

Enhancing decentralized frequency regulation approach in mixed source of generation diversified with wind and PV integration deploying artificial gorilla troops algorithm

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Abstract. Nowadays, the penetration of renewable energy sources, mainly wind and solar photovoltaic systems, into the existing power systems, destabilizes the grid, especially in the aspect of frequency regulation. AGC is one of the most important tasks in this mixed-generation environment to maintain the balance between the generated and consumed electricity, thus keeping the system frequency at an acceptable level. Therefore, AGC needs to be optimized for the noisy and volatile output of RESs. AGTA is a recent optimization method developed based on the social foraging behavior of gorillas, being a sophisticated way of exploration and exploitation. Therefore, the method is implemented in AGC. By mimicking the social behaviour and foraging strategy, the group gives rise to a new technique for enhancing the efficiency and response of the AGC system in light of wind and PV energy generation variation. A two-area power system model has been formulated characterized by the existence of wind and PV generation in addition to the conventional sources of the power system. This model is meant to simulate diverse situations to give an idea as regards the capability of the new algorithm to enhance grid stability and adaptability. The simulated results show that the proposed AGTA significantly surpasses other conventional optimization methods for AGC and results in an effective frequency control strategy. It confirms the potential of the AGTA from a new perspective in providing a feasible option for decentralized frequency regulation in a multi-generation landscape.

Keywords: Artificial gorilla troops algorithm (AGTA), Decentralized frequency regulation, Renewable energy integration, Wind and solar PV systems, Grid stability optimization.

1 Introduction

1.1 Basics: problem under study case

RESs like wind and solar photovoltaic (PV) are widely considered the main departures within the framework of global energy systems toward low carbon emissions and sustainable growth. This vital transformation process, backed by both environmental and economic motivations, raises important technical challenges in terms of power grid stability. The integration of wind and PV systems with the power grid changes the traditional pattern of generation and grid support. Contrary to a traditional power plant, a RES has much output variation and is also quite unpredictable which is highly dependent on changing environmental conditions like wind speed or solar irradiation. In contrast, a classical power plant is found to be more

controllable and predictable power output variation. Among the technical issues, AGC is one of the most important mechanisms for frequency support toward a stable power system, which integrates many different power generation sources, especially RES, whose output is intrinsically variable and uncertain. Variability and unpredictability in RESs are primarily responsible for initiating challenges when it comes to regulating the frequency of power systems incorporated with them. Because of such intermittences, the scheduled frequency cannot be maintained easily, because the output from these sources is variable and may not be available instantaneously according to demand. Furthermore, RESs in general have low inertia, especially if this parameter is compared with the inertia of conventional thermal generators, so their contribution to system stability, especially to frequency response, is low. AGC is a system capable of automatic adjustment of the outputs of generation to maintain a constant frequency, instantaneous in its nature; it also checks the tie-line power

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interchange and thus ensures a well-balanced, secure, and reliable electricity supply in an environment characterized by sources of generation of different natures such as variability and intermittency. The increase in the proportion of RES in the energy pool increases the complexity of maintaining balance, necessitating the need for new optimization approaches customized to the modern power scenario [1]. Optimization largely plays a role in AGC with regard to the complexities brought about by RES. An effective optimization algorithm could make the AGC system more responsive through automatic generation change. It can reduce the possibilities for the occurrence of frequency deviation, hence making a system secure in light of wind and solar variability [2].

1.2 Literature survey

The literature survey provides a thorough exploration of studies examining the integration of RESs into power systems, with a focus on their implications for frequency dynamics, grid operations, and control strategies. The work conducted in [3, 4] investigated the impact of renewable integration on frequency dynamics by analyzing factors such as reduced inertia and primary control. Furthermore, studies such as [5] have explored the consequences of PV solar power variability and forecast uncertainty on grid operation. The research work included in [6] proposed microgrid systems that leverage solar and wind energy sources and employ control strategies to maintain voltage and frequency levels effectively. Similarly, [7] introduced a hybrid standalone power generation system that combines wind and PV sources supplemented by battery energy storage to ensure stability under various conditions. In [8], a standalone hybrid power generation system that employed fuzzy logic control to maintain a stable load voltage and frequency was proposed. Meanwhile, [9] explored the optimal sizing of a hybrid PV and wind energy system by considering factors such as battery backup to postpone grid expansion. The study [10] presented an efficient power delivery system for hybrid microgrids, with frequency deviation and battery voltage serving as crucial inputs. The studies in [11] emphasized the importance of proper frequency regulation in isolated microgrids integrating RESs. The studies in [12] proposed a converter-less solar PV control strategy for a grid-connected hybrid system that offers cost-efficient integration. A long-term analysis of RES generation and its impact on power systems was conducted in [13]. Moreover, [14] dealt with distributed generation systems, whereas [15] focused on the mathematical modeling of a wind-diesel-PV hybrid system. The authors in [16] provided a smart grid power system control solution using adaptive techniques and model predictive control. Additionally, [17] presented an autonomous wind-solar hybrid energy system with a performance analysis under various conditions. [18] investigated the vulnerability of the network frequency response in the context of evolving RES renewable energy sources. This study also reviews the contributions of optimizing photovoltaic (PV) systems through bioinspired algorithms and soft computing techniques [19–24]. It covers innovative approaches to enhancing MPPT efficiency, designing high-performance DC-DC converters, and selecting optimal

components for various converter topologies. By integrating predictive control models and accurate shadow detection, their work significantly improved the adaptability and efficiency of solar PV deployment. Each study offers unique insights and merits that contribute to advancements in power system optimization. However, challenges, such as computational complexity, remain, highlighting the need for further research. This comprehensive review underscores the diverse optimization techniques applied to AGC, showcasing the dynamic nature of research in this field.

1.3 Analysis: literature work-study

An analysis of the literature reveals an advancement in control strategies, grid stability considerations, and economic feasibility assessment. Previous studies have consistently underscored the critical importance of proper frequency regulation and grid stability in the context of RES integration. Although innovative control techniques and system designs show promise in addressing operational challenges, the economic viability of RESs remains a major concern. Furthermore, the evolving nature of renewable energy technologies and their impact on power system dynamics necessitates ongoing research efforts to ensure the resilience and sustainability of future energy systems.

1.4 Motivation and the proposed approach

Ensuring power supply and system stability is crucial, particularly with the increasing complexity of modern grid operations. Although traditional optimization methods have been widely used in LFC systems, they can sometimes struggle to handle the dynamic and nonlinear characteristics of power systems. As the demand for resilient and flexible control strategies increases, it is essential to explore new approaches to deliver better performance in LFC applications.

In recent years, bio-inspired optimization algorithms have emerged as promising contenders for tackling complex optimization problems across various domains, including power-system control. Among these, the artificial gorilla troops algorithm (AGTA) is notable for its unique capability to mimic the collective behavior and adaptive strategies observed in gorilla troops within their natural habitats. It was inspired by the social structure and behavior of gorilla troops. This algorithm models the way gorillas interact within their groups, particularly focusing on the leadership of the silverback and the collaborative dynamics among troop members. In the context of solving optimization problems, AGTA simulates this social hierarchy and interaction to efficiently explore and exploit the solution space. The role of the silverback is analogous to guiding the search process towards promising areas, whereas the other gorillas contribute by diversifying the search, thus enhancing the algorithm's ability to find optimal or near-optimal solutions to complex problems. The algorithm incorporates elements of cooperation (as seen in foraging and protection behavior) and competition (such as challenging the alpha for leadership) to explore and exploit the solution space effectively. This approach is ideally suited to address

complex challenges by optimizing settings in dynamic and multidimensional environments.

Unlike traditional methods, which may face issues with computational complexity or premature convergence, AGTA uses the principles of swarm intelligence and social dynamics to navigate complex solutions with agility and resilience. Its decentralized nature aligns well with the distributed architecture of power systems, making it well-suited for implementation in large-scale grid environments. AGTA's ability of AGTA to respond adaptively to changing operating conditions and system disturbances further enhances its suitability for LFC applications. In this work, a comprehensive investigation into the efficacy of AGTA for LFC applications is presented, and its performance is compared with some recent algorithms through simulation studies. This study aimed to demonstrate AGTA's capabilities in achieving efficient LFC.

1.5 Key contribution

- (a) *Application of AGTA*: This study pioneered the application of AGTA in the realm of decentralized frequency regulation for power systems incorporating wind and PV sources.
- (b) *Enhanced grid stability with renewable integration*: The demonstration of improved grid frequency stability in the designed power system with the penetration of wind and PV generation is shown.
- (c) *Comprehensive Performance Evaluation*: A performance evaluation of the AGTA-optimized frequency regulation strategy is performed by comparing it with CHOA, COA, AEFA, ARO, SO, and the proposed AGTA methods, which provides evidence of the efficacy of AGTA in optimizing frequency regulation parameters.

1.6 Subsequent sections

The subsequent sections of the manuscript are organized as follows: [Section 2](#) contains concise descriptions of the test system. [Section 3](#) discusses the implementation of an AGC controller. [Section 4](#) outlines the problem formulation for the LFC. [Section 5](#) presents details of the proposed algorithm. [Section 6](#) summarizes the simulation results. [Section 7](#) presents the limitations and constraints of the study. [Section 8](#) concludes the paper with a summary of the research outcomes and potential future research directions.

2 Test system modeled and investigated

2.1 Basic description of the model

This study investigated a two-area multisource power system model for LFC simulations. The test system consists of areas 1–2, each equipped with reheated turbines and a mix of thermal, hydro, and gas-generating units (see [Fig. 1](#)) [25]. In Area 1, the wind turbine generating units are connected, whereas in Area 2, the PV model is integrated. This study explores the design of a Proportional-Integral-Derivative with Notch (PIDN) controller using the AGTA algorithm, and implementing it in the test system.

2.2 Basic details on WTG: for LFC contribution

Area 1 features a blend of conventional power generation units and renewable sources, emphasizing wind integration. Wind power plants utilize wind kinetic energy to rotate turbines and generate electricity, thereby presenting a renewable energy alternative with minimal environmental impact.

$$G_{WTG}(s) = \left(\frac{0.7625s + 1.25}{s + 1} \right) \left(\frac{1}{0.041s + 1} \right) \left(\frac{1.4}{s + 1} \right) \quad (1)$$

2.3 Basic details on PV: for LFC contribution

PV panels convert solar energy into electricity and their output is influenced by solar radiation and temperature changes. To optimize power generation, maximum power point tracking (MPPT) is crucial for regulating the operating point. Inverters are employed to convert DC energy from the PV panels into AC energy. The transfer function of the PV system comprising the PV panel, MPPT, inverter, and filter is described by equation (2) [26].

$$G_{PV}(s) = \frac{-18s + 900}{s^2 + 100s + 50} \quad (2)$$

3 Modelling of controller: for LFC contribution

Integration of RESs, especially wind and solar PV systems, with power grids makes the AGC task much more complicated and challenging, as the grid has to maintain stability with variable power outputs. The typical PID controller is simple in controlling the outputs of systems to attain desired set points and is incapable of handling RES's frequency variability and power variations. This has led to the use of a PID controller, augmented with a filter coefficient known as PID with noise rejection, PIDN, to handle the dynamics of today's power system in a better way. The significant role of the derivative filter component in the PIDN controller is in the computation of the measured noise brought by environmental conditions affecting renewable energy output so that the developed control action is dependent on the actual dynamics of the system instead of the transients. This further enhances the stability and performance of the control system under a wide range of conditions. [28] ([Fig. 2](#)).

$$G_{PID}(s) = K_p + \frac{K_i}{s} + K_d \frac{N}{1 + N/s} \quad (3)$$

4 Problem formulation: defining LFC objective function

At the time of formulation of AGC schemes for mathematical investigations, in particular, to optimize control parameters in order to improve system performance and stability, the objective function plays a crucial role as it characterizes the optimization criteria. ITAE serves well as a target for

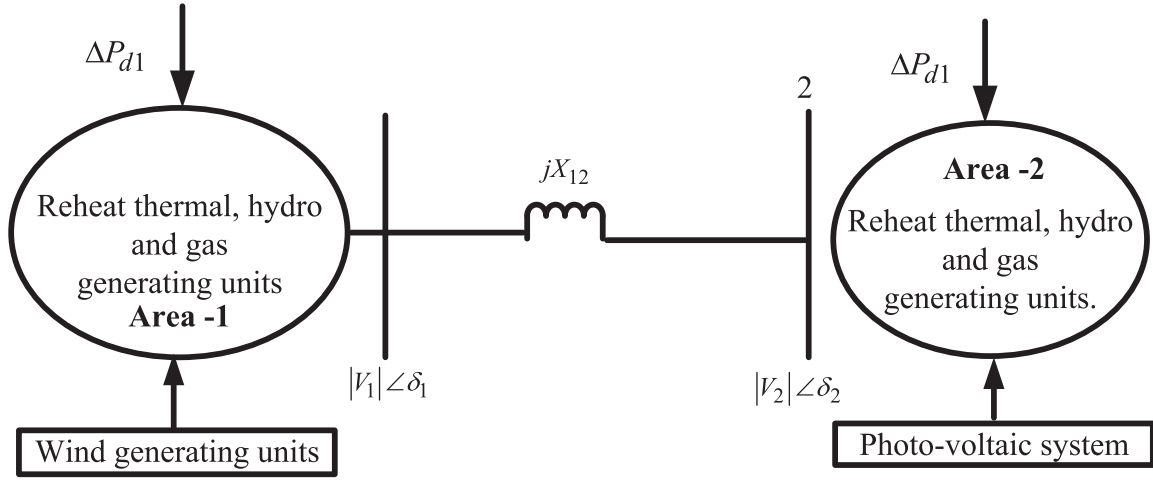


Figure 1. Studied test system diagram.

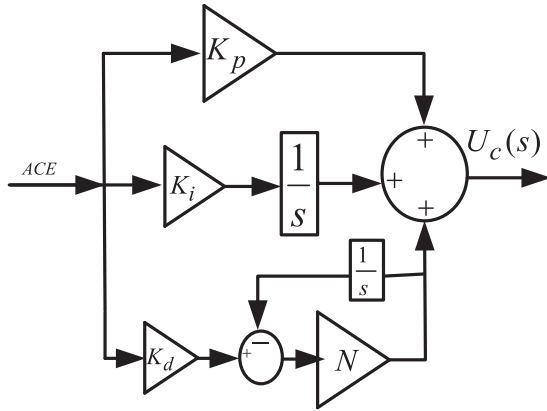


Figure 2. Implemented controller in the studied test system.

control-system optimization in AGC applications. The ITAE is very relevant because it quantifies the performance of a system over time with respect to the error over time associated with the response, whereby with time, the errors that persist are given heavier weights [29].

4.1 Objective: defining optimization goals and objective function

The ITAE objective function is applicable for control and, in AGC, used for enhancing system response and stability. This is designed to penalize the longer-term errors more strongly than by normal ways in order to put some weightage on absolute error with time and encourage methodologies that give convergence to setpoints in a way that is not only fast but also accurate. This leads to a decrease in the total error in the system and the satisfaction of important requirements: stabilization is fast after a severe disturbance. The ITAE objective function is expressed mathematically as [30]:

$$FOD = ITAE = J = \int_0^{t_s} \{|\Delta f_i| + |\Delta P_{tieij}|\} t dt \quad (4)$$

4.2 Constrained optimization: defining the boundaries of the constraints

- (a) The PID controller gains are the constraints for the optimization task of this model. The boundaries of these parameters are bounded, as given in (5).

$$\left. \begin{aligned} K_p^{min} &\leq K_p \leq K_p^{max} \\ K_i^{min} &\leq K_i \leq K_i^{max} \\ K_d^{min} &\leq K_d \leq K_d^{max} \\ N^{min} &\leq N \leq N^{max} \end{aligned} \right\} \quad (5)$$

4.4 Measure of performance: defining performance indices

By incorporating a broad range of performance indices in the optimization process, it can be ascertained that the AGC systems are not only effective in maintaining grid stability but also in ensuring efficient control actions in adaptively managing variability introduced by renewable energy sources. The present work helps in a thorough comparative analysis of the IAE, ITSE, and ISE indices in search of the best control strategy that offers a harmonious trade-off among quick responses to disturbances, reduced long-term errors, and an overall improvement in the system performance. IAE represents the total magnitude of error in reflecting the overall control accuracy and therefore gives a simple judgment of deviations from the setpoint. ITSE is a type of quadratic time weighting and will penalize prolonged errors; it will promote rapid system stabilization. ISE is more focused on the squared value of errors, which will fix the greater deviation more to make the system run smoothly. These indices jointly support a comprehensive optimization strategy for identifying AGC solutions that facilitate fast recovery from disturbances. The mathematical expressions for these three indices are defined in the order of (6)–(8) [31, 32].

$$IAE = \int_0^{t_s} (|\Delta f_i| + |\Delta P_{tieij}|) dt \quad (6)$$

$$ITSE = \int_0^{t_s} \left((\Delta f_i)^2 + (\Delta P_{tieij})^2 \right) t dt \quad (7)$$

$$ISE = \int_0^{t_s} \left((\Delta f_i)^2 + (\Delta P_{tieij})^2 \right) dt \quad (8)$$

Here, t_s is the time of simulation, Δf_i is the deviation of the frequency of the i th area, ΔP_{tieij} is the net deviation of the tie-line power plot connecting between the i th and the j th area.

4.5 Transient specifications: defining transient parameters

In the domain of dynamic frequency response analysis, several key parameters play a crucial role in assessing and enhancing the system's performance. Rise time (t_r), a measure of a system's responsiveness to input changes, is essential in scenarios demanding swift and seamless reactions. The concept of settling time (t_s), which denotes the duration needed for the system to reach and maintain a state within a predetermined range, is vital for maintaining generation load equilibrium. Additionally, peak value (M_p), indicative of the maximum amplitude observed during transient responses, holds significant importance in control systems where minimizing overshoot is a priority. Peak time (t_p), the period taken to achieve this peak value serves as an indicator to evaluate the speed of overshoot occurrence [27]. The primary objective of this research is to refine the controller gain parameters, aiming to enhance the dynamic response of the power system.

5 Proposed algorithm

5.1 Origin of the algorithm

AGTA is a metaheuristic approach inspired by the behavior of gorilla groups in nature. It was developed by drawing insights from various aspects of gorilla life, particularly their foraging behavior.

5.2 Concept of the algorithm

AGTA was conceived to replicate the behavior of gorilla troops, with the aim of designing an efficient metaheuristic algorithm. Researchers were inspired by the social dynamics and foraging behavior of gorillas, seeking to create a mathematical model based on these principles to address

optimization problems [33–35]. They observed that gorillas, led by a dominant silverback, often explored new areas independently. It represents the space of possible solutions to an optimization problem, where each dimension corresponds to a different decision variable. In these landscapes, each point represents a specific combination of variables and the corresponding values of the objective function, visually forming peaks (maximum values) and valleys (minimum values). The AGTA navigates these complex landscapes by employing exploration and exploitation techniques.

5.3 Mathematical formulation

1. *Initialization and Exploration Phase:* The AGTA, inspired by the gorilla groups' food search behavior, employs diverse mechanisms for optimization. It begins by initializing a random population of candidate solutions, each of which represents a gorilla. [33]. Exploration involves searching broadly across the landscape to identify diverse regions of interest and avoiding local optima by considering a wider range of possible solutions. In the exploration phase, gorillas navigate the search space using three mechanisms: migration to unknown or known locations and interaction with other gorillas, determined by a parameter termed "p." The exploration phase is mathematically represented by equation (9) [33].

See the Equation (9) bottom of the page

2. *Exploitation Phase:* Exploitation focuses on refining solutions within promising areas to find optimal or near-optimal solutions. Following the exploration phase, group formation occurred. The cost of each gorilla solution is evaluated, and if a solution surpasses the current one, it is supplied. The optimal solution across the entire population is designated as the silverback gorilla [33].

$$\left. \begin{aligned} C &= F \times \left(1 - \frac{Ite}{MaxIte} \right) \\ F &= \cos(2 \times r4) \\ L &= c \times l \end{aligned} \right\} \quad (10)$$

In equation (10), $MaxIte$ and Ite denote the maximum and current iteration numbers, respectively, and $r4$ is a random number ranging from 0 to 1. When the value of C equals or exceeds W , the "following the silverback" mechanism is activated. Otherwise, the algorithm proceeds with the "competing for the adult females" mechanism. The "following the silverback" mechanism is mathematically defined by the following equations (11)–(13) [33].

$$GX(t+1) = L \times M \times (X(t) - X_{silverback}) + X(t) \quad (11)$$

$$GX(t+1) = \left\{ \begin{aligned} &((UB - LB) \times r_1 + LB, \text{rand} < p) \\ &(r_2 - C) \times X_r(t) + L \times H, \text{rand} \geq 0.5 \\ &X(i) - L \times (L \times (X(t) - G \times X_r(t))) + r_3 \times (X(t) - G \times X_r(t)), p \leq \text{rand} < 0.5 \end{aligned} \right\} \quad (9)$$

$$M = \left(\left| \frac{1}{N} \sum_{i=1}^N GX_i(t) \right|^g \right)^{\frac{1}{g}} \quad (12)$$

$$g = 2^L \quad (13)$$

Throughout the exploration and exploitation phases, AGTA facilitates communication and collaboration among individual optimization agents, akin to the social behavior observed in gorilla troops [33]. This collaborative search mechanism enables AGTA to leverage collective intelligence and share information about promising solutions, thereby accelerating the discovery and refinement processes. A flowchart of the proposed algorithm is shown in Figure 3.

3. *Termination*: The algorithm continues the exploration and exploitation phases until a stopping condition is satisfied, such as reaching the maximum number of iterations. The competition mechanism for adult females'' is described by the following equation:

$$GX(i) = X_{silverback} - (X_{silverback} \times Q - X(t) \times Q) \times A \quad (14)$$

$$Q = 2 \times r_5 - 1 \quad (15)$$

$$A = \beta \times E \quad (16)$$

$$E = \begin{cases} N_1, & rand \geq 0.5 \\ N_2, & rand < 0.5 \end{cases} \quad (17)$$

The mathematical formulation of AGTA involves the use of equations to update the location and fitness values of gorillas. The equations used in the algorithm are described in detail in [33]. The flowchart is shown in Figure 3. The pseudocode of AGTA is presented in Algorithm 1.

5.4 Computational complexity

The computational complexity of AGTA is comparable to that of other swarm intelligence algorithms. It primarily depends on the number of agents (gorilla troop members), the dimensionality of the problem, and number of iterations required to converge to a solution. While AGTA is efficient in navigating complex search spaces, its computational demand increases with problem size and complexity. However, its design ensures that it remains scalable and effective for a broad spectrum of optimization challenges.

6 Simulation results and analysis

This section presents a detailed analysis of the simulation results obtained by evaluating the dynamic performance of the two-area power system. The focus of this study is a comparative assessment of applied algorithms, including CHOA, COA, AEFA, ARO, SO, and the proposed AGTA. These algorithms were examined based on computational time, effectiveness in handling transient responses, and their overall impact on the performance and stability of AGC

systems under various operational scenarios. This study assessed the computational efficiency and performance of various algorithms in AGC, focusing on their speed, resource use, and impact on system stability through metrics such as frequency deviation, settling time, and area control error (ACE). Additionally, it examines the transient response of the AGC system to disturbances and evaluates the effectiveness of each algorithm in restoring stable operations, controlling frequency deviations, and managing tie-line power flows. This analysis is crucial for determining the suitability of algorithms for real-time AGC applications and highlighting their potential to enhance system resilience and performance. The frequency stability assessment considered a range of operational conditions under various scenarios, as listed below.

Scenario A: Analysing the performance of the test power system under SLP in both areas (refer Fig. 4).

Scenario B: Assessing the functionality of the studied test system under the influence of random load perturbation in area-1 (refer Fig. 5).

Scenario C: Assessing the functionality of the studied test system under the influence of random load perturbation in both areas.

Scenario A: *Analysing the performance of the test power system under SLP in both areas*

In this case, the applied load profile is SLP, that is, SLP is applied in both areas at $t = 0$ s, as shown in Figure 6. This load profile pattern holds significant value in LFC studies, providing a baseline for understanding the system behavior and controller performance and guiding initial controller tuning. This makes them invaluable for understanding fundamental LFC dynamics, benchmarking new approaches, and simplifying the analysis before diving into the complexities of real-world unpredictable load variations.

The optimized PID controller gain values for the case study are listed in Table 1. The results of the MATLAB-based simulations are shown in Figure 6. This figure demonstrates a comparative LFC dynamic performance analysis based on the various algorithms applied, including the CHOA, COA, AEFA, ARO, SO, and the proposed AGTA. The performance evaluation revealed that AGTA outperformed the other algorithms, showing its superiority in terms of less settling time, minimal oscillations, and reduced steady-state error. The lower settling time of AGTA highlights its proficiency in achieving a fast response and stability following a disturbance in the test system. This characteristic is essential for AGC systems because it ensures a prompt and precise response to maintain the power system frequency within acceptable limits. The minimal oscillations observed in the dynamic response of the AGTA emphasize its damping characteristics. The presence of oscillations in the power system parameters can lead to instability, and AGTA's ability to mitigate these oscillations contributes to improved overall system stability. Moreover, the reduced steady-state error in AGTA indicates its effectiveness in minimizing long-term deviations from the desired operating point. This aspect is

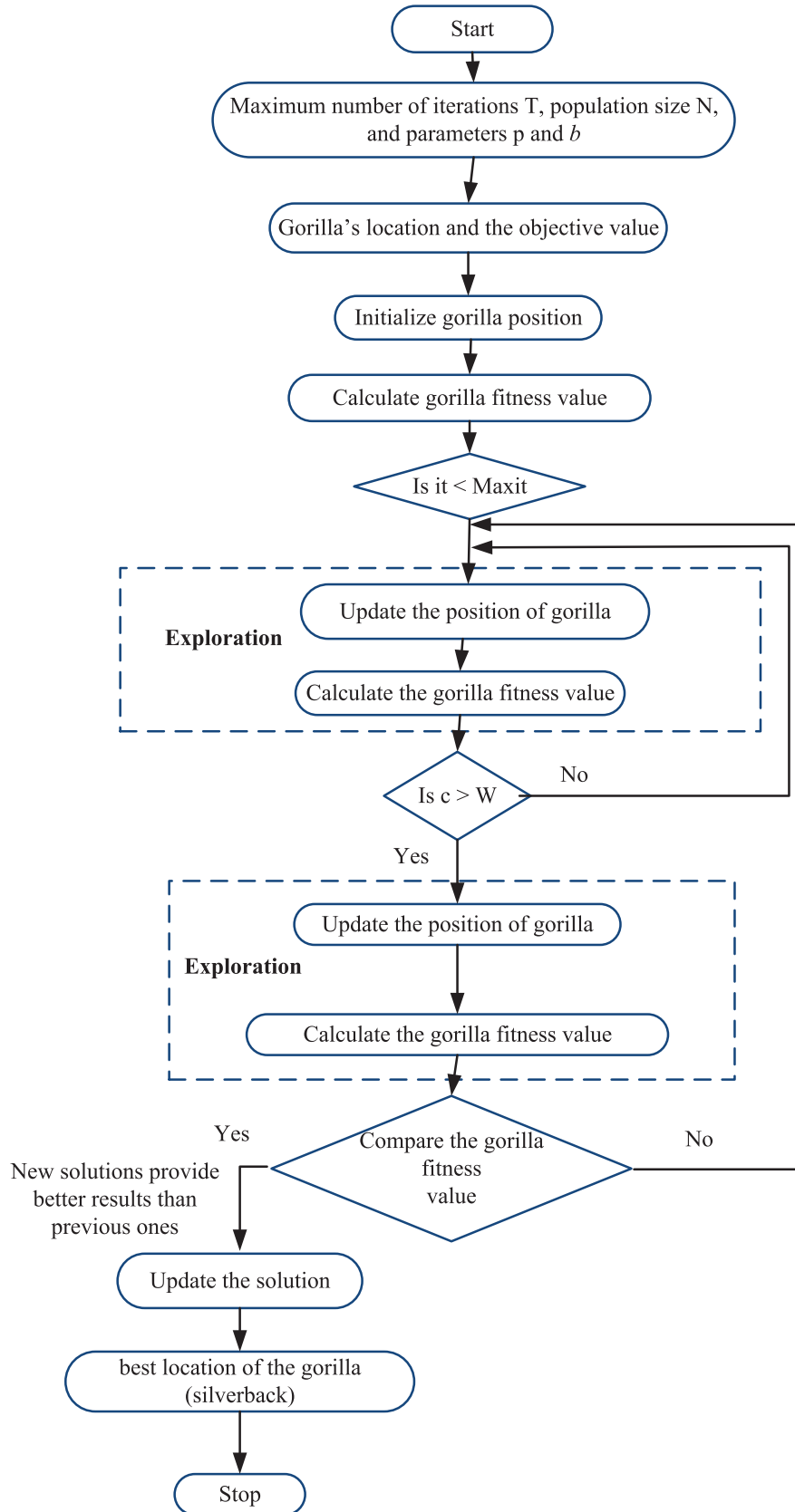


Figure 3. Illustrating the process flow of the implemented AGTA.

Algorithm 1. Pseudocode of AGTA.

Inputs: Initialize the population size (N), maximum iteration number (T), β and p parameters

Outputs: Calculation of the gorilla position and its associated fitness value

Initialize the random initial population

Calculate the gorilla position and its associated fitness value

while (Stopping criteria) **do**

Update the C value (refer Eq. 8)

Update the F value. (refer Eq. 8)

Update the L value. (refer Eq. 8)

% Exploration phase

for (each Gorilla) **do**

Update the location of Gorilla

end for

% Create group

Calculate the fitness value of Gorilla.

If the new fitness value is better, change with the former one.

Set the Silverback location as

% Exploitation

for (each Gorilla) **do**

if ($|C| \geq 1$) **then**

Update the location of Gorilla.

Else

Update the location of Gorilla

End if

end for

% Create group

Calculate the fitness value of Gorilla.

If the new fitness value is better, change with the former one.

Set the Silverback location as it is.

end while

Return

Figure 4 AGTA pseudo-code

Figure 5 The convergence curve of AGTA-PI controller

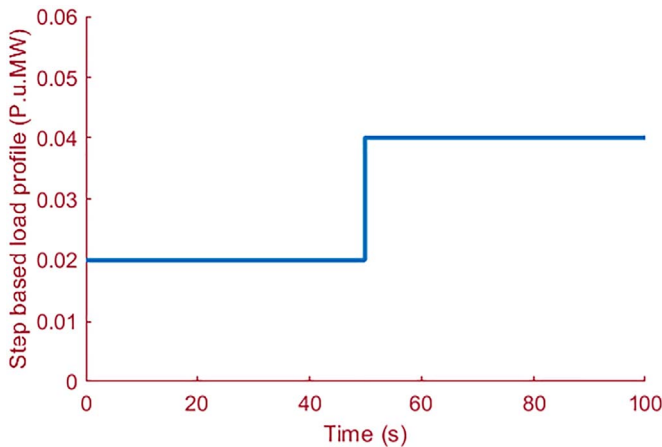


Figure 4. Load profile applied to both areas at the initial time ($t = 0$ s) according to Scenario 1.

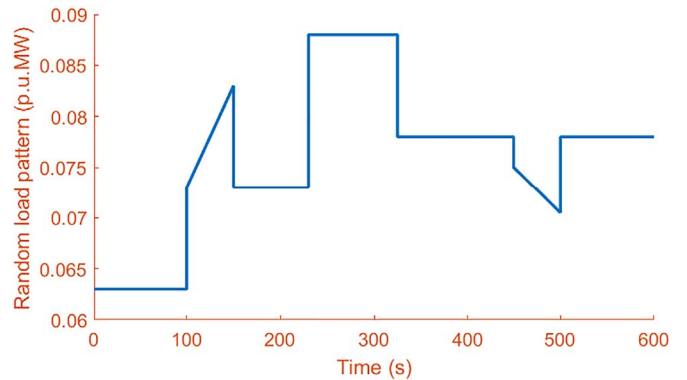


Figure 5. Studied random load pattern.

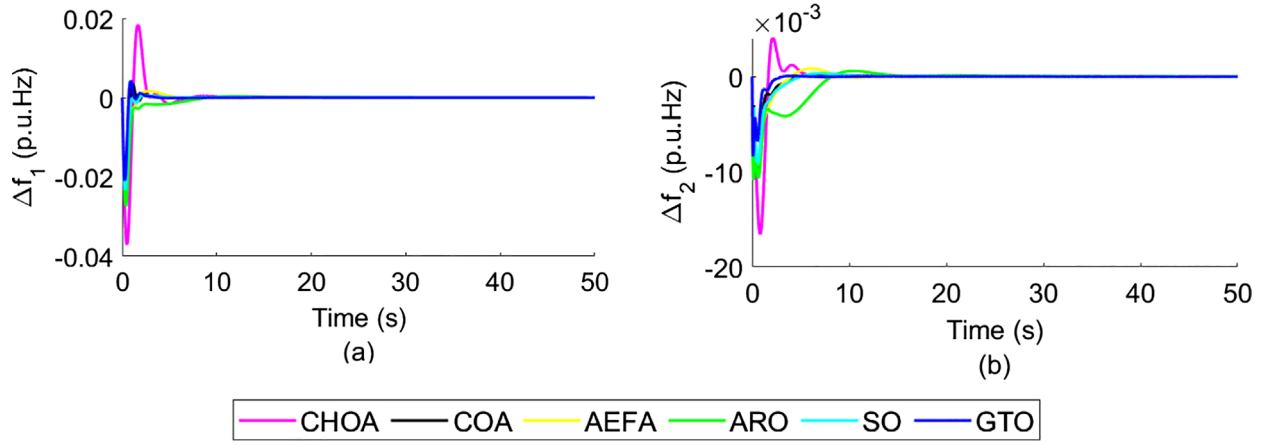


Figure 6. Depiction of time-domain frequency deviation response in the test system under SLP conditions (refer to Scenario 1): (a) Δf_1 and (b) Δf_2 .

Table 1. Optimized PID controller gains for the test system Scenario 1.

Areas	Techniques	K_p	K_i	K_d
Area-1	CHOA [Studied]	0.0026	1.0000	0.3302
	COA [Studied]	1.0000	1.0000	0.7856
	AEFA [Studied]	0.4983	1.0000	1.0000
	ARO [Studied]	0.4393	0.3822	0.7658
	SO [Studied]	0.9609	0.9609	0.9609
	AGTA [Proposed]	2.0000	2.0000	1.1357
Area-2	CHOA [Studied]	0.0063	0.0092	0.0010
	COA [Studied]	1.0000	0.9147	1.0000
	AEFA [Studied]	0.7609	1.0000	0.8864
	ARO [Studied]	0.1877	0.4903	0.4461
	SO [Studied]	0.9609	0.9609	0.9609
	AGTA [Proposed]	2.0000	0.6480	0.5654

crucial for an AGC system to maintain a stable and reliable power grid over extended periods. The transient details of the dynamic responses are presented in Table 2. In the evaluation of the transient performance of the studied algorithms, AGTA demonstrated better dynamic response characteristics and emerged as a better option among the studied techniques. With a shorter settling time, reduced overshoot, and efficient rise time, AGTA has proven its effectiveness in achieving faster and more stable control in the context of AGC. In contrast, other algorithms, such as CHOA, COA, AEFA, ARO, and SO, exhibit longer settling times, higher overshoot percentages, and relatively slower rise times. The acceptable transient performance of AGTA makes it a promising choice for applications in which rapid and precise control responses are essential.

The simulation analysis conducted on tie-line power deviations across the interconnected areas, as depicted in Figure 7, underscores the dynamic response of AGTA. This analysis shows that among the examined algorithms, AGTA is an effective solution. The rapid restoration of equilibrium in the AGTA dynamic response, as evidenced

by its settling time, is critical for maintaining tie-line power deviations within the desired limits. AGTA exhibits better damping characteristics, as evidenced by its minimal oscillations, which are essential for mitigating instability in the power system (Refer Tab. 3). The reduced oscillations also significantly contribute to the overall stability and reliability of the tie-line power exchange between the different areas.

The ACE plot is an essential tool in LFC studies of power systems and serves as a critical metric for assessing the balance between supply and demand, frequency stability, and inter-area power flows. This indicates imbalances that affect system stability and efficiency, with a direct impact on frequency deviations and the power exchange between control areas (see Tab. 4). Monitoring and adjusting the ACE helps maintain system reliability and prevents instability and blackouts. ACE plots enable the identification of patterns and system responses to disturbances, thereby facilitating the evaluation of control strategies. This comprehensive analysis supports the optimization of LFC schemes, enhancing the overall performance and resilience of power systems (Fig. 8).

Table 2. Calculated transient parameters of frequency, for the studied test system Scenario 1.

Algorithms	Δf_1				Δf_2			
	T_r (s)	T_s (s)	M_p (%)	T_p (s)	T_r (s)	T_s (s)	M_p (%)	T_p (s)
CHOA [Studied]	5.753e−05	6.0166	0.0371	0.4932	2.4126 e−04	5.2488	0.0166	0.8231
COA [Studied]	1.21e−04	2.8206	0.0253	0.3380	0.0180	8.2149	0.0100	0.6218
AEFA [Studied]	7.79e−04	4.9314	0.0237	0.3298	0.0055	8.6827	0.0094	0.5780
ARO [Studied]	0.04	7.5737	0.0274	0.3774	0.0204	13.5655	0.0109	0.1485
SO [Studied]	0.001	2.7756	0.0233	0.3133	0.0127	9.2105	0.0091	0.5584
AGTA [Proposed]	4.75 e−05	2.4572	0.0209	0.2753	0.0081	2.6834	0.0084	0.1022

The bold font represents that the proposed algorithm provide better results as compared to the other algorithms.

The output response of a PID controller in an LFC response study is of paramount importance because it directly influences the system's ability to maintain stable frequency levels and effectively manage power flows across interconnected areas. In the context of the LFC, a PID controller adjusts the power output of the generators to match the load demand precisely, thus minimizing the frequency deviations from its nominal value (e.g., 50 or 60 Hz) (refer to Fig. 9). The proportional component reacts to the immediate frequency error, thereby providing a response that is directly proportional to the error magnitude. The integral component addresses the accumulated error over time, effectively eliminating steady-state errors and ensuring that the frequency error integrates to zero over time. The derivative component predicts future errors based on the rate of change of the frequency error, thereby enhancing the responsiveness of the system to disturbances. This sophisticated combination allows the PID controller to fine-tune the power system response to fluctuations in demand and supply, ensuring a quick and stable return to equilibrium after disturbances. The effectiveness of a PID controller in an LFC system is crucial for optimizing the dynamic performance of the power system, enhancing the system's reliability, reducing the risk of power outages, and ensuring efficient power distribution, making it an indispensable tool in the management of modern power systems.

The performance indices provide a detailed evaluation of the studied algorithms, encompassing various metrics, such as FOD, ITAE, IAE, and ITSE (Fig. 10). Notably, the proposed AGTA has the lowest performance indices, featuring an FOD of 0.0449, ITSE of 0.0227, IAE of 0.0001, and ISE of 0.0002 (Tab. 5). These reduced values indicate the ability of AGTA to minimize deviation and error and enhance the overall system response in the context of AGC. In comparison, other algorithms, including CHOA, COA, AEFA, ARO, and SO, exhibited higher performance indices, signifying comparatively less effective control and optimization of the system.

The evaluation of computational times for the studied algorithms demonstrates that AGTA exhibits efficiency, with a notably brief duration of 445.152 s (Tab. 6). In comparison, other algorithms, such as COA, AEFA, and ARO, require significantly longer computational times, ranging from 504.6677 to 1472.642 s. CHOA and SO fall in between, with times of 452.3216 and 517.4608 s,

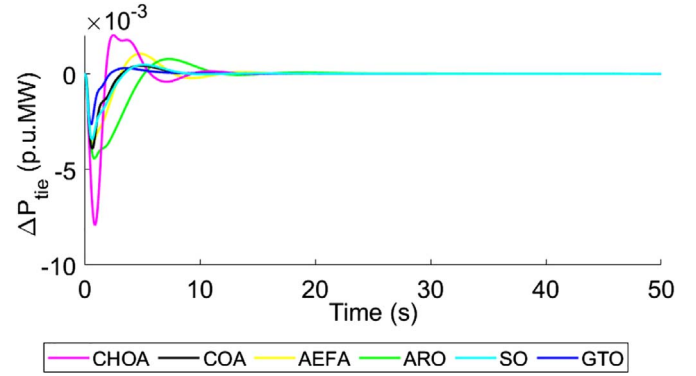


Figure 7. Depiction of time-domain tie-line power deviation response (ΔP_{tie12}) in the test system under SLP conditions (refer to Scenario 1).

respectively. The computational performance of AGTA highlights its proficiency in optimizing the AGC system. Its capacity to deliver superior results in a brief timeframe not only enhances its applicability but also showcases the resource-efficient characteristics of the algorithm.

In the MATLAB-based simulation results focusing on the convergence curve, a comparative analysis of algorithms such as CHOA, COA, AEFA, ARO, SO, and the proposed AGTA reveals that the AGTA-based convergence curve is effective and efficient. The superior performance of the AGTA-based convergence curve can be attributed to the most suitable optimization techniques among the studied algorithms. The steepness of the convergence curve for AGTA indicates a rapid convergence towards the desired solution. This characteristic is crucial in optimization problems, where achieving an optimal outcome quickly is highly desirable for efficiency. Furthermore, the AGTA convergence curve demonstrated minimal oscillations or fluctuations, reflecting the stability of the optimization process.

The better performance of the AGTA-based PID controller can be attributed to several factors. First, the inherent optimization techniques of AGTA are likely to contribute to the tuning of the PID parameters, resulting in a more precise and adaptive control response. The fast settling time exhibited by the AGTA-based PID controller is indicative of its efficiency in quickly restoring stability

Table 3. Calculated transient parameters of ACE, for the studied test system Scenario 1.

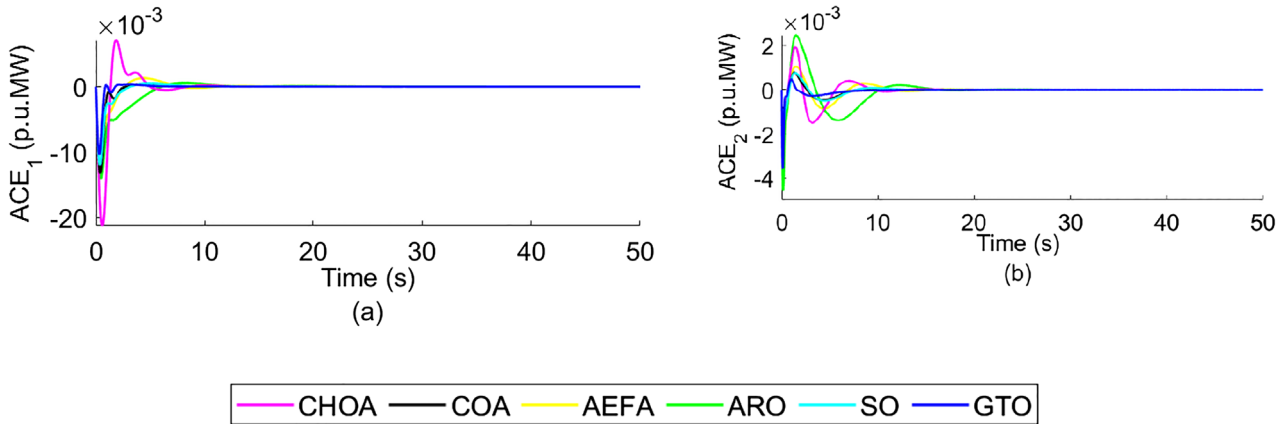
Algorithms	ACE_1				ACE_2			
	T_r (s)	T_s (s)	M_p (%)	T_p (s)	T_r (s)	T_s (s)	M_p (%)	T_p (s)
CHOA [Studied]	1.13e-04	7.1455	0.0213	0.585	8.72e-05	11.7275	0.0032	0.076
COA [Studied]	0.0100	6.3383	0.0132	0.400	1.18e-04	7.1842	0.0032	0.076
AEFA [Studied]	0.0019	7.0044	0.0122	0.367	6.27e-05	13.2966	0.0033	0.078
ARO [Studied]	0.0164	10.6112	0.0141	0.457	1.17e-04	14.5165	0.0046	0.148
SO [Studied]	0.0052	7.1381	0.0120	0.368	6.70e-05	10.4595	0.0032	0.078
AGTA [Proposed]	2.40e-05	4.4556	0.0104	0.319	8.86e-05	7.1145	0.0036	0.102

The bold font represents that the proposed algorithm provide better results as compared to the other algorithms.

Table 4. Calculated transient parameters of Tie line power, P_{tie} , for the studied test system Scenario 1.

Algorithms	ΔP_{tie12}			
	T_r (s)	T_s (s)	M_p (%)	T_p (s)
CHOA [Studied]	0.0126	8.5834	0.0079	0.9179
COA [Studied]	0.0132	7.9469	0.0039	0.6769
AEFA [Studied]	0.0139	14.7236	0.0036	0.7174
ARO [Studied]	5.1536	11.1434	0.0044	0.8666
SO [Studied]	0.0139	8.2913	0.0034	0.6547
AGTA [Proposed]	0.0115	7.5111	0.0027	0.5613

The bold font represents that the proposed algorithm provide better results as compared to the other algorithms.

**Figure 8.** Depiction of time-domain ACE response in the test system under SLP condition (refer to Scenario 1): (a) ACE_1 and (b) ACE_2 .

after perturbations. This rapid response is a key attribute of PID controllers, ensuring timely corrections and minimizing overshoots or oscillations in the system. Furthermore, the reduced oscillations in the response of the AGTA-based PID controller suggested superior damping characteristics. Effective damping is essential for achieving a stable and reliable control system, and the ability of AGTA to minimize oscillations significantly contributes to the overall performance improvement. Additionally, the AGTA-based PID controller demonstrated a lower steady-state error, emphasizing its effectiveness in minimizing long-term

deviations from the desired setpoint. This is critical for achieving precise control and maintaining the system's stability over extended periods.

Scenario B: Assessing the functionality of the studied test system under the influence of random load perturbation in area-1

This study captures the sudden nature of load changes, providing a more realistic assessment of LFC performance compared to fixed or step load patterns. It uncovers potential issues that might not be evident with simpler step load

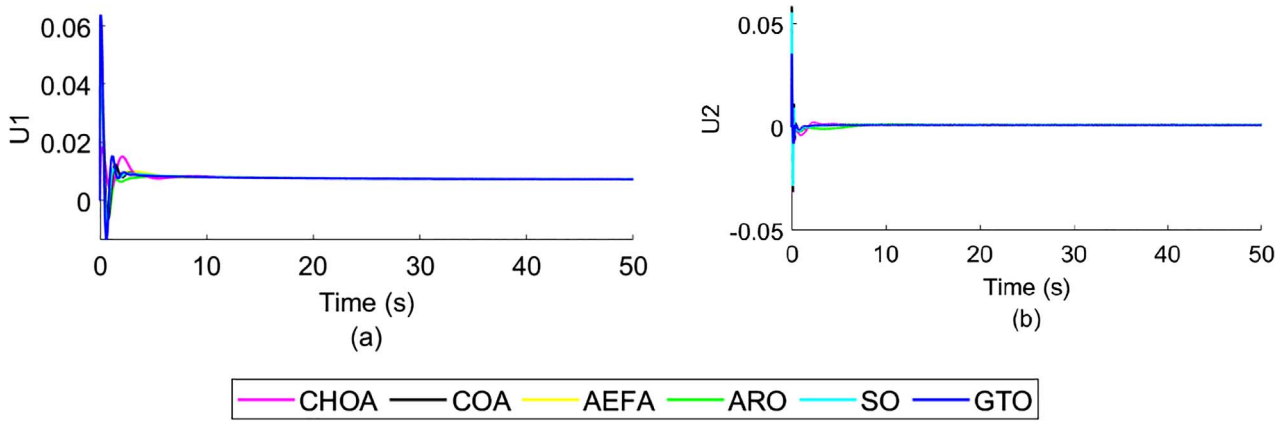


Figure 9. Depiction of controller output response in the test system under SLP conditions (refer to Scenario 1): (a) U_1 and (b) U_2 .

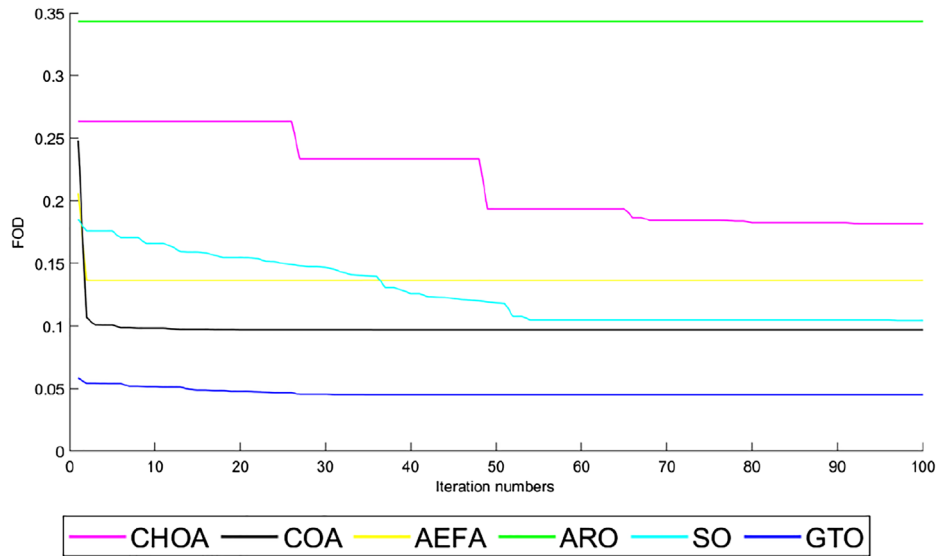


Figure 10. Depiction of FOD response in the test system under the applied algorithms (refer to Scenario 1).

Table 5. Comparative measure of performance indices for test system Scenario 1.

Algorithms	FOD	Performance indices		
	ITAE	IAE	ITSE	ISE
CHOA [Studied]	0.1818	0.0011	0.0851	0.0013
COA [Studied]	0.0970	0.0002	0.0371	0.0003
AEFA [Studied]	0.1364	0.0002	0.0469	0.0003
ARO [Studied]	0.3433	0.0006	0.0811	0.0006
SO [Studied]	0.1044	0.0001	0.0366	0.0003
AGTA [Proposed]	0.0449	0.0001	0.0227	0.0002

Table 6. Study of computational time for test system Scenario 1.

Algorithms	Computational time (s)
CHOA [Studied]	452.3216
COA [Studied]	1087.589
AEFA [Studied]	1472.642
ARO [Studied]	504.6677
SO [Studied]	517.4608
AGTA [Proposed]	445.152

patterns, thereby ensuring robustness under various operating conditions. With this load profile, this case study reveals how the LFC system responds to sudden and unpredictable load changes, including the settling time, overshoot, and

damping. It also assesses how effectively the controllers maintain the frequency within acceptable limits under continuous load fluctuations. It explores the potential interactions between load variations and other system dynamics that can impact stability. It also evaluates the robustness

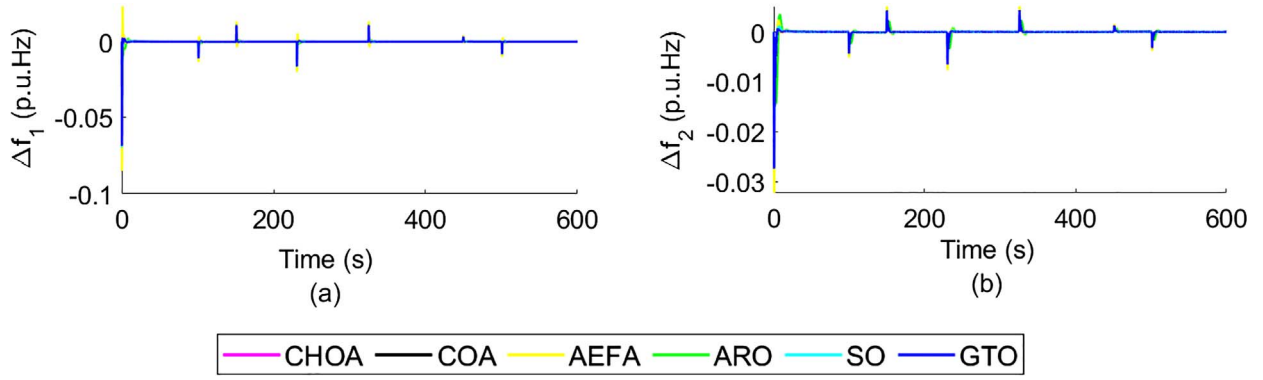


Figure 11. Depiction of time-domain frequency deviation response in the test system under RLP conditions (refer to Scenario 2): (a) Δf_1 and (b) Δf_2 .

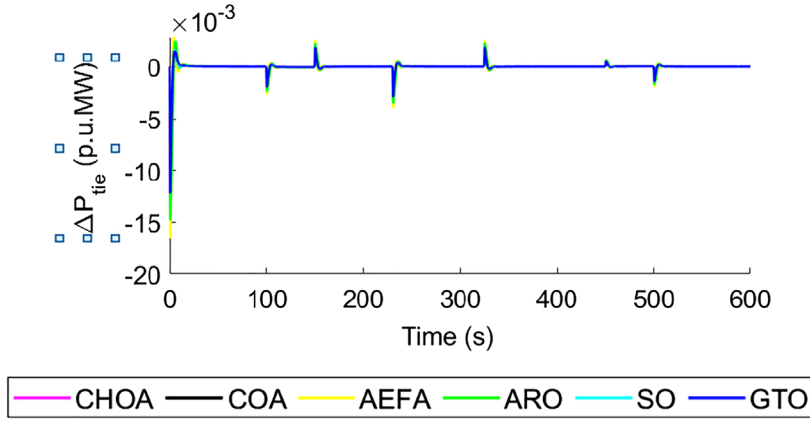


Figure 12. Depiction of time-domain tie-line power deviation response (ΔP_{tie12}) in the test system under RLP conditions (refer to Scenario 2).

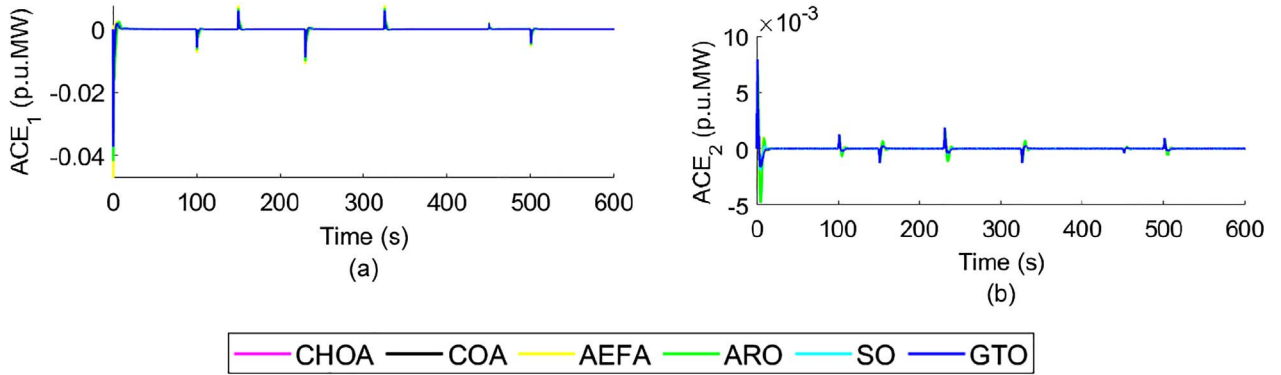


Figure 13. Depiction of time-domain ACE response in the test system under RLP condition (refer to Scenario 2): (a) ACE_1 and (b) ACE_2 .

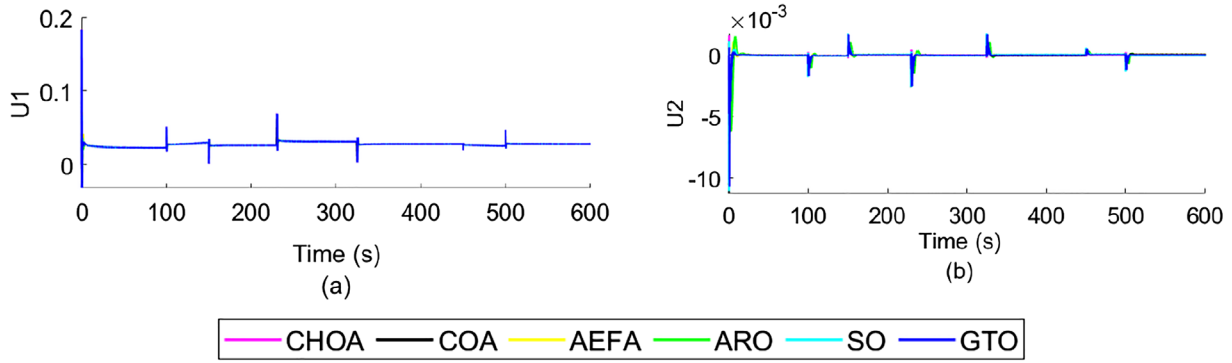


Figure 14. Depiction of controller output response in the test system under RLP conditions (refer to Scenario 2): (a) U_1 and (b) U_2 .

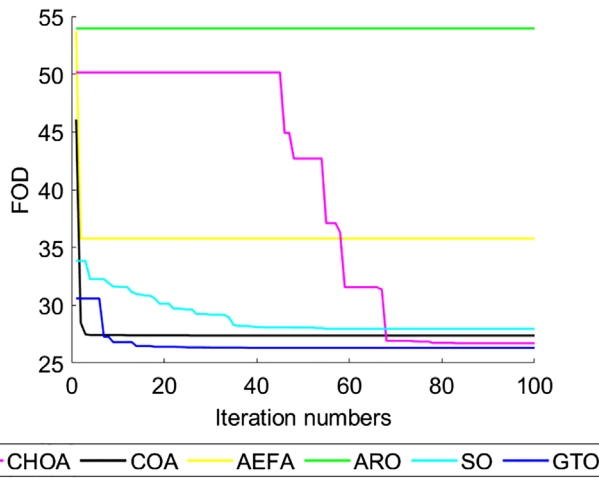


Figure 15. Depiction of FOD response in the test system under the applied algorithms (refer to Scenario 2).

of LFC systems to unexpected load events such as large disturbances or equipment failures. From the controller performance point of view, this case study evaluates controller sensitivity, that is, assesses how controller parameters and design choices affect performance under different loading conditions. It also helps in guide fine-tuning, that is, facilitates adjustments to optimize the controller response for diverse load scenarios, and shows the performance of the controllers to a wide range of load variations, revealing their ability to handle uncertainties and maintain frequency stability.

A plot of the random load pattern is shown in Figure 5. The generated LFC dynamic responses are shown in Figs. 11–15–order. From the obtained responses, it is clear that the proposed AGTA-based LFC responses are stable and regain stability after multiple disturbances within 600 s of simulation time. This shows that AGTA works well in the studied test system with the designed controller. The performance of the controller is quite robust, and the comparative measure of the performance indices for the test system is shown in Table 7. Table 8 shows the comparative

measures of the performance indices for the test system. The computational times for the test system are listed in Table 9.

Scenario C: Assessing the functionality of the studied test system under the influence of random load perturbation in both areas

Assessing the functionality of a test power system under the influence of random load perturbations in both areas involves evaluating the capability of the system to maintain stability, control frequency, and manage power flows despite unexpected changes in load demand. This case study assessment is crucial for understanding the resilience and reliability of the power system under the designed conditions where load demand can fluctuate unpredictably owing to various factors, such as weather conditions, industrial activities, and changes in consumer behavior. The comparative measures of the performance indices for the test system are shown in Table 10. Table 11 shows the comparative measures of the performance indices for the test system. The computational times for the test system are listed in Table 12.

By examining the frequency response of both areas shown in Figure 16, it can be observed that the speed and extent of the frequency deviation following a disturbance is minimal and the system returns to its nominal frequency swiftly; therefore, the system is a robust LFC system for the proposed algorithm. The proposed algorithm-based frequency deviations are minimized, and the system returns to its nominal frequency swiftly as compared to the studied algorithms. As shown in the figure, the settling times, overshoots, and undershoots in both areas were lower for the proposed algorithm.

The tie-line power deviation response shown in Figure 17 provides insights into the inter-area power exchanges with random load perturbation applied in both areas. This figure shows that the power flow between the two areas and the LFC system's effectiveness in managing these flows to maintain the system stability and meet the power demand are the most satisfactory for the proposed algorithm with the disturbance effect. In addition, the time taken for the tie-line power flows to return to their scheduled values and any persistent deviations is less.

Table 7. Optimized PID controller gains for the test system Scenario 2.

Areas	Techniques	K_p	K_i	K_d
Area-1	CHOA [Studied]	1.0000	1.0000	1.0000
	COA [Studied]	0.9998	0.9996	0.9998
	AEFA [Studied]	0.7494	1.0000	0.6260
	ARO [Studied]	0.5046	0.4965	0.8650
	SO [Studied]	0.9763	0.9763	0.9763
	AGTA [Proposed]	1.0000	1.0000	1.0000
Area-2	CHOA [Studied]	1.0000	0.4341	0.4402
	COA [Studied]	0.9997	0.9995	0.9996
	AEFA [Studied]	0.4090	1.0000	0.7953
	ARO [Studied]	0.1718	0.9084	0.6640
	SO [Studied]	0.9763	0.9763	0.9763
	AGTA [Proposed]	1.0000	0.3403	0.1556

Table 8. Comparative measure of performance indices for test system Scenario 2.

Algorithms	FOD		Performance indices	
	ITAE	IAE	ITSE	ISE
CHOA [Studied]	26.7124	0.0824	0.2061	0.0026
COA [Studied]	27.3718	0.0841	0.2123	0.0027
AEFA [Studied]	35.7691	0.1476	0.2803	0.0047
ARO [Studied]	53.9587	0.1478	0.4146	0.0046
SO [Studied]	27.9634	0.0869	0.2165	0.0028
AGTA [Proposed]	26.3251	0.0822	0.2031	0.0026

Table 9. Study of computational time for test system Scenario 2.

Algorithms	Computational time (s)
CHOA [Studied]	399.3966
COA [Studied]	1079.0733
AEFA [Studied]	1397.688
ARO [Studied]	446.8054
SO [Studied]	459.1944
AGTA [Proposed]	400.1363

ACE is a critical measure of the imbalance between scheduled and actual power exchanges adjusted for frequency bias. An effective LFC should promptly reduce the ACE to zero. The proposed algorithm-based responses shown in [Figure 18](#) indicate that the ACE is corrected quickly in each area, and the oscillatory behavior or stability of the ACE response is better.

Table 10. Optimized PID controller gains for the test system Scenario 3.

Areas	Techniques	K_p	K_i	K_d
Area-1	CHOA [Studied]	1.0000	1.0000	1.0000
	COA [Studied]	1.0000	1.0000	1.0000
	AEFA [Studied]	0.2518	0.7089	0.4983
	ARO [Studied]	0.7919	0.6950	0.7417
	SO [Studied]	0.9952	0.9952	0.9952
	AGTA [Proposed]	1.0000	1.0000	1.0000
Area-2	CHOA [Studied]	1.0000	1.0000	0.7078
	COA [Studied]	1.0000	1.0000	1.0000
	AEFA [Studied]	0.7433	1.0000	1.0000
	ARO [Studied]	0.5795	0.9645	0.9979
	SO [Studied]	0.9952	0.9952	0.9952
	AGTA [Proposed]	1.0000	0.7856	0.4903

Table 11. Comparative measure of performance indices for test system Scenario 3.

Algorithms	FOD		Performance indices	
	ITAE	IAE	ITSE	ISE
CHOA [Studied]	28.6597	0.0986	0.2215	0.0031
COA [Studied]	28.7680	0.0968	0.2222	0.0031
AEFA [Studied]	49.3789	0.2560	0.3858	0.0081
ARO [Studied]	38.2738	0.1455	0.2932	0.0046
SO [Studied]	28.8693	0.0974	0.2230	0.0031
AGTA [Proposed]	28.5280	0.1001	0.2199	0.0032

Table 12. Study of computational time for test system Scenario 3.

Algorithms	Computational time (s)
CHOA [Studied]	436.622
COA [Studied]	1143.743
AEFA [Studied]	1460.708
ARO [Studied]	461.429
SO [Studied]	464.742
AGTA [Proposed]	430.453

The controller output response is indicative of how the LFC system modulates the generation output to counteract frequency and power flow deviations. By discussing the dynamics of the controller output [Figure 19](#), shows that the proposed algorithm-based responses respond aggressively to disturbances. The presence of oscillatory output was also low, which might be an indication of controller

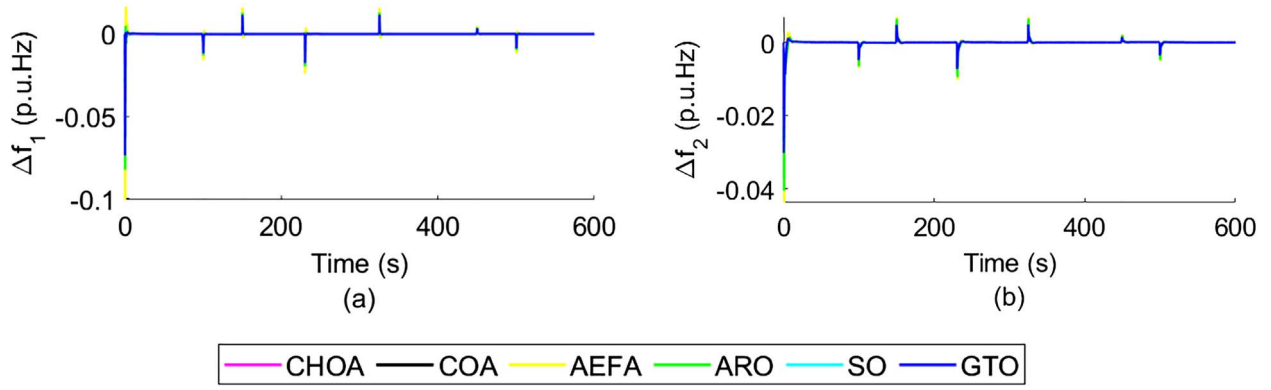


Figure 16. Depiction of time-domain frequency deviation response in the test system under RLP conditions (refer to Scenario 3): (a) Δf_1 and (b) Δf_2 .

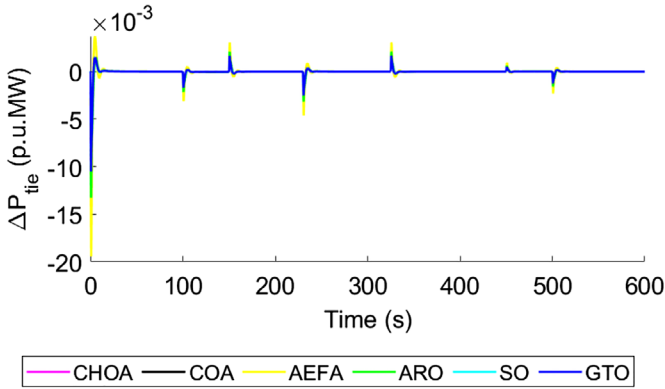


Figure 17. Depiction of time-domain tie-line power deviation response (ΔP_{tie12}) in the test system under RLP conditions (refer to Scenario 3).

tuning issues. The responses were well aligned with the system's requirements for stability and efficiency.

The FOD curve is crucial for understanding the operational efficiency and stability of the system under varying load conditions (Fig. 20).

7 Limitations and constraints of this study

Understanding the context and limitations of this study involves several key factors.

- Simplified Power System Models:* The study applies this method to various power system models, including traditional two-area interconnected systems. However, these simplified models cannot fully capture the complexities and challenges of real-world power systems.
- Assumptions and Idealized Conditions:* Idealized settings are assumed, such as ignoring system dynamics, assuming ideal communication, and having perfect knowledge of the system parameters.
- Limited Experimental Validation:* The proposed approach was assessed through simulation-based tests,

which can provide insights but might not fully reflect real-world implementation issues and uncertainties.

- Application:* This study concentrates on the AGC problem in power systems and performs well in the examined power-system models. However, its application and effectiveness in other configurations, operating scenarios, and optimization challenges may require further investigation.
- Comparison with Other Algorithms:* While the study evaluated the performance of the proposed algorithm in power system models, a more comprehensive analysis could compare it to other state-of-the-art optimization algorithms used in AGC or related optimization problems to identify its strengths and weaknesses.
- Practical Implementation Considerations:* This research explores the utility of the algorithm in simulated scenarios, but actual deployment necessitates further examination of practical implementation issues, such as processing requirements, scalability, and robustness in large-scale power systems or real-time constraints.

8 Conclusions and scopes of future work

This paper has explored the potentials of optimum decentralized frequency control across different power generation landscapes, mainly in the integration of wind and solar photovoltaic sources, by employing AGTA. From the simulation results, it was highlighted that AGTA could overcome a multitude of issues related to the variability and intermittency of renewable sources and resultantly has further superiority in guaranteeing grid stability with optimized frequency control. This work affirms the prospective superiority of the algorithm in outperforming traditional optimization and presenting an optimum robust solution for the critical issue of maintaining grid reliability in a scenario with renewable energy penetration. The findings of this work contribute greatly to increasing the existing body of knowledge in power systems optimization and display practical applicability along with the benefits of using computational algorithms such as AGTA. This study opens up opportunities for more sustainable and resilient

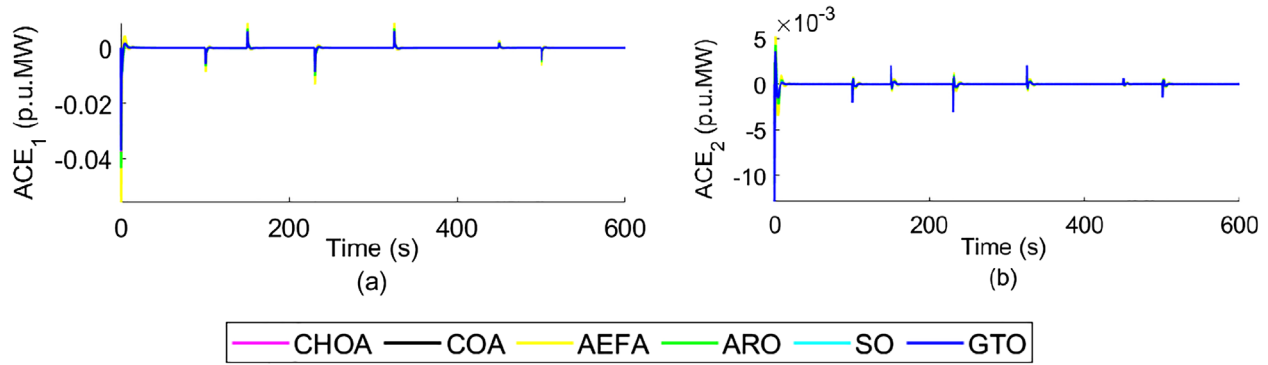


Figure 18. Depiction of time-domain ACE response in the test system under RLP condition (refer to Scenario 3): (a) ACE_1 and (b) ACE_2 .

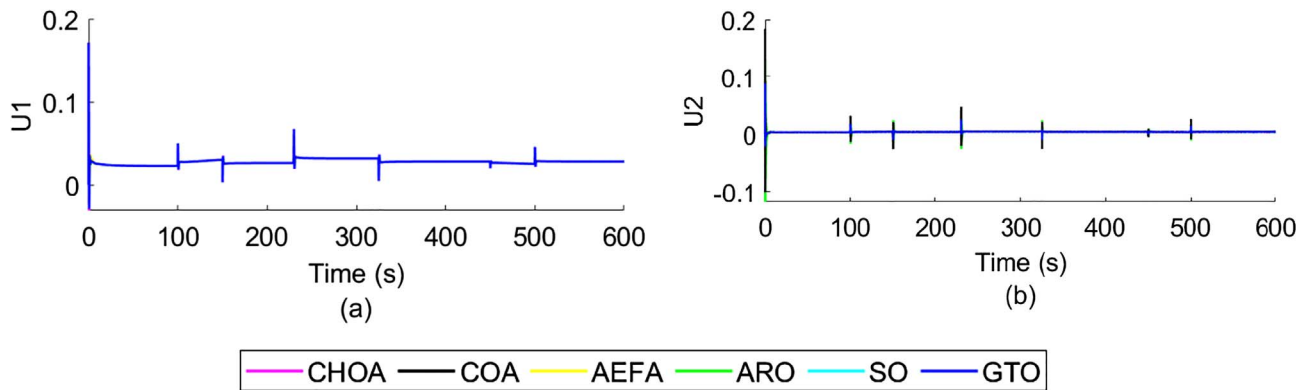


Figure 19. Depiction of controller output response in the test system under RLP conditions (refer to Scenario 3): (a) U_1 and (b) U_2 .

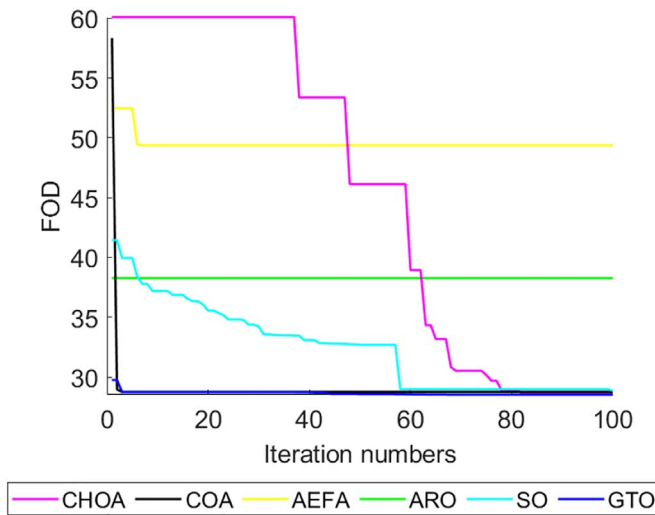


Figure 20. Depiction of FOD response in the test system under the applied algorithms (refer to Scenario 3).

power systems, thereby allowing for the mix of large amounts of renewable energy with efficiency and reliability in the regulation of frequency. This research suggests future directions focusing on enhancing the AGTA for power system optimization, broadening its application to various

management tasks, creating hybrid models with other techniques for improved efficiency, conducting real-world validations, and integrating it with smart grid technologies for advanced grid management and optimization.

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Conflicts of Interest

All authors are associated with the submitted work, which is their original work and has not been submitted elsewhere for publication.

Data availability statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the study.

Author contribution statement

Shruthi Nookala and Chandan Kumar Shiva designed the simulation work for the study. Shruthi Nookala and Chandan Kumar Shiva wrote most of the paper's content. B. Vedik checked the grammar and contributed to writing the paper. All authors read and approved the manuscript.

Ethics approval

The authors affirm adherence to accepted ethical standards for original studies.

Informed consent

All authors agree with the manuscript's content and have followed all relevant instructions provided by the journal's rules, regulations, and editors.

Research involving human participants and/or animals

This research did not involve animals or physical participation.

AI declaration

AI tools were used to enhance the readability and language of the research article but were not employed to replace key tasks that should be performed by the authors, such as interpreting data or conducting scientific calculations.

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