J. Integr. Sci. Technol. 2025, 13(6), 1144

Journal of Integrated
SCIENCE & TECHNOLOGY

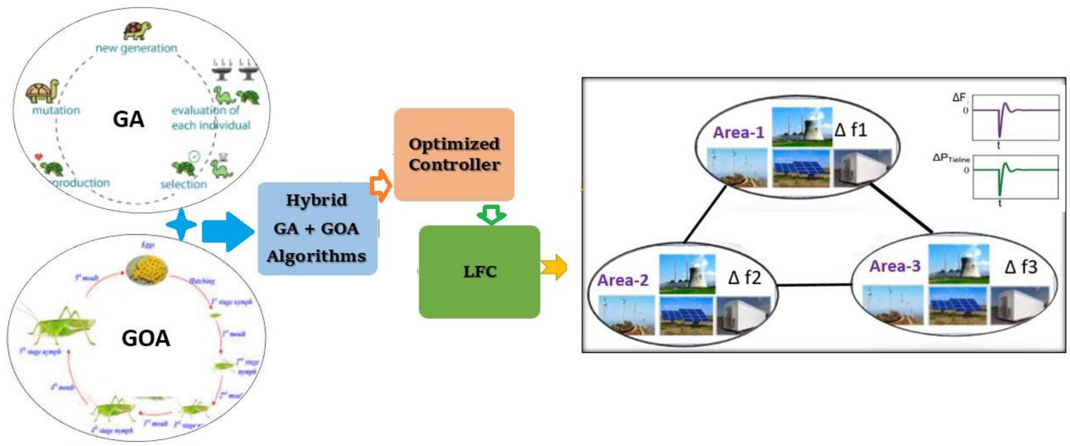
Optimizing Load frequency control of multiple areas power system using HGAGOA integrating with renewable energy and SMES effect

Harendra K. Pushpat,* Sanjiv Kumar Jain

Electrical Engineering Department, Medi-Caps University, Indore. India.

Submitted on: 16-Oct-2024, Revised accepted::28-Mar-2025, Published on: 30-May-2025

Article



ABSTRACT

Load frequency control is pivotal in maintaining grid stability, particularly with the growing integration of renewable energy sources into power systems. This paper describes a new way to use a sophisticated metaheuristic optimization technique for multi-source and multi-area-based LFC that includes RES. By integrating various energy sources, including conventional thermal units and variable RES, like wind and solar, and considering the Superconducting Magnetic Energy Storage (SMES) system, the proposed methodology dynamically adjusts control parameters to optimize LFC performance. The results indicate that the Hybrid Genetic and Grasshopper Optimization Algorithm (HGAGOA) is the most effective algorithm for minimizing the objective function in only 10 iterations, followed by the Genetic Algorithm (GA) with 40 iterations and then the Grasshopper Optimization Algorithm (GOA) with greater than 50 iterations. HGAGOA is a great choice for optimization tasks that need fast and reliable convergence because it combines the best features of GA and GOA. Hence, the HGAGOA outperforms the GOA and GA in both objective functions-change in frequency deviation and power deviation. This framework looks like a good option, and it could be used for real-time implementation and integration with advanced grid management systems to make things even better in terms of performance and resilience

Keywords: Load frequency control, Renewable Energy, Multi area-multi source, Optimization, Superconducting Magnetic Energy Storage

INTRODUCTION

The power sector is an important aspect of people's lives due to the country's expanding economy and society. The installed capacity of large power grids always grows with the increasing number of electrical devices connected to them [1]. In recent years, issues regarding environmental conservation have gained more prominence, particularly concerning global trends in low-carbon and clean energy. Alternative forms of power generation have become necessary due to constraints that are inherent in traditional forms, like thermal power generation. This involves transforming heat from traditional sources of energy combustion into electrical energy; however, it is affected by economic and environmental problems. Therefore, new ideas must be developed that would help in generation [2]. Renewable energy sources like solar photovoltaic (PV) power generation and wind power generation were invented and applied to contemporary power systems, thus shrinking the share of traditional electric power generation modes in the total installed capacity. The need to meet socially sustainable development goals drives this shift.

High levels of RES can have big effects on the inertia of a system, even though most RES don't have a rotational mass, which is what causes inertia [3]. The use of renewable energy sources is among the most effective methods for the generation of electrical power since they do not require any fuel, they do not release any harmful emissions into the environment, and they are accessible virtually all year round. The world extensively uses energy from renewable sources like tidal, geothermal, wind, and solar power [4].

*Harendra K. Pushpat, Research Scholar, Medi-Caps University, Indore
Tel: +91-9737347008; Email: harendra.pushpat@gmail.com

Cite as: *J. Integr. Sci. Technol., 2025, 13(6), 1144.*
URN:NBN:sciencein.jist.2025.v13.1144
DOI:10.62110/sciencein.jist.2025.v13.1144

People mostly use wind and solar power, two of the many renewable energy sources, due to their low initial investments and lower operational costs. Since these units are highly flexible, it becomes easy to incorporate them into traditional power generation systems. Figure 1 shows how various renewable energy sources appear.

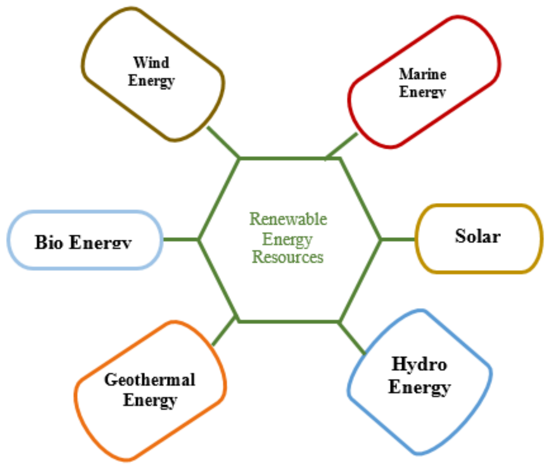


Figure 1: Renewable Energy Systems [5]

The power system's reliability can only be sustained with the successful integration of renewable energy sources in order to meet the challenges posed by a dynamic energy industry [6]. The LFC is one of the most significant aspects, which serves as a mechanism for ensuring that there is a balance between power generation and consumption. LFC is a portion of an electric power system that controls and maintains the uniform distribution of frequencies, divides the load between generators, and schedules the exchange of tie-lines [7]. This study explores the integration of various types of distributed generation from across the globe into power networks. It investigates methods for regulating load frequency using alternative energy sources to ensure system consistency and high quality. This study mainly investigates the inclusion of renewable resources with specific attention to how load frequency can be simultaneously managed across many sites using different types of resources and Superconducting Magnetic Energy Storage (SMES) system. Superconducting Magnetic Energy Storage (SMES) systems represent a sophisticated energy storage technology capable of storing electrical energy within the magnetic field generated by a coil made of superconducting wire, which exhibits zero energy loss. These systems are characterized by their ability to rapidly store and release substantial amounts of energy, enabling them to discharge high power levels within a fraction of a cycle. This feature is particularly valuable for preventing abrupt power losses in the grid. Compared to other energy storage technologies, SMES units offer enhanced reliability, primarily due to the stationary nature of their components.

There are different energy grids, especially those that incorporate renewables, which have distinct management challenges [8]. The introduction of RES makes conventional power systems more complex due to their unpredictable and variable nature. The issue of control becomes much more complex when dealing with multiple sources and areas. Researchers in the field of optimization are now investigating ways to improve the effectiveness of load frequency control systems in order to address these issues. Metaheuristic optimization techniques are a group of computational techniques based on natural phenomena or processes. These are well-structured techniques that can be used to easily navigate through complicated non-linear optimization problems in their search for feasible solutions [9]. Traditional optimization methods may not readily provide optimal solutions in real-time situations involving LFC and RES. This problem emanates from the unpredictability of renewable energy generation. The multiple sources introduce further disparities in the system and disrupt the delicate balance between generation and consumption. In the absence of a well-coordinated controller, the system can be vulnerable to significant strain from undesired disruptions, leading to deviations from its typical operating conditions. Thus, the GOA with decreasing coefficients is implemented to address the issue realistically, accounting for a broader variety of unforeseen variables and events [10]. The dynamic coefficients can effectively enhance both local and global search capabilities. It can help the system consider several situations involving undesirable disturbances, uncertainties, and random load changes. Figure 2 presents the process of the grasshopper optimization algorithm.

Figure 1: Grasshopper Optimization Algorithm [11

At every stage of optimization, the algorithm must identify a specific objective for grasshoppers to proceed. In the context of the GOA, the grasshopper with the highest objective value is the fittest and represents the desired outcome of the optimization process. This approach will enable GOA to efficiently preserve the most favorable objective in the exploration area during each iteration, necessitating the movement of grasshoppers toward it. It is accomplished with the intention of discovering a superior and more precise objective that serves as the most suitable estimation for the actual global maximum within the exploration domain [12]. It may have been updated to overcome constraints and improve both convergence rate and solution quality. The contradictory behavior of LFC and security constraints related to load frequency control have presented evidence that genetic algorithms (GAs) are appealing for addressing automatic generation control coordination challenges involving high-dimensional problems with conflicting objective functions [13]. To find a suitable operating point, the GA can be used to figure out the decentralized control parameters and centralized generation levels of the online units [14]. The use of

LFC model properties in conjunction with a genetic algorithm has the potential to significantly enhance convergence speed. This paper presents a hybrid algorithm by combining the grasshopper optimization algorithm and genetic algorithm approaches, and it shows enormous promise for implementation in multi-area power systems. So, this study is intended to provide some insights into how sustainable operating systems are supposed to be efficient, especially in a world where renewable energy has become an important power source. These issues should be addressed by examining new approaches that meld advanced optimization techniques with renewable energy sources. Electric power systems are continuously being reinvented to accommodate more renewable energy sources as experts study them to understand their operations in the future.

RELATED WORK

Environmental concerns associated with conventional electricity generation have made it imperative to adopt RES in power systems in recent years. Therefore, advanced control systems should be used to integrate these renewable energy resources into the existing electrical grid for stability reasons. This study seeks to analyze previous works on multi-source and multi-area-based LFC using novel metaheuristic optimization techniques so as to incorporate renewable energy sources.

Gouran et al. (2023) [15] introduced the GOA with descending coefficients. Therefore, one of the best ways to improve global search through local search is changing these coefficients with time. Several system and algorithm tests were included in each stage of testing in which random findings, uncertainty, and load variations were considered. According to numerical data, the suggested technique surpassed previous methods by more than 25% in time and frequency domains. The frequency and time domains revealed that the S-plane stability of this system was greater than that of other systems available in the literature with respect to undershoots and overshoot times, as well as lower settlement. Nyquist and Bode's evaluations show that the system performs well at many operating points.

Naderipour et al. (2023) [16] employed a fuzzy logic self-tuning controller to handle classical uncertainties of controller parameters such as operating conditions, change in microgrid operating point, and microgrid modeling uncertainty. The fractional-order and fuzzy logic controllers were used for load-frequency control of off-grid microgrids with renewable resources since the last one was robust and flexible. The optimum meta-heuristic whale algorithm was applied to find out the fuzzy controller's scales (input and output coefficients) and the fractional order controller's fractional orders that make the optimal control. This recommended approach has been implemented on diesel generators, wind turbines, solar, and storage-based microgrids. When it came to operational characteristics, response times, and frequency deviations, fractional-order self-tuning fuzzy controllers outperformed conventional PI controllers in managing alternating loads.

Zheng et al. (2023) [17] introduced a method known as linear active disturbance rejection control (LADRC) that was derived from the soft actor-critic (SAC) algorithm. A strategy was developed to counterbalance the adverse impacts resulting from renewable energy. Two power systems were created, each having an intelligent LFC controller. One system had a solar thermal power plant (STPP), while the other one had a wind turbine generator (WTG), PV cells, and a hydro turbine. It has been designed so that it can eliminate unknown disturbances in addition to supporting the decision-making approaches of the SAC algorithm through LADRC. Simulation results were also compared to PID, MPC, and traditional LADRC controllers that showed their efficiency.

Ragab et al. (2023) [18] demonstrated that the design of a PID controller based on ARA can be used for load frequency control in MAPSs, leading to effective and successful ITAE minimizations, whose superiority was confirmed by statistical analysis. These suggested ARAs may augment ITAE values of particle swarm optimization (PSO), DE, JAYA, and SAMPE-JAYA by 1.949%, 3.455%, 2.077%, and 1.949%, respectively, based on the shift in load in area 1. These suggested ARAs may increase ITAE values of PSO, DE, JAYA, and SAMPE-JAYA by 7.587%, 8.038%, 3.322%, and 2.066%, respectively, due to the change in load in area 2. It is also proposed that the following suggested ARA may enhance ITAE values of PSO, DE, JAYA, and SAMPE-JAYA by 60.89%, 38.13%, 55.29%, and 17.97%, respectively, when loads were changed simultaneously in areas 1 as well as 2.

Raj et al. (2023) [19] improved the PID controller configuration using Bald Eagle Sparrow search optimization (BESSO). Several bald eagle and sparrow characteristics were combined to produce this algorithm. The comparison of BESSO's results with those of more conventional approaches would determine a lot. After the BESSO-PID controller had been found successful in reducing system error, as indicated by Integral Time Absolute Error (ITAE), this metric was preferred. Lastly, sensitivity and stability analyses illustrate the robustness of the designed controller. The tie-line power flow settling period frequency variation in area-1 and area-2 was all significantly less than those according to conventional methods, i.e., 10.4767 s, 8.5572 s, and 11.436 s, respectively. Therefore, it can be concluded that among other alternative proposals, the proposed mechanism was more efficient because of its minimum settling time for all tie-line power flow and area-1 and area-2 frequency deviations compared to traditional ones.

Zhang et al. (2023) [20] explained how one specific modified proportional integral derivative with filter (PIDF) could improve the performance of MMS (a maritime microgrid system) via LFC. They used a bio-inspired serval optimization algorithm (SOA) to optimize MPIDF controller coefficients. The controller was tested on a marine microgrid having solar panels, wind turbines, and wave energy as sources of electricity. The recommended MPIDF controller outperformed other current alternatives like PIDF and PI. Moreover, other meta-heuristics such as PSO, ant colony optimization (ACO), and jellyfish swarm optimization (JSO) were compared with the proposed method in relation to proofing this proposal.

Gbadega et al. (2023) [21] developed a system model with physical constraints such as Reheat Turbines (RT), Time Delay (TD), Generation Rate Constraint (GRC), and Dead Band. The dynamic performance of the proposed controller was then studied, taking into consideration these physical constraints. EWOA is an algorithm for system-optimal PID controllers that are adjusted dynamically. Performance evaluation regarding SMES units for both system models was done in order to determine its impact on them. Governor speed regulation (R) and modified frequency bias parameter (B) are the two system parameters that affect how the controller reacts to changes in frequency and, therefore, determine the stability of the power system under frequency deviations. The suggested controller had better dynamic performance than the standard WOA, which makes it more resilient and stable under various loading conditions, parameter variations, step load perturbations, etc.

Dhanasekaran et al. (2023) [22] assessed how the proposed supervisory approach could use a PID controller as a subordinate to retain a system's response during an intense power demand situation. The optimal values of its gain were solved by using PSO. The optimization of controller gain settings involved using cost criteria such as ITAE, IAE, ISE, and ITSE. The performance of standard DE and GA-based PID controllers in the system was compared to prove that the PSO technique was better. The settling response of the PSO-PID controller during an emergency in a power system was faster by 79% than the old one, 55% than GA, and 24% than DE.

Reddy et al. (2022) [23] described a more efficient way of working, one that increased stability and the ability to use information. The suggested approach proposed some changes in the method's structure and also modified some parts of the standard algorithm's update equations. The indicated algorithm was thus evaluated in relation to the modern MOT and upgraded WOA in accordance with recommendations made in the literature. After testing it on CEC 2019 benchmark functions, it was found that using this procedure yielded the best results in seven out of ten tests with the highest overall rank. The algorithm consistently demonstrated its effectiveness in handling real-life scenarios. It was further observed that it had a greater speed of convergence in comparison with other techniques that were investigated.

RESEARCH PROBLEM

The availability of electricity is the lifeblood of modern society for both domestic and industrial use. Therefore, managing the fluctuation between load and frequency is important to achieving a stable power supply. In multi-area power systems integrating renewable energy sources and superconducting magnetic energy storage (SMES) units, load frequency regulation remains a huge technical challenge. Effective load frequency control needs a well-tuned PID controller that ensures optimum real-time performance in the entire interconnected system. However, conventional load frequency control techniques alone cannot handle the highly variable load profiles from conventional generators, renewable sources, SMES devices, and interconnections. Consequently, there has been an increasing demand for better oscillations in tie-line power flows, enhanced frequency regulation capabilities to minimize deviations in frequency, and improved control effort. As more renewables are integrated into the grid and as dynamic characteristics of both generators and loads continue to evolve, effective solutions regarding coordinated frequency control across interconnected multi-area power systems with SMES are yet to be developed by researchers. Advanced controller schemes need to be able to work reliably in a lot of different situations, like when renewable energy sources go down and demand changes. This is because stability problems are common in real life.

PROPOSED METHOD

The hybrid-genetic and grasshopper optimization algorithm, the PID controller, the SMES control, the RES power output, the load dynamics, and the performance evaluation are all parts of the multi-area LFC methodology. Figure 3 presents a diagrammatic depiction of the operation. The steps below are necessary to explain the process flow of the proposed methodology.

a) Multi-Area Power System Model

- Represents the dynamic model of the multi-area power system, including conventional generators, RES units, SMES devices, and tie-lines.
- Includes governor-turbine dynamics, frequency deviations, and tie-line power flow.

b) The Hybrid-Genetic and Grasshopper Optimization Algorithm

- Implements the improved hybrid-genetic and grasshopper optimization algorithm for optimizing the PID controller parameters.
- Takes objective functions representing desired performance metrics as input.
- Outputs optimized values for the PID controller gains.

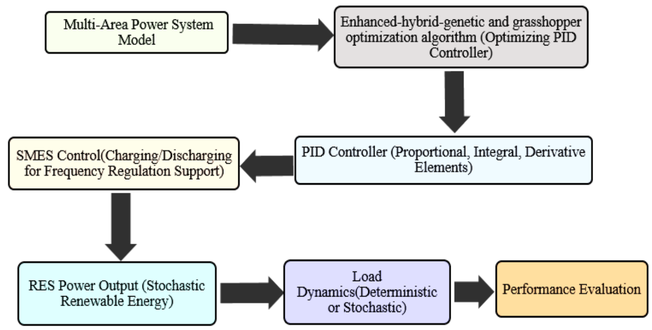


Figure 3: Proposed Methodology

c) PID Controller

- Designed with proportional, integral, and derivative elements for each control area.
- Receives frequency deviation and tie-line power error signals as input.
- Generates control signals based on the optimized PID gains.

d) SMES Control

- Manages the charging and discharging of the SMES units to provide frequency regulation support.
- Receives control signals from the PID controller.
- Adjusts the SMES power output based on system requirements.

e) RES Power Output

- Represents the stochastic nature of renewable energy sources like wind and solar.
- Modeled using appropriate probability density functions.
- Provides intermittency and uncertainty to the system dynamics.

f) Load Dynamics

- Represents the variations in power demand across different areas.

- It can be modeled as deterministic or stochastic, depending on the scenario.
- Introduces disturbances to the system that require LFC action.

g) Performance Evaluation

- Analyzes the effectiveness of the proposed method using selected metrics.
- Compares frequency deviations, tie-line power oscillations, and control effort with conventional LFC techniques.
- Provides insights into the system response under different conditions.

The study presents a multi-area load frequency control method for power systems with renewable energy sources and SMES devices. To make frequency regulation and tie-line power flow control work better, an improved hybrid-genetic and grasshopper optimization algorithm finds the best PID controller parameters. Unpredictable outputs from renewable generators and changes in the load cause disturbances that are handled by coordinating PID control and SMES charging and discharging. Detailed system modeling and simulation demonstrate the effectiveness of the proposed approach over conventional techniques.

RESULTS AND DISCUSSIONS

SYSTEM PARAMETERS

Table 1 presents key parameters associated with three different areas: Area-1, Area-2, and Area-3. Each area corresponds to distinct aspects of renewable energy systems or power generation. For solar systems, the time constant values range from 1.52 to 1.72 across the three areas, indicating the response time of the system to changes. Similarly, for wind systems, the time constant values range from 1.65 to 1.76, reflecting the responsiveness of the wind energy generation. Load time constants, representing the response time of the load, vary from 1.18 to 1.22.

Table 1. System parameter settings

Parameters	Area-1	Area-2	Area-3
Solar system time constant	1.52	1.64	1.72
Wind system time constant	1.65	1.71	1.76
Load time constant	1.18	1.2	1.22
Damping constant	0.0182	0.0196	0.0225
Frequency bias factor (B)	0.545	0.644	0.672
Speed regulation parameter	0.505	0.556	0.504

Additionally, damping constants, which influence system stability, range from 0.0182 to 0.0225. Moreover, frequency bias factors (B) exhibit variations from 0.545 to 0.672, indicating the system's bias toward frequency adjustments. Lastly, speed regulation parameters (R), reflecting the system's ability to maintain speed under load changes, vary between 0.505 and 0.556 across the three areas. These parameters are crucial for understanding and optimizing the performance of renewable energy systems, facilitating efficient power generation and distribution.

The improved controller parameters from the HGAGOA (Hybrid Genetic Algorithm and Grasshopper Optimization Algorithm) algorithm are shown in Table 2 for three different areas. Each row corresponds to a specific controller gain (K1 to K8), while each column represents a different area of optimization. The values in the table denote the optimized parameter values for each gain in each area. These parameters are very important for the proportional-integral-derivative (PID) controller, which is a key part of controlling how well systems work, like renewable energy systems or industrial processes. The optimization process aims to fine-tune these parameters to enhance the controller's effectiveness in achieving desired objectives, such as stability, response speed, and disturbance rejection. The different parameter values in different areas show how well the algorithm can adapt and improve the controller's performance to the unique operational or environmental conditions in each area.

Table 1. Controller parameters optimized by HGAGOA algorithm.

Gain	Area-1	Area-2	Area-3
K1	0.4312	0.4245	0.4553
K2	0.41667	0.4257	0.4263
K3	0.41667	0.4257	0.4263
K4	0.41667	0.4257	0.4263
K5	0.543478	0.52357	0.52357
K6	0.326084	0.38346	0.38346
K7	0.130438	0.14235	0.14235
K8	6.8933	6.5773	6.7643

Results 1: Load Changes in Per Unit with Respect to Time

Figure 4, depicts fluctuations in electrical load over a short period (in seconds). The load is measured per unit and varies slightly between positive and negative values to contain complete deviations along both directions. These changes reflect shifts in power consumption due to daily usage patterns or the influence of variable renewable energy sources with power demand changes.

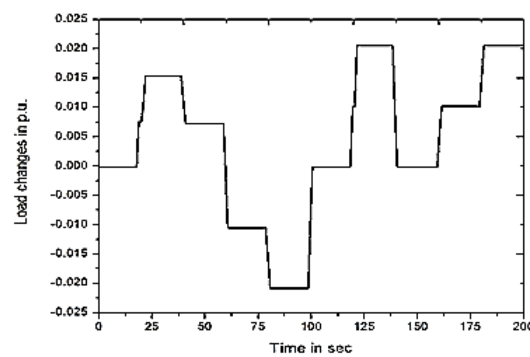


Figure 4: Load Changes in per unit with respect to time.

Results 2: LFC Model with 1 PID

Table 3 shows the PID tuning parameters (P, I, D) that are used in a multi-area model for an LFC-based system. The parameter values used in the block are obtained using the HGAGOA algorithm to optimize the proposed system. This optimization technique ensures that the proposed system achieves optimal performance, maximizing efficiency and stability in LFC operations with SMES integration. Figure 5 depicts a control methodology aimed at effectively integrating renewable energy sources into the power grid. This strategy prioritizes the maintenance of system stability and the attainment of optimal performance. It achieves this through a combination of metaheuristic optimization techniques, SMES systems, and the implementation of a single PID controller. Furthermore, the transfer function modeling provides insight into how these components influence critical aspects such as system frequency deviations and flow.

Table 2. PID tuning parameters

Parameter	Area-1	Area-2	Area-3
Proportional (P)	10	8.4	8.85
Integral (I)	10	7.5	8.25
Derivative (D)	1.7339	1.5764	1.6337

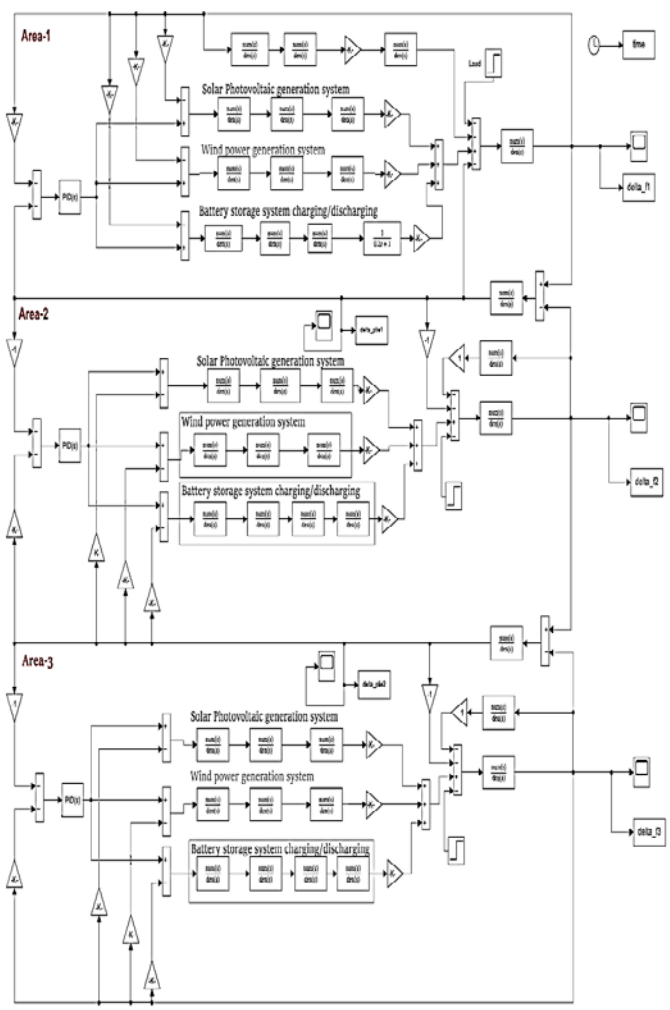
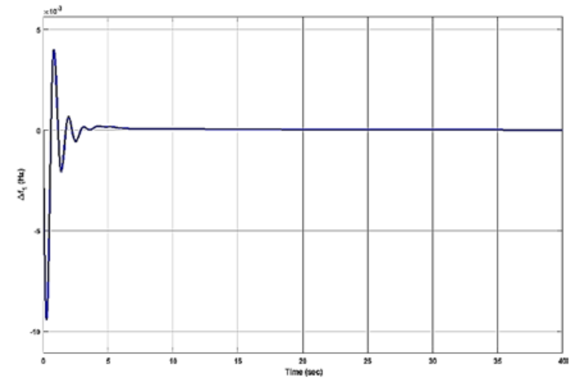
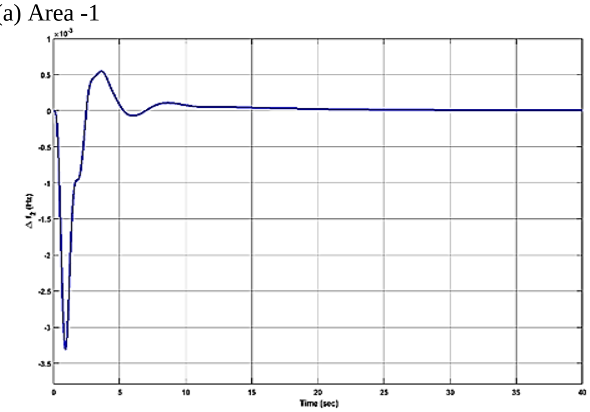


Figure 5: LFC model with 1 PID per area

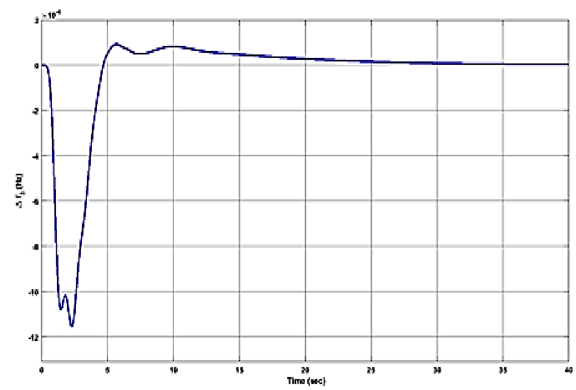
As shown in Figure 6 (a), (b), and (c), in a three-area power system with SMES units, each area is controlled by a single PID controller to control frequency deviations and power balance. Frequency deviation plots in each area (Δf1, Δf2, Δf3) show initial spikes followed by damped oscillations after load changes. The graph shows frequency deviations in each area with larger settling times and more harmonics leading to higher system instability. The PID controllers' effectiveness is evaluated by how quickly deviations return to near zero, aided by the SMES unit's rapid power control. A well-tuned system exhibits quick stability restoration with minimal overshoot/undershoot. PID tuning also mitigates inter-area power oscillations, ensuring deviations in one area don't overly impact neighboring ones.



(a) Area -1



(b) Area-2



(c) Area-3

Figure 6: Frequency response with 1 PID for Δf with respect to time.

Results 3: LFC Model with 3 PID

Figure 7 illustrates a control strategy designed to effectively assimilate renewable energy sources into the power grid. This strategy prioritizes the maintenance of system stability and optimal performance through the utilization of metaheuristic optimization techniques, SMES systems, and three PID controllers. Additionally, transfer function modeling is employed to characterize the dynamics of the system. The graph serves to visually depict the impact of these components on crucial aspects such as system frequency deviations, flow, and the optimized objective functions J1 and J2, which are combined to produce J as the final objective function for minimization, i.e., error based on the HGAGOA algorithm, which is to be minimized.

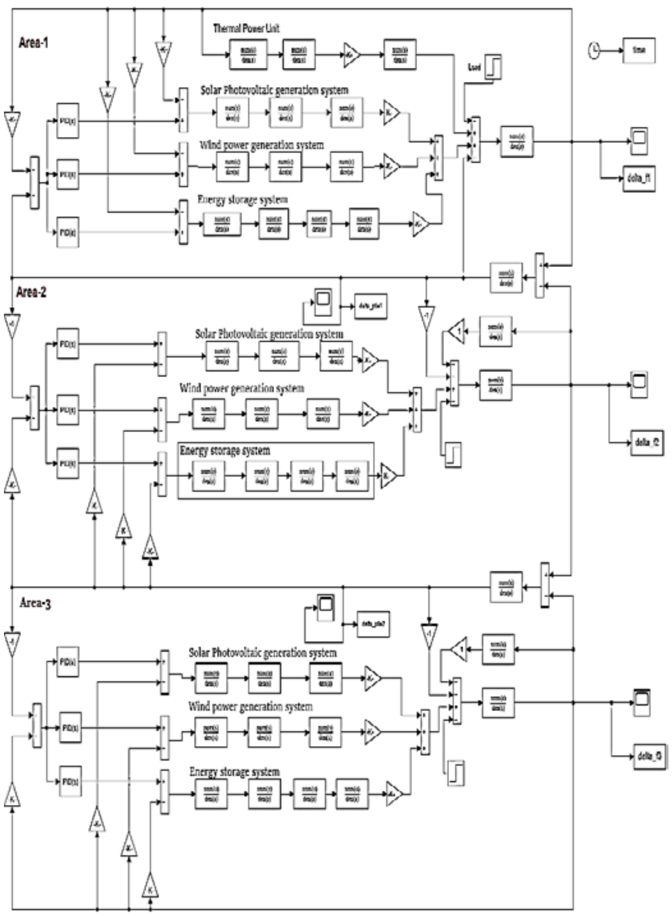
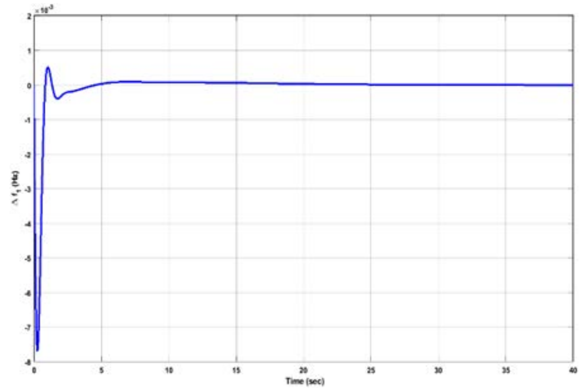
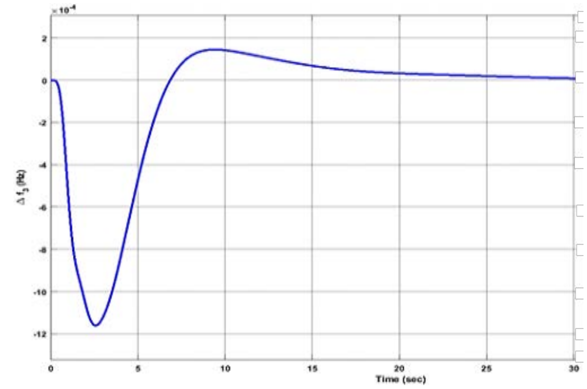


Figure 7: LFC model with 3 PID per area

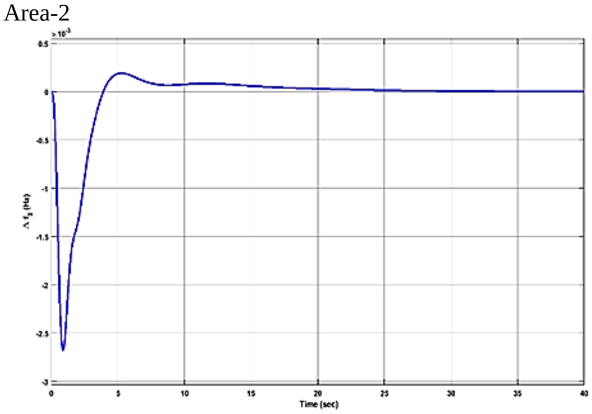
A three-area power system with SMES units is shown in Figures 8(a), (b), and (c). Three PID controllers control the frequency and power balance in each area. The curves show higher settling time and system instability initially with larger frequency deviations without a PID controller. Frequency deviation plots show initial spikes followed by steady oscillations after changes in load. PID controllers are used to quickly restore system stability with the help of better power control from the SMES unit. The efficiency of PID controllers is determined by their ability to promptly return deviations to near-zero levels with minimal overshoot/undershoot, showcasing the importance of precise tuning for optimal system performance. Furthermore, PID tuning not only addresses frequency deviations but also mitigates inter-area power oscillations, ensuring disturbances in one area do not excessively impact neighboring ones and thereby maintaining overall system stability and reliability.



(a) Area -1



(b) Area-2

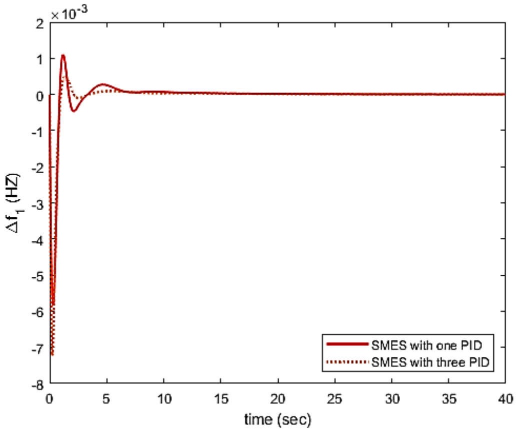


(c) Area-3

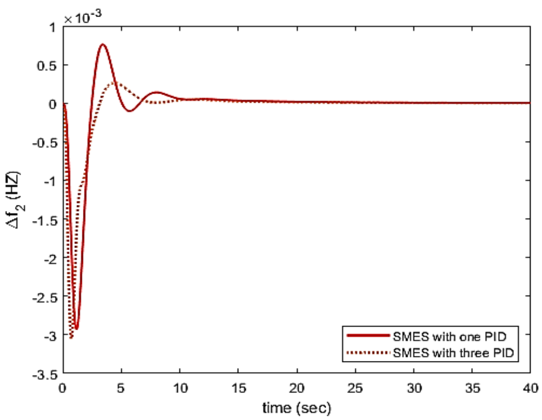
Figure 8: Frequency response with 1 PID for Δf with respect to time.

Results 4: LFC-based SMES for delta f and P_{tie}.

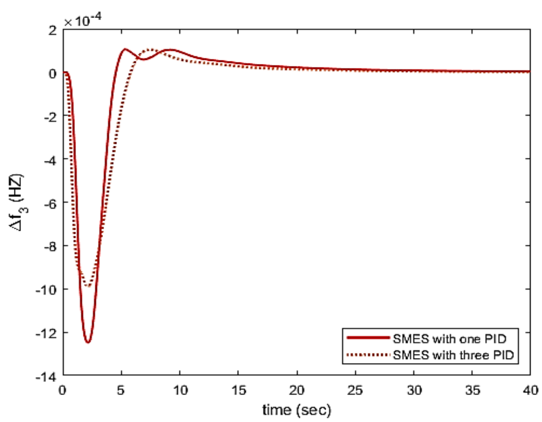
As shown in Figures 9 (a), (b), and (c), a comparison between a three-area multi-source power system managed by a single PID controller and three PID controllers for each area reveals that the latter demonstrates superior performance. In the system with a single PID controller, frequency deviations (Δf1, Δf2, Δf3) exhibit larger amplitudes and longer settling times post-disturbance due to compromised settings across all areas. Conversely, three PID controllers tailored to each area's dynamics lead to quicker stabilization, reduced overshoot, and enhanced system stability. The integration of SMES units further improves performance, with the most significant benefits observed in the system employing three PID controllers due to its more precise control strategy.



(a) Area-1



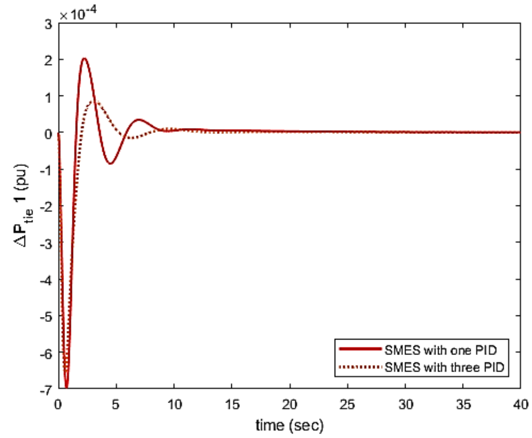
(b) Area-2



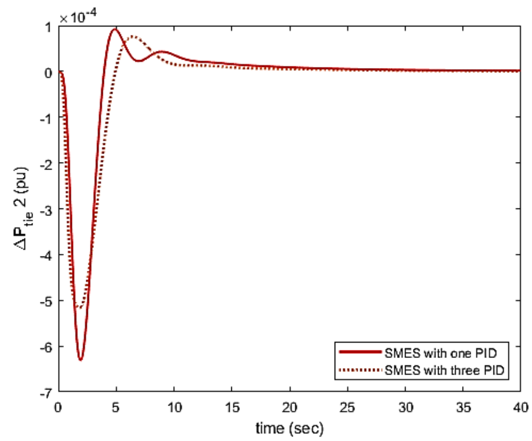
(c) Area-3

Figure *9*: Change in frequency (SMES with one PID and three PID) with respect to time.

Figure 10 (a) and (b) show a comparison between a single PID controller and three PID controllers for each area in a three-area multi-source power system. The second configuration has better performance because it can tune better and has less settling time and peak overshoot. So, in the case of three PID controllers working together, quicker stabilization is achieved with reduced variations and enhanced overall system stability as compared to a single PID controller setup. The integration of LFC-based SMES units further enhances the overall system performance, enabling precise control and improved response to changes.



(a) Tie line-1



(b) Tie line-2

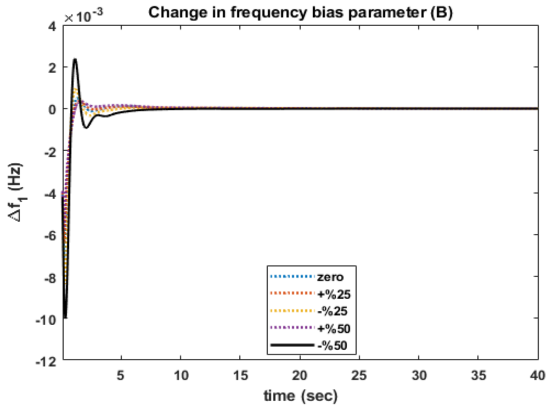
Figure 10: Change in tie line power (SMES with one PID and three PID) with respect to time.

Table 4. Comparative result of SMES with one PID and three PID controller.

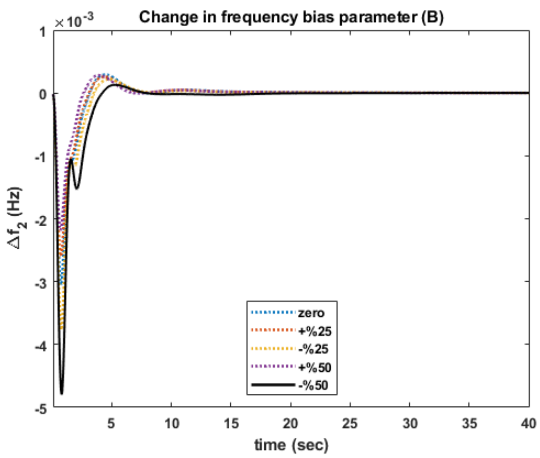
Parameter	**SMES with one PID**	**SMES with three PIDs**
Frequency Deviation (Δf_1)	7.5×10^{-3}	6.9 × 10–3
Frequency Deviation (Δf_2)	3.2×10^{-3}	2.9×10^{-3}
Frequency Deviation (Δf_3)	1.3×10^{-3}	1.3×10^{-3}
Settling Time for area-1	12 s	8 s
Settling Time for area-2	15 s	11 s
Settling Time for area-3	17 s	12 s
Tie-line Power Deviation (ΔPtie1)	6.8×10^{-4}	6.5×10^{-4}
Tie-line Power Deviation (ΔPtie2)	4.5×10^{-4}	4.2×10^{-4}
Settling Time for ΔPtie1	14 s	10 s
Settling Time for ΔPtie1	16 s	12 s

Results 5: Robustness Check (Effects of B)

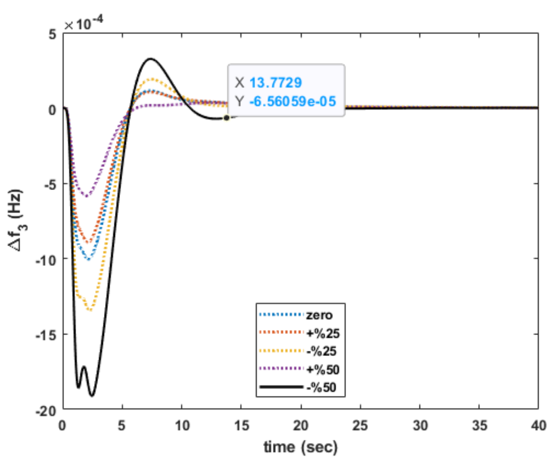
As shown in Figures 11 (a), (b), and (c), varying the frequency bias parameter (B) affects an LFC-based SMES system in a three-area configuration with three PID controllers. Adjusting B from the baseline influences system responsiveness and stability.



(a) Area-1



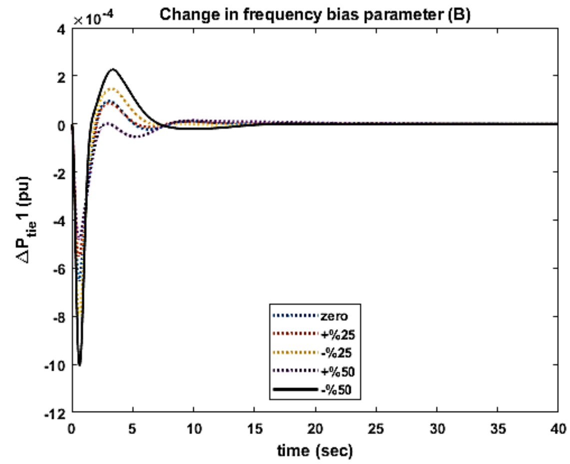
(b) Area-2



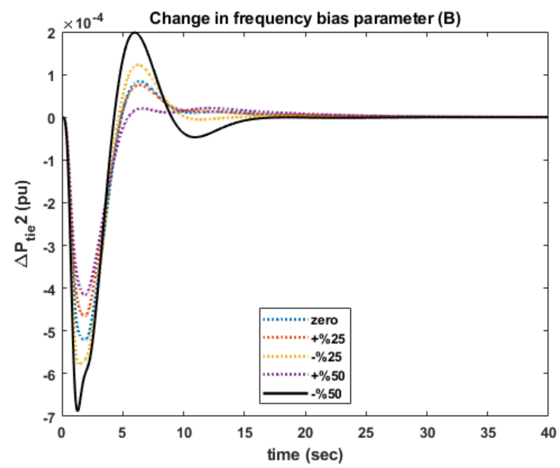
(c) Area-3

Figure 11: Change in frequency bias parameter (B) Δf with respect to time.

Lower and negative B values (-25%, -50%) lead to increased sensitivity, causing larger oscillations and potential instability. Higher and positive B values (+25%, +50%) result in minimized frequency deviations and power loss. Maintaining B at baseline ensures optimal system robustness, confirming the importance of carefully tuning B for balanced control and stability.



(a) Tie line-1



(b) Tie line-2

Figure *12*: Change in frequency bias parameter (B) ΔP_{tie} with respect to time.

As shown in Figure 12 (a) and (b), the evolution of the frequency bias parameter (B) influences the tie-line power deviation over time in a three-area LFC system with SMES, as depicted in the graph. Adjusting B from its baseline affects system responsiveness and stability in which lower and negative values (-25%, -50%) increase sensitivity, leading to larger oscillations and potential instability, while higher and positive values (+25%, +50%) result in less power deviation in both the tie lines. Thus, maintaining B at baseline ensures optimal system robustness, emphasizing the need for careful tuning for balanced control and stability over time.

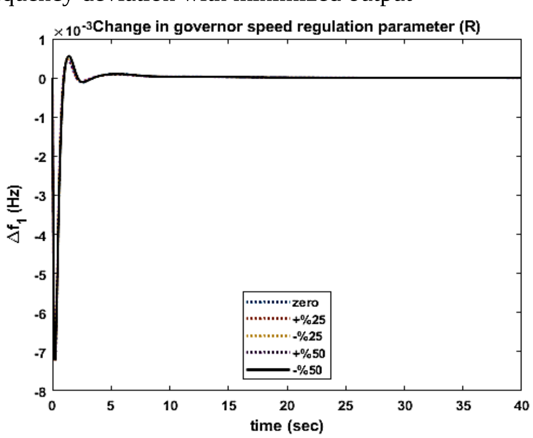
Table 6 illustrates the impact of varying the frequency bias parameter on the SMES-based Load Frequency Control (LFC) system, demonstrating how different parameter changes affect the system's dynamic behavior, including frequency deviations and tie-line power variations.

Table 5. Effect of change in frequency bias parameter (B) on SMES based LFC system

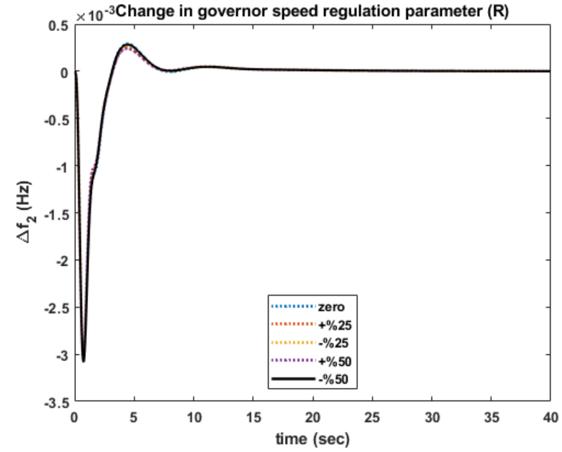
Parameters	Change in frequency bias parameter (B)				
	Zero Change	+25%	-25%	+50%	-50%
Δf_1	10.5×10^{-3}	9.8×10^{-3}	11.2×10^{-3}	9.0×10^{-3}	12.0×10^{-3}
Δf_2	3.5×10^{-3}	$3.2 \times 10{-}3$	3.7×10^{-3}	3.0×10^{-3}	4.0×10^{-3}
Δf_3	1.6×10^{-3}	1.5×10^{-3}	1.8×10^{-3}	1.3×10^{-3}	2.0×10^{-3}
t_s for (Δf_1)	12 s	10 s	14 s	9 s	16 s
t_s for Δf_2	14 s	12 s	16 s	11 s	12 s
ts for Δf_3	16 s	13 s	18 s	12 s	20 s
$\Delta Ptie_1$	8.2×10^{-4}	7.6×10^{-4}	8.8×10^{-4}	7.0×10^{-4}	9.5×10^{-4}
$\Delta Ptie_2$	6.5×10^{-4}	6.0×10^{-4}	7.0×10^{-4}	5.5×10^{-4}	7.5×10^{-4}
t_s for $\Delta Ptie_1$	14 s	12 s	16 s	11 s	18 s
t_s for $\Delta Ptie_2$	16 s	14 s	18 s	13 s	20 s

Results 6: Robustness Check (Effects of R)

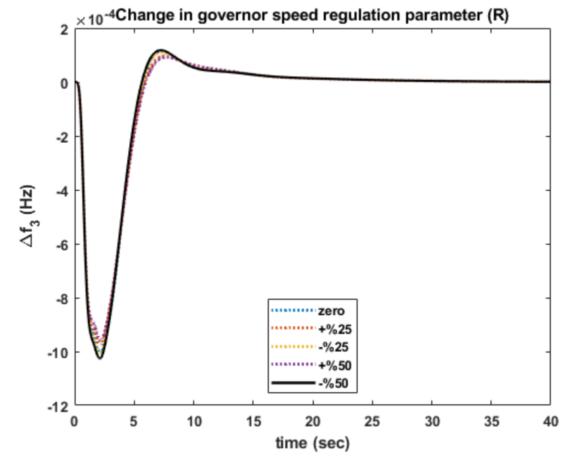
As shown in Figure 13, (a), (b), and (c) illustrate the impact of adjusting the governor speed regulation parameter (denoted as R) with respect to time on a load frequency control system. This parameter R is a key component of the governor control system in power plants, influencing how rapidly the frequency deviation (Hz) reacts to fluctuations in load demand. The graph indicates how alterations to this parameter influence the performance of the load frequency control system, a critical aspect for ensuring grid stability, particularly in power systems incorporating renewable energy sources. Modifying the value of the R parameter from its baseline has repercussions on system responsiveness and stability in which lower and negative values (-25%, -50%) amplify sensitivity, resulting in larger oscillations and potential instability, while higher and positive values (+25%, +50%) yield smoother frequency deviation with minimized output



(a) Area-1



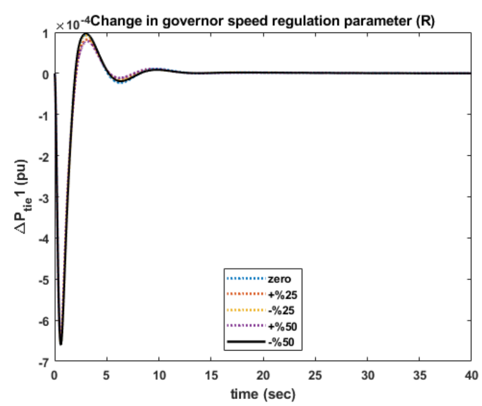
(b) Area-2



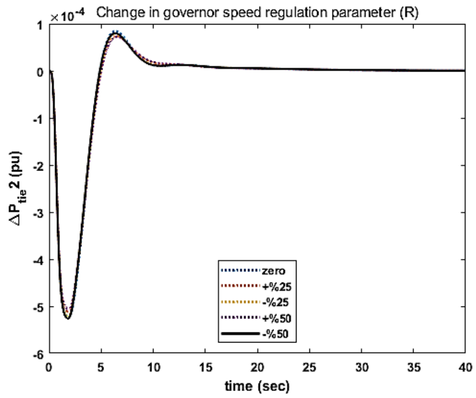
(c) Area-3

Figure 2: Change in governor speed regulation parameter (R) Δf with respect to time.

As shown in Figures 14 (a) and (b) demonstrates how adjusting the governor speed regulation parameter (R) affects the change over time in a load frequency control system. The y-axis represents the change in frequency (Hz), while the x-axis indicates time in seconds. Increasing R results in less responsiveness of the governor at higher speeds, leading to slower adjustments to changes in speed.



(a) Tie line-1



(b) Tie line-2

Figure *14*: Change in governor speed regulation parameter (R) ΔP_{tie} with respect to time.

Altering R from its baseline impacts system stability and responsiveness in which lower and negative R values (-25%, -50%) increase sensitivity, causing larger oscillations and potential instability, while higher and positive R values (+25%, +50%) result in smoother adjustments but reduced responsiveness. The table 6 presents the quantitative impact of variations in the governor speed regulation parameter (R) on key performance indicators of the system. It includes frequency deviations (Δf_1 , Δf_2 , Δf_3), tieline power deviations (ΔP□ie□, ΔP□ie□), and their respective settling times (ts).

Table 6. Effect of Governor Speed Regulation (R) Changes on Frequency, Tie-Line Power, and Settling Time

Parameters	Change in governor speed regulation parameter (R)				
	Zero Change	+25%	-25%	+50%	- 50%
Δf_1	7.5×10^{-3}	7.15 × 10−3	7.89×10^{-3}	6.98×10^{-3}	8.05×10^{-3}
Δf_2	3.2×10^{-3}	3.1×10^{-3}	3.3×10^{-3}	3.02×10^{-3}	3.37×10^{-3}
Δf_3	1.1×10^{-3}	1.05 × 10−3	1.15×10^{-3}	1.01×10^{-3}	1.18×10^{-3}
t_s for Δf_1	20.5 s	19.2 s	22.1 s	18.0 s	23.1 s
t_s for Δf_2	18.2 s	17.1 s	19.3 s	16.4 s	20.1 s
ts for Δf_3	22.1 s	21.4 s	23.3 s	19.7 s	24.5 s
$\Delta Ptie_1$	6.8×10^{-4}	6.53×10^{-4}	7.10×10^{-4}	6.34×10^{-4}	7.23×10^{-4}
$\Delta Ptie_2$	6.5×10^{-4}	6.27×10^{-4}	6.75×10^{-4}	6.12×10^{-4}	6.9×10^{-4}
t_s for $\Delta Ptie_1$	21 s	19.8 s	22.3 s	18.6 s	23.5 s
t_s for $\Delta Ptie_2$	19.6 s	18.7 s	21.0 s	17.5 s	22.2 s

Result 7: Convergence Plot for GA, GOA, and HGAGOA

Figure 15 illustrates the objective function, a performance metric wherein the x-axis represents the number of iterations while the y-axis represents the value of the objective function. The convergence curves illustrate the optimization algorithm's performance by tracking changes in the objective function value across iterations. HGAGOA, a hybrid of GA and GOA, demonstrates superior convergence, rapidly reducing the objective function value due to its combined exploration and exploitation capabilities.

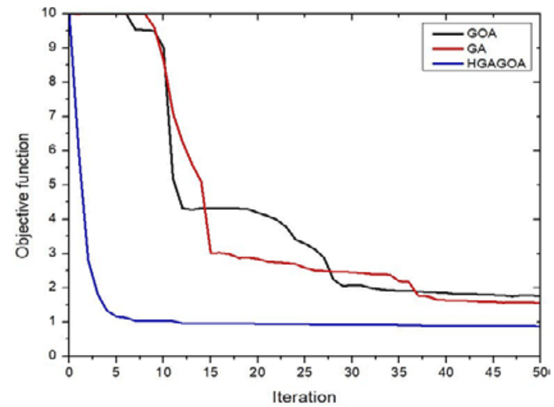


Figure 15: Convergence plot for GA, GOA, and HGAGOA with respect to iteration.

GA follows with a steady decline in the objective function value with a minimum convergence value of 1.633 around 40 iterations, outperforming GOA at 1.758 on 50 iterations but lagging behind HGAGOA, which converges quickly to 0.957 in 15 iterations. Conversely, GOA exhibits slower convergence and potential premature convergence issues attributed to its limited exploration-exploitation balance. Despite its simplicity, GOA optimization efficiency falls short compared to both GA and HGAGOA, especially in complex problems with an increased number of iterations. The effectiveness of the proposed controller model, as shown in Table 7, has been compared with the conventional strategies using the following performance indices: the integral of time multiplied by the absolute value of the error (ITAE), the integral of square error (ISE), and the integral of the absolute value of the error (IAE) combined together to generate the objective function (J).

Table 7. Objective function value

Parameter	Value
J1	-0.0068744
J2	-0.0081163
J	-0.0102763

Result 8: Change in frequency (Hz) with respect to time.

Figure 16, indicates a comparison between the change in frequency between GS, GOA, and HGAGOA in Hz. The graph shows that GOA has a bigger change in frequency up to 0.07 Hz compared to GA, which has a maximum at 0.065 Hz, and HGAGOA, which has a maximum at 0.0615 Hz. The GA and GOA combined algorithm works much better, with the shortest peak time, overshoot, and settling time at 18 seconds and the smallest frequency deviation. This shows that the results are optimal, while GA and GOA take a lot longer to reach the best settling time with the smallest frequency deviation. Therefore, we can conclude that HGAGOA outperforms both GOA and GA in terms of minimized frequency deviation. The table 8, presents a quantitative comparison of frequency response metrics for three optimization techniques: GOA, GA, and HGAGOA. Key parameters such as peak overshoot, settling time, and steady-state error are analyzed to evaluate the performance of each method in stabilizing frequency deviations.

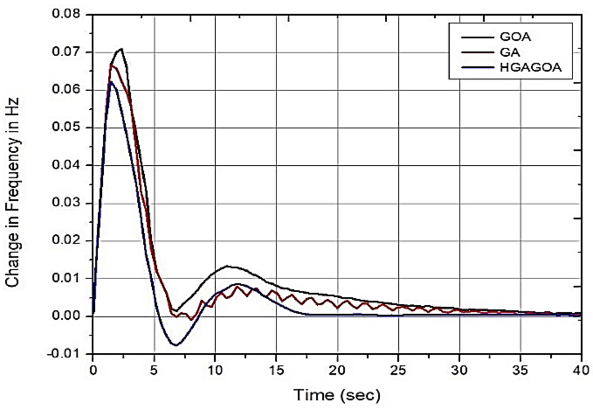


Figure 16: Change in frequency with respect to time.

Table 8. Comparison of frequency response metrics for GOA, GA, and HGAGOA optimization techniques

Performance	GOA	GA	HGA GOA
Peak Overshoot (Hz)	0.065	0.062	0.060
Peak Time (sec)	4.8	4.5	3.5
Settling Time (sec)	22.0	18.5	14.0
Steady-State Error (Hz)	0.02	0.0015	0.0005

The quantitative analysis of the frequency response for different optimization techniques (GOA, GA, and HGAGOA) reveals significant performance variations. The HGAGOA method exhibits the lowest peak overshoot and the fastest settling time, indicating its superior capability in minimizing frequency deviations effectively. In contrast, GOA and GA show higher overshoot and longer settling times, which suggest slower system stabilization.

Conclusion and Future Scope

The implementation of multi-source (renewable energy sources) and multi-area with LFC-based SMES utilizing novel metaheuristic optimization techniques presents a promising path for enhancing the efficiency and reliability of power systems. Through the integration of RES into LFC-based SMES frameworks, the challenges posed by intermittent renewable sources can be effectively mitigated, leading to improved system and reduced dependency on conventional generation. The results indicate that LFC-based SMES control using multi-area, multi-source units by employing three PID controllers performs better in system performance compared to one PID controller setup in each area of the SMES model. The study also shows how important it is to fine-tune parameters like frequency bias (B) and governor speed regulation (R) in order to keep the system steady when the load changes, the frequency changes between three areas, and the power changes in the tie line. The convergence plots clearly show that the HGAGOA graph does better than both GA and GOA. This shows that the HGAGOA optimization algorithm works to improve system performance. Overall, the findings from the system developed emphasize the critical role of advanced control strategies and optimization techniques in ensuring the efficient integration of renewable energy sources while maintaining grid stability. Further research in this field holds promise for advancing toward a cleaner, more reliable energy and development will help enhance its abilities, leading to a more reliable and sustainable power system in the future.

Conflict of Interest statement

Authors do not have acdemic or financial conflict of intetrest for this work as no financial aid was received from any agency.

References

1. H. Bevrani. Robust Power System Frequency Control; Springer, New York, **2009**; Vol. 4.
2. N. Zhao, D. Yue, L. Chen, Z. Cheng. Load Frequency Control for Multi-area Power Systems with Renewable Energy Penetration. In *IECON Proceedings (Industrial Electronics Conference)*; **2020**; Vol. 2020-October, pp 4895–4900.
3. H. Bevrani, T. Ise, Y. Miura. Virtual synchronous generators: A survey and new perspectives. *Int. J. Electr. Power Energy Syst.* **2014**, 54, 244–254.
4. K. Arora, A. Kumar, V.K. Kamboj, et al. Impact of renewable energy sources into multi area multi-source load frequency control of interrelated power system. *Mathematics* **2021**, 9 (2), 1–21.
5. M.M. Gulzar, M. Iqbal, S. Shahzad, et al. Load Frequency Control (LFC) Strategies in Renewable Energy-Based Hybrid Power Systems: A Review. *Energies* **2022**, 15 (10).
6. B. Turley, A. Cantor, K. Berry, et al. Emergent landscapes of renewable energy storage: Considering just transitions in the Western United States. *Energy Res. Soc. Sci.* **2022**, 90.
7. M. Al-Amin Sarker, K. Hasan. Load Frequency Control in Power System. *SEU J. Sci. Eng.* **2016**, 10 (2), 23–30.
8. X. Liang. Emerging Power Quality Challenges Due to Integration of Renewable Energy Sources. *IEEE Trans. Ind. Appl.* **2017**, 53 (2), 855–866.
9. M.A. Rahman, R. Sokkalingam, M. Othman, et al. Nature-inspired metaheuristic techniques for combinatorial optimization problems: Overview and recent advances. *Mathematics* **2021**, 9 (20).
10. M. Abdel-Basset, D. El-Shahat, A.K. Sangaiah. A modified nature inspired meta-heuristic whale optimization algorithm for solving 0–1 knapsack problem. *Int. J. Mach. Learn. Cybern.* **2019**, 10 (3), 495–514.
11. S.Z. Mirjalili, S. Mirjalili, S. Saremi, H. Faris, I. Aljarah. Grasshopper optimization algorithm for multi-objective optimization problems. *Appl. Intell.* **2018**, 48 (4), 805–820.
12. S. Saremi, S. Mirjalili, A. Lewis. Grasshopper Optimisation Algorithm: Theory and application. *Adv. Eng. Softw.* **2017**, 105, 30–47.
13. H. Golpîra, H. Bevrani. A framework for economic load frequency control design using modified multi-objective genetic algorithm. *Electr. Power Components Syst.* **2014**, 42 (8), 788–797.
14. M. Ourahou, W. Ayrir, B. EL Hassouni, A. Haddi. Review on smart grid control and reliability in presence of renewable energies: Challenges and prospects. *Math. Comput. Simul.* **2020**, 167, 19–31.
15. S. Gouran-Orimi, A. Ghasemi-Marzbali. Load Frequency Control of multi-area multi-source system with nonlinear structures using modified Grasshopper Optimization Algorithm. *Appl. Soft Comput.* **2023**, 137, 110135.
16. A. Naderipour, Z. Abdul-Malek, I.F. Davoodkhani, H. Kamyab, R.R. Ali. Load-frequency control in an islanded microgrid PV/WT/FC/ESS using an optimal self-tuning fractional-order fuzzy controller. *Environ. Sci. Pollut. Res.* **2023**, 30 (28), 71677–71688.
17. Y. Zheng, J. Tao, Q. Sun, et al. Deep reinforcement learning based active disturbance rejection load frequency control of multi-area interconnected

power systems with renewable energy. *J. Franklin Inst.* **2023**, 360 (17), 13908–13931.

18. R. El-Sehiemy, A. Shaheen, A. Ginidi, S.F. Al-Gahtani. Proportional-Integral-Derivative Controller Based-Artificial Rabbits Algorithm for Load Frequency Control in Multi-Area Power Systems. *Fractal Fract.* **2023**, 7 (1).
19. T.D. Raj, C. Kumar, P. Kotsampopoulos, H.H. Fayek. Load Frequency Control in Two-Area Multi-Source Power System Using Bald Eagle-Sparrow Search Optimization Tuned PID Controller. *Energies* **2023**, 16 (4).
20. G. Zhang, I.A. Khan, A. Daraz, A. Basit, M.I. Khan. Load Frequency Control of Marine Microgrid System Integrated with Renewable Energy Sources. *J. Mar. Sci. Eng.* **2023**, 11 (4).
21. P.A. Gbadega, Y. Sun. Multi-area load frequency regulation of a stochastic renewable energy-based power system with SMES using enhanced-WOA-tuned PID controller. *Heliyon* **2023**, 9 (9).
22. B. Dhanasekaran, J. Kaliannan, A. Baskaran, N. Dey, J.M.R.S. Tavares. Load Frequency Control Assessment of a PSO-PID Controller for a Standalone Multi-Source Power System. *Technologies* **2023**, 11 (1).
23. K. Reddy, A.K. Saha. A modified Whale Optimization Algorithm for exploitation capability and stability enhancement. *Heliyon* **2022**, 8 (10).
24. C.R. Balamurugan. Three Area Power System Load Frequency Control Using Fuzzy Logic Controller. *Int. J. Appl. Power Eng.* **2018**, 7 (1), 18.
25. S.K. Jain, S. Bhongade, S. Agrawal, et al. Interrelated Solar and Thermal Plant Autonomous Generation Control Utilizing Metaheuristic Optimization. *Energies* **2023**, 16 (8).
26. K. Peddakapu, M.R. Mohamed, P. Srinivasarao, et al. Review on automatic generation control strategies for stabilising the frequency deviations in multi-area power system. *Int. J. Ambient Energy* **2022**, 43 (1), 5571–5594.
27. P. Mukherjee, V. V. Rao. Superconducting magnetic energy storage for stabilizing grid integrated with wind power generation systems. *J. Mod. Power Syst. Clean Energy* **2019**, 7 (2), 400–411.
28. M. Sumathy, A. Kilicman, M.M.S. Manuel, J. Mary. Property Analysis of Riccati Difference Equation for Load Frequency Controller of Time Delayed Power System U sing IMMKF. 2020, pp 1–16.
29. T. Docquier, Y.Q. Song, V. Chevrier, L. Pontnau, A. Ahmed-Nacer. Performance evaluation methodologies for Smart Grid Substation Communication Networks: A survey. In *Computer Communications*; **2023**; Vol. 198, pp 228–246.
30. R.R. Shukla, M.M. Garg, A.K. Panda. Driving grid stability: Integrating electric vehicles and energy storage devices for efficient load frequency control in isolated hybrid microgrids. *J. Energy Storage* **2024**, 89, 111654.
31. M.H. El-Bahay, M.E. Lotfy, M.A. El-Hameed. Effective participation of wind turbines in frequency control of a two-area power system using coot optimization. *Prot. Control Mod. Power Syst.* **2023**, 8 (1).
32. V. Rajaguru, K.I. Annapoorani. Virtual synchronous generator based superconducting magnetic energy storage unit for load frequency control of micro-grid using African vulture optimization algorithm. *J. Energy Storage* **2023**, 65.
33. I.A. Khan, H. Mokhlis, N.N. Mansor, et al. Load Frequency Control Using Golden Eagle Optimization for Multi-Area Power System Connected Through AC/HVDC Transmission and Supported With Hybrid Energy Storage Devices. *IEEE Access* **2023**, 11, 44672–44695.