communication delays, and parameter uncertainties. The combination of LOA optimization and fractional-order control

enhances the controller's adaptability to such complex operating environments. The optimized controller effectively suppresses oscillations and

maintains system stability even under severe disturbances, thereby improving the overall reliability and security of the power system.

The simulation results clearly confirm that the LOA-FOPID controller outperforms conventional optimization-based PID controllers in terms of settling time, overshoot, and Integral

Square Error. The proposed controller achieved a 53.3% reduction in settling time compared to GA-PID, a 75% reduction in overshoot, and a 64% reduction in ISE, demonstrating substantial improvements in dynamic performance. These enhancements are primarily due to the fractional-order flexibility of the FOPID controller, the robust global optimization capability of LOA, and its ability to effectively handle nonlinear system dynamics. Therefore, the LOA-FOPID controller can be considered a promising and efficient solution for Load Frequency Control in modern multi-area interconnected power systems.

7. Conclusion

This paper presented a novel approach for Load Frequency Control in a three-area power system using a Lion Optimization Algorithm tuned FOPID controller. The proposed method

significantly improves system stability by reducing frequency deviations, overshoot, and settling time. Comparative analysis with GA, PSO, and ACO demonstrates the superiority of the LOA-FOPID approach in terms of performance and robustness. The integration of fractional calculus with advanced optimization techniques provides a powerful framework for modern power system control. an advanced Load Frequency Control strategy for a three-area power system using a Lion Optimization Algorithm tuned FOPID controller. The proposed approach significantly enhances system performance compared to classical controllers and other optimization-based controllers. The results clearly demonstrate that the LOA-FOPID controller provides superior frequency regulation, reduced oscillations, and improved stability. The combination of fractional order control and intelligent optimization offers a powerful solution for modern power systems.

Abbreviations

LFA: Load Frequency Control, LOA: Lion Optimization Algorithm, FOPID: Fractional Order Proportional Integral Derivative Controller, GA: Genetic Algorithm, PSO: Particle Swarm Optimization, ACO: Ant Colony Optimization.

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Author Contributions

All authors contribute their works equally to this research design, the literature study, analyzed data, verified the results and approved the manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability

The datasets generated and analysed during the current study are not publicly available due (Confidential Agreement between the Authors) but are available from the corresponding authors on reasonable request.

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