



Research Article

Robust load frequency control using an improved tilted integral derivative controller in interconnected diverse unit networks

Alok KUMAR¹, Mohammad Atif SIDDIQUI¹, Mohammed ASIM^{1,*}

¹Department of Electrical Engineering, Integral University, Lucknow, 226026, India

ARTICLE INFO

Article history

Received: 09 January 2026

Revised: 08 February 2026

Accepted: 30 March 2026

Keywords:

Load Frequency Control (LFC);
Fractional Order Proportional
Integral Derivative (FO-PID)
Controller; Tilted Integral
Derivative (TID) Controller

ABSTRACT

Modern electrical power systems are expected to be dominated by various interconnected systems, furthermore, the incorporation of various renewables sources of energy into the power grid which increases the difficulty and load of the power system, a key indicator of modern power systems' safe and efficient performance is their frequency. Maintaining the frequency stability in an interconnected multi area power system has become more challenging and complex due to the reduced system inertia and high penetration of renewable energy resources. Conventional load frequency control techniques suffer from high overshoot, slow settling time and degraded robustness under various parameter uncertainties and various constraints that are nonlinear in a power system such as generation rate constant and governor dead band. This study proposes an improved tilted integral derivative controller for a heterogeneous multi area power system that contains a thermal plant, hydro plant and a gas unit. Various controller parameters are tuned using a one-to-one based population optimizer that minimizes the integral square error and integral time weighted absolute errors. The simulation results demonstrate that the proposed strategy reduces the settling time by approximately 40 percent when compared to the grey wolf optimization and 25 percent when compared to particle swarm optimization under identical conditions. The overshoot also reduces by 30 to 45 percent and also the tie line power oscillations are damped. Under integral time weighted absolute error tuning the settling time of area 1 frequency deviation is reduced from 25 seconds to 15 seconds in case of grey wolf optimization. Also, the controller also maintains stable performance under nonlinear constraints. The uniqueness of the proposed controller in the first application of the one-to-one based optimizer for tuning a cascade tilted integral derivative controller in multi area load frequency control, with the dual objective validation and robustness verification. The suggested method exhibits better damping properties and dynamic stability making it appropriate for contemporary low inertia linked power systems.

Cite this article as: Kumar A, Siddiqui MA, Asim M. Robust load frequency control using an improved tilted integral derivative controller in interconnected diverse unit networks. Sigma J Eng Nat Sci 2026;44(4):2889–2904.

*Corresponding author.

*E-mail address: masim@iul.ac.in

This paper was recommended for publication in revised form by
Editor-in-Chief Ahmet Selim Dalkilic



INTRODUCTION

The complexity and immensity of a linked power grid with hundreds of variables required to be regulated have exacerbated the difficulties of network control and stability [1]. Controlling the generation capacity of facilities is undoubtedly most important control issue in the systems. LFC is the process of managing the output power of generating sub-stations so that the transient frequency difference of each region and the power source variation between connected areas remain within the necessary limits and achieve zero-steady state error [2]. An essential part of a reliable system is the load frequency controller, which regulates and maintains the power of the system and overall, the frequency of the system [3, 4]. Interconnected power system is a common example of a real-world example of a linked electric power system. However, when load variations produce frequency inconsistencies, problems occur. Load disturbances have a significant effect on the operating characteristics of the power system. The daily rise in electricity usage is one of the reasons for frequency fluctuations [5]. The issues become significantly more complex when multiple power systems are interconnected, as they add arbitrary components to the system.

These contemporary power systems have decreased power system inertia, also with the introduction of various other sources, the penetration levels in power systems increase [6]. Compared to traditional non-renewable energy sources, this leads to poor frequency stability and large frequency spikes. The high levels of RES penetration in modern electrical power systems have led to problems with security, stability, and reliability [7, 8]. LFC duties in power systems have been accomplished with the help of conventional controllers such as the proportional integral (PI), PI derivative (PID), and other controllers [9]. However, as the power landscape shifted and more renewable energy sources are added, the power systems changing aspects become more intricate and difficult to control. It provides power to the system, but by introducing irregular and changing power sources, they also introduce an element of uncertainty. Because of this, the controllers sometimes battle to keep the system stable and at the right frequency levels [10, 11]. The conventional method for load frequency control (LFC) was done by speed governors. However, modern power networks that depend on renewable energy sources cannot have their frequency and tie-line power fluctuations exactly reduced by speed governors alone [12]. Power generation and load demand cannot be balanced solely by the speed governors. To preserve the deviation in the steady state frequency of various regions and associated tie line power deviations as close to zero. It is imperative to employ suitable control approaches and improved design methodologies [13, 14]. The problems of the traditional controllers are solved in this study by using a Modified tilted integral derivative (TID). To sum up, this

work significantly advances the science of power system control in several ways:

1. For the multi-area power system, an enhanced fractional order based LFC technique is proposed. The tilt-integral-derivative's cascade structure is used by the proposed novel controller [15].
2. When compared with cascaded LFC architectures and contemporary LFC systems, the proposed controller reduces the deviations obtained in the frequency of the system and also the tie line power [16].
3. The functionality of the offered LFC approach is enhanced by optimising the parameters of the suggested controller using the marine predator's optimisation algorithm POA. Furthermore, the POA performance is validated by comparisons with the different approaches already in use [17].
4. The data is used for a comprehensive comparison study, and different cases are looked at according to the system whose results are confirmed. Additionally, the proposed controller is contrasted.

Research Gap and Contributions

There is various significant restriction even though the literature has documented a number of load frequency management schemes based on fractional order controllers and proportional integral derivative. The majority of the research mainly focus on traditional optimization methods including grey wolf optimization, particle swarm optimization and the Archimedes optimization algorithm for controller tuning [18, 19]. These methods show decreased population diversity and premature convergence. Additionally, prior research on slanted integral derivative based controller has mostly assessed performance in the cases with low disturbance and without conducting robustness validation under nonlinear parameters such as governor dead band and generation rate constraint [20]. Furthermore, there has not been a comparison validation under objective functions like integral square error and integral time weighted absolute error. The current work contributes in the following way to close the gaps:

1. Development of an improved cascade integral derivative controller for heterogeneous interconnected power systems that include thermal, hydro and gas units.
2. Implementation of a one to one based population optimization algorithm for tuning the controller parameters in the load frequency controller.
3. Dual objective optimization using integral square error and integral time weighted absolute error for enhanced transient and steady state performances.
4. Validation under nonlinear constraints including generation rate constant and governor dead band.
5. Comprehensive and detailed comparative analysis against different optimization techniques under identical conditions.

The above-mentioned contribution show improved convergence behavior, improved damping and robustness for modern interconnected power systems.

Literature Review

Stability, efficiency, and overall system performance are all improved in real-world power systems by enabling accurate and reliable control of power flow over transmission lines [21]. Researchers have made a large number of research and suggestions related to LFC design methodologies. The literature has made substantial use of sliding mode controllers, intelligent controllers, adaptive controllers, resilient, internal model-based, decentralized control techniques, and model predictive [22, 23]. Furthermore, when it comes to their ability to reject disturbances, the conventional methods have shown good results. Furthermore, fuzzy control techniques have been used with other different techniques to adjust and improve the LFC's performance under various operating conditions and disturbances. Recently, innovative and data driven frequency control systems have also been proposed to overcome the frequency regulation concerns [24]. However, for optimal performance, they require a large amount of training data.

Numerous techniques, such as hybridized gravitational searching and particle swarm optimizer, water cycle algorithm (WCA), educational competition optimiser, genetic algorithm, and constrained population external optimization, were used to optimize PI, PID, cascaded PDN-PI, and FOPID settings [25, 26]. The method of artificial bee colonies has been used in tandem with the weighted sum approach to reduce the operating frequency's settling time and overshoot. Additionally, a teaching-learning algorithm was used to modify the settling time, overshoot, etc. Furthermore, the literature has introduced hybrid and combination FO-based LFC techniques. For a two area power systems based on superconducting energy storage systems (SMES), another fractional order controller was suggested. They introduced a modified hybrid decentralized FO-based LFC and EV controller [27, 28]. The FOPID and the TID controllers are combined in the proposed LFC and EV controllers [29]. Additionally, the reported controller parameters were optimized using the artificial ecosystem optimiser (AEO) algorithm.

For multi-area power systems, the series fuzzy control technique with an ICA optimizer was introduced. The water cycle optimization algorithm (WCA) and a cascaded fuzzy approach using FOPID were first presented. Fuzzy logic was first presented utilizing PID with a filter and FOPI controllers [30]. The stated controller has been optimized using the imperialist competition optimization method (ICA). It is evident that in order to enhance the frequency regulation the system, further research and sophisticated LFC techniques are required. Furthermore, the uncertainties in electrical power system model parameters and the related issues of high-RES penetration levels in existing power systems provide additional difficulties for

current controllers and/or design methodologies [31, 32]. The most recent research on load frequency controllers is summarized in Table 1.

LFC methods

LFC is the most important factor that must be addressed in any modern power system. Various methods are already used by researchers in this field. Based on the literature survey these control methods can be broadly classified into 4 types- Conventional or classical techniques, adaptive control techniques, robust approach and intelligent control methods.

Classical/ Traditional Methods

Owing to their straightforward structure and ease of practical implementation, classical control techniques have been extensively applied in the development of LFC systems. However, a number of studies have shown that when subjected to system nonlinearities and parameter variations, their dynamic performance is insufficient [33]. Because it is frequently difficult to design controllers that use complete state-variable information, suboptimal and quasi-optimal LFC techniques have been studied. An alternative LFC methodology was created using only necessary and measurable state variables, improving implementation feasibility in contrast to traditional optimal control approaches that depend on state-feedback estimators.

By combining the bang-bang control strategy with Lyapunov's second method, the load frequency problem for a multi area power system was solved, producing an easy-to-analyze and implement controller. Furthermore, the hierarchical control structure was introduced to ensure reliable system performance. The outcomes of global control systems that make use of tie-line interactions have been promising [34]. Additionally, the perturbation approach—which modelled the system dynamics as slow and fast subsystems—was introduced to reduce the control action required for LFC in IMAPSs.

Adaptive Methods

Functional problems related to the implementation of adaptive LFC have been investigated in detail. In order to meet hyper-stability conditions, an adaptive control-based LFC architecture was developed for the Hungarian power system [35]. Further, an adaptively tuned PI controller was proposed in order to effectively accommodate system parameter variations. Fuzzy logic systems were used to develop adaptive governor laws and constraint update mechanisms for handling uncertainties in interconnected load frequency control areas. Stringent guarantees of closed-loop stability were provided while developing a tracking performance criterion that aims at minimizing the approximation errors and rejecting the effect of external disturbances [36, 37]. Further, an adaptive multi-objective fractional-order PID controller was developed for enhancing the LFC performance in islanded microgrids.

Table 1. Comparative review of various recent optimization based load frequency control techniques and their research challenges

S.No.	Author/ Year	Existing Research Challenge	Methodology	Reference
1.	Amarendra et al. 2023 [1]	Time domain parameters including frequency deviation overshoot and settling periods are utilized to contrast the performance of the optimized controllers which can be improved by selecting the appropriate control depending upon the type of the system.	Here, an MGO-based 2DOF-PID Control technique is used to control the load frequency deviation of an interconnected microgrid. Furthermore, in contrast to the conventional PSO approach, MGO minimizes the objective function to the lowest feasible value. Since there is a significant decrease in ITAE values as well as variations in frequencies and tie-line power, the MGO optimal 2DOF-PID controller is the best option for the two-area microgrid system under analysis.	[1]
2.	Kumar and Anwar 2021 [2]	In this the controller was designed for the multi area system which was optimized on PSO and GWO algorithm. Further testing with the disturbances and latest optimization technique is required.	A sliding mode control technique is used with the Grey wolf optimization (GWO) and particle swarm optimisation (PSO) strategies and is used to determine the controller's parameter in order to get an ideal outcome.	[2]
3.	Ahmed 2022 [3]	The suggested controller's performance is assessed in relation to the cascaded controller. Simulation studies verify its efficacy.	A modified fractional controller was created in order to enhance load frequency control in a multi-area interconnected power system with multiple energy sources. The Archimedes optimisation algorithm (AOA), a recently developed bio-inspired optimisation method, was used to adjust the ID-T controller's parameters.	[3]
4.	Qian and Lv 2025 [4]	Despite its shown efficacy, the AGFTSMC approach still has limitations, including high processing requirements. Dynamic frequency regulation capabilities could be significantly enhanced by the use of artificial intelligence, including deep learning, and event-triggered techniques.	An advanced LFC scheme is developed using adaptive global fast terminal sliding mode control. The proposed strategy formulates a nonlinear, time-varying global fast terminal sliding surface and integrates an adaptive sliding mode control law to ensure finite-time convergence, enhanced robustness, and improved dynamic performance of the power system under uncertainties and disturbances.	[4]
5.	Izci 2024 [5]	It should concentrate on strengthening the resilience of hSA-QIO tuned against such disturbances, guaranteeing the integrity of control systems, given the growing danger of threats to power grids.	In the proposed LFC framework, the parameters of the filtered PID controller are optimally tuned using a hybrid simulated annealing-based quadratic interpolation optimizer. This hybrid optimization approach enhances the tuning process, leading to improved control accuracy and dynamic performance of the system.	[5]

Robust Methods

The dynamic performance of a load frequency controller (LFC) may be less than ideal in real-world electric power systems when the controller is built using nominal system data. This controller is synthesized through a methodical procedure based on quantitative feedback theory (QFT), which makes use of loop-shaping techniques to enhance system performance [38]. However, there are significant

parametric deviations in the behavior of the closed-loop system due to the several sources of uncertainty (such as load demand, model errors, non-linear behaviour, and changes in equipment parameters). The techniques employed in this QFT methodology produce a thorough and methodical approach to controller design and analysis by incorporating in-depth knowledge of the system's behavior. To mitigate the consequences of minor parametric uncertainties, a

hybrid strategy that combines adaptive control with robust constraints was devised, while adaptive control strategies were used to address larger parametric uncertainties [39, 40].

By guaranteeing that all closed-loop poles stay in the left half-plane, the hybrid technique ensures both excellent transient response and closed-loop stability under all operating conditions. Furthermore, compared to conventional robust control methods, including μ -analysis and linear quadratic Gaussian (LQG) control, the Q-parameterization controller can achieve a drastically reduced controller order [41]. The stabilizing controller's family is described with one free design parameter (Q), as the controller synthesis is simpler in Q context. If both parameter variations are kept within an acceptable range, the choice of Q will guarantee satisfactory dynamic performance and system stability.

Intelligent Approaches

Nonlinear power system dynamics can be approximated with linear models, but such linearized representations are only valid within limited operating ranges. This can force you to have many models since the same system will require multiple models in order to model it in different operational conditions [42]. New developments in artificial intelligence (AI) have enabled us to have the answers to these challenges that were previously unimaginable. Another major benefit of AI-based approaches is their ability to address nonlinear control issues in power systems over a wide operating region. In recent years AI-based systems approaches, including artificial neural networks (ANNs), fuzzy logic control (FLC) and genetic algorithms (GAs), have been commonly investigated for the control of load frequency

control (LFC) systems. Feed forward neural networks and back propagation-through-time learning algorithms based neural controllers for the LFC problem have been specifically designed. The controllers exhibited a good resistance to frequency changes with zero steady-state error. An advantage of this approach is that no knowledge about the system model is needed, thus creating more flexibility in controller design [43]. Besides, the central goal of these systems is to prevent the uncertainties and change of parameters that cause oscillations in the system. In the adaptive control domain, self-tuning strategies have been widely studied in LFC applications. In this work, a multivariable self-tuning controller was built by optimizing a generalized performance index that takes into account system output as well as control effort. Additionally, controlling the load by a simple load compensation mechanism allowed for effective treatment of the load disturbances with non-zero mean components.

Studied Power System

Load Frequency Control (LFC) helps control the steady-state error (SSE) in a power system by tuning the excitation voltage in response to load changes, and ensuring that the scheduled frequency and power interchange occurs in interconnected power systems. Figure 1 shows an automatic voltage regulator. The article describes a multi-area interconnected power system comprising thermal, hydro, and gas power plants [44] (Fig. 2). The automatic voltage regulator (AVR) manages generator output by monitoring load demands and mitigating frequency deviations, thereby maintaining stable and reliable system operation. Component nonlinearities play a crucial role in

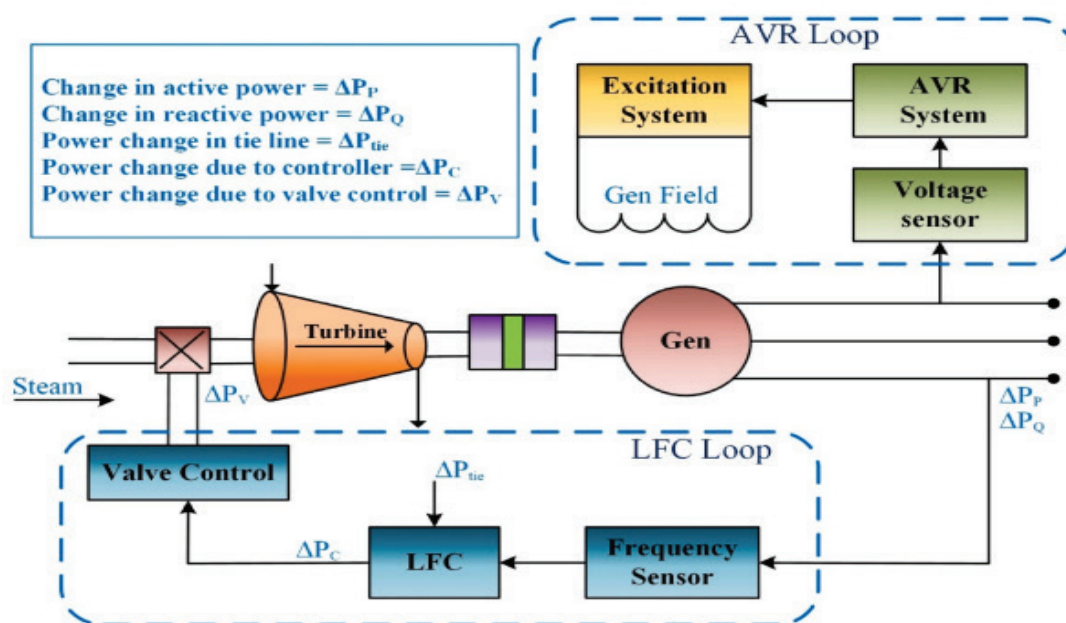
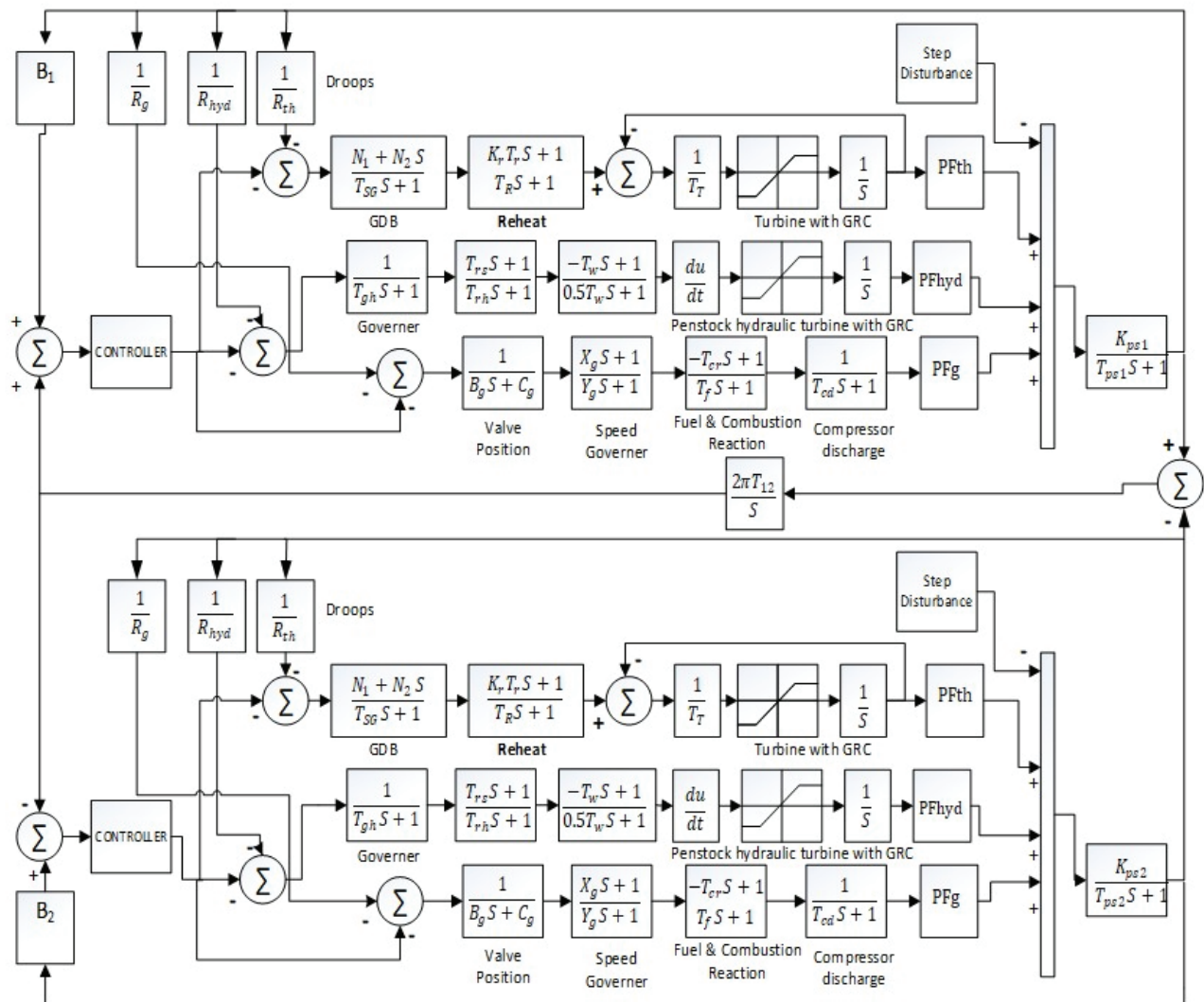


Figure 1. Automatic voltage regulator.



the design and evaluation of the proposed controllers. The system takes into consideration the physical constraints of the generating units, which include generation rate constraints (GRC) and governor dead band (GDB). For thermal units, the GRC is set at 10% pu/min (0.0017 pu·MW/s) for both increasing and decreasing rates. In contrast, for the hydro plant, the GRC limits are defined as 360 pu/min (0.06 pu·MW/s) for increasing rates and 270 pu/min (0.045 pu·MW/s) for decreasing rates [45]. A linearized representation of the GDB is utilized to evaluate speed deviations along with their rates of change. The GDB transfer function derived from the Fourier series is provided by:

Where N_1 & N_2 are the Fourier coefficients. ($N_1=0.8$ and $N_2=-0.2/\pi$)

Area Control Error (ACE)

$$\text{For Area 2, } ACE_2(t) = B_2 \Delta f_2(t) - \Delta P_{tie,12}(t) \quad (3)$$

Where B_i is the frequency bias factor and Δ_f denotes the frequency deviation or area i .

$$G_{pi}(s) = \frac{K_{psi}}{T_{psi}s+1} \quad (4)$$

In time domain form the equation can be represented as:

$$T_{psi} \frac{d\Delta f_i}{dt} + \Delta f_i = K_{psi}(\Delta P_{mi} - \Delta P_{Li} \pm \Delta P_{tie}) \quad (5)$$

$$\text{Where, } \Delta P_{mi} = \Delta P_{th,i} + \Delta P_{hyd,i} + \Delta P_{g,i} \quad (6)$$

Tie line power model

$$\Delta P_{tie,12}(s) = \frac{2\pi T_{12}}{s} (\Delta f_1 - \Delta f_2) \quad (7)$$

In time domain form the equation can be represented as:

$$\frac{d\Delta P_{tie,12}}{dt} = 2\pi T_{12}(\Delta f_1 - \Delta f_2) \quad (8)$$

Thermal unit model

$$(a) \text{ Governor: } G_{gov,th}(s) = \frac{1}{T_{gh}s+1} \quad (9)$$

In time domain form the equation can be represented as:

$$T_{gh} \left(\frac{d\Delta P_{g,th}}{dt} \right) + \Delta P_{g,th} = \Delta P_{c,th} \quad (10)$$

$$(b) \text{ Turbine } G_{rh}(s) = \frac{K_r T_r s + 1}{T_r s + 1} \quad (11)$$

Hydro unit

$$G_{hyd}(s) = \frac{-sT_w + 1}{0.5sT_w + 1} \quad (12)$$

Gas turbine

$$G_{sg}(s) = \frac{sX_g + 1}{sY_g + 1} \quad (13)$$

From Equation number 2 to 13 represents the modeling of the interconnected power system representing different components with the function in s domain.

Where,

B= Frequency bias factor

Δ_f = Frequency deviation

ACE= Area control error

$\Delta P_{tie,12}$ = Tie-line power deviation between Areas 1 and 2

ΔP = load disturbance

X_g = Gas governor numerator constant

Y_g = Gas governor denominator constant

T_w = water starting time constant

T_r = Reheater time constant

Tilted Integral Derivative (TID) Controller

The transient and steady state response of a two-area interconnected power system to a unit step disturbance in area one is investigated through an one on one based optimization technique employing the modified controller, which is a kind of enhanced version of the PID controller [46]. The unit step signal is taken into consideration in the disturbance because it allows for the study of both transient and steady-state responses. If a ramp or other signal is used as the disturbance, then only a transient study can be obtained (Fig. 3).

The controller equation can be studied as:

$$E(s) \propto \frac{K_p}{s^{1/n}} + \frac{K_i}{s} + SK_d \quad (14)$$

The following are the transfer functions of PID and TID controllers:

$$PID = K_p + \frac{K_i}{s} + K_d s \quad (15)$$

$$TID = \frac{K_p}{s^{1/n}} + \frac{K_i}{s} + SK_d \quad (16)$$

Objective Function

A variety of system parameters, including ISE, ITAE, IAE, ITSE, and others, can be used to adjust the TID

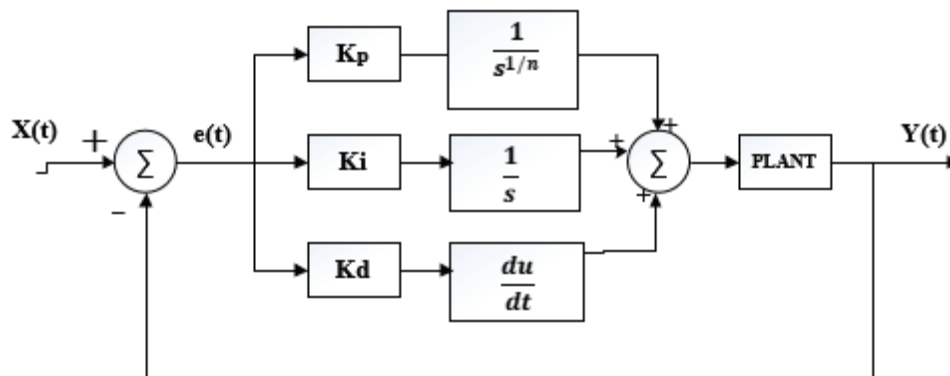


Figure 3. Structure of TID controller.

controller's parameters [47, 48]. The objective functions taken into consideration in this paper are ITAE and ISE. These performance indicators should be taken into account. Applications that need fast response and quick settling time can use this requirement. ISE favors reducing large errors over little errors due to the squaring of error quantities [49]. If this condition is satisfied, the system might have to use more effort to keep things under control and react faster. ITSE penalizes higher errors during the initial transient reaction, combining aspects of ITAE and ISE.

This criterion balances control effort and response speed but may increase oscillatory behavior. The Integral Absolute Error (IAE) treats all errors equally, offering faster responses with lower control effort, though slower reactions may still occur. The Integral of Time-weighted Squared Error (ITSE) penalizes sustained errors, reducing settling time, while the Integral of Time-weighted Error Squared (ITES) imposes a stronger penalty on large deviations, helping to limit peak errors and improve overall system stability. The formula for ITAE, ISE, IAE and ITSE are shown in equations [50].

$$ITAE = \int_0^{\infty} t|e(t)|dt \quad (17)$$

$$ISE = \int_0^{\infty} e^2(t)dt \quad (18)$$

$$IAE = \int_0^{\infty} |e(t)|dt \quad (19)$$

$$ITSE = \int_0^{\infty} te^2(t)dt \quad (20)$$

One-to-One Based Optimizer (OOBO)

In an iteration-based process, the population-based metaheuristic algorithm OOBO efficiently solves optimization problems by utilizing the population search power in the problem-solving space. The foundation of OOBO is that, given the problem's restrictions, a number of workable solutions are first produced. Then, using the fundamental principle of the algorithm, the position of these answers in the search space is updated in each iteration. Accurately scanning the problem's search space is made impossible by an updating method that relies too much on particular population members. The algorithm might so converge to nearby ideal areas. The main idea underlying the proposed OOBO algorithm's design is that it avoids becoming too dependent on specific population members, such as the best, worst, and mean members, by making effective use of data on each population member throughout the algorithm's population update process (Fig. 4).

Consequently, the following factors are taken into account during this updating process: (a) population updates do not depend on any particular members; (b) all members participate in the updating process; and (c) every

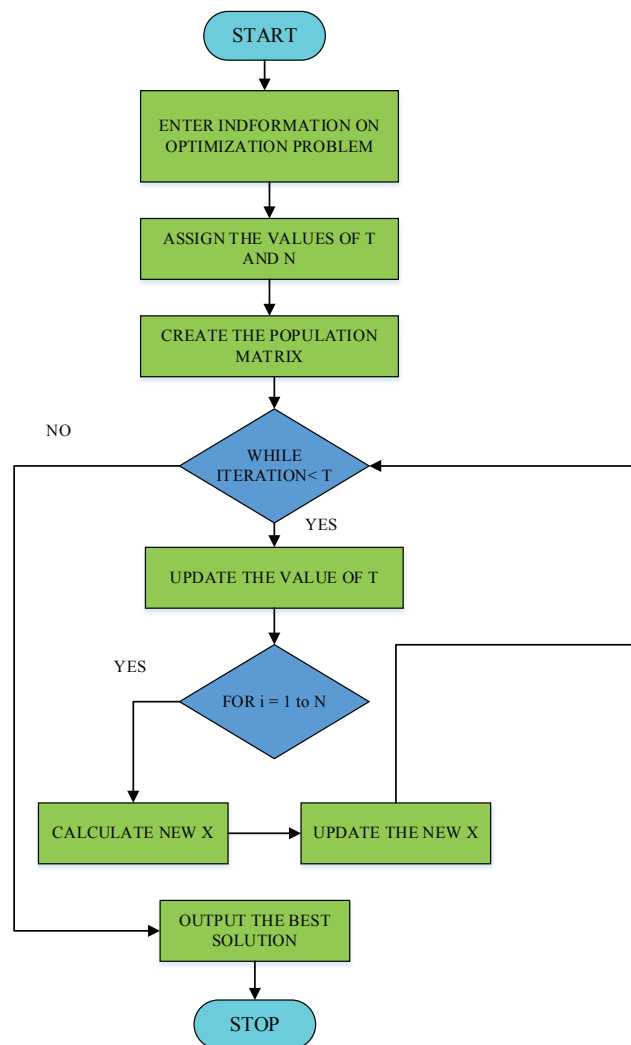


Figure 4. Flowchart of one to one based optimizer (OOBO).

population member is utilized to direct another member in the search space in a one-to-one communication.

Pseudo code for OOBO algorithm

1. Information on input optimisation problems.
2. Assign T and N.
3. Construct a preliminary population matrix.
4. Assess the function of the objective.
5. do for t → 1 to T
6. Using Equation (9), update → K.
7. Do for i → 1 to N
8. Using Equations (10) and (11), compute X new i.
9. Determine f new i using X new i.
10. Use Equation (12) to update Xi.
11. Finish for
12. Keep the greatest solution so far discovered.
13. Finish for 14. The best quasi-optimal solution should be output.
- Stop OOBO.

RESULTS AND DISCUSSION

The system was modelled in MATLAB/Simulink, and controller tuning was performed using the OOBO algorithm with the ISE and ITAE as objective functions. The algorithm was evaluated for different population sizes with a fixed maximum of 100 iterations and was interfaced with the Simulink model to obtain optimal controller parameters. The resulting gains provide fast convergence to steady state with reduced overshoot and minimal oscillations. The performance of the proposed OOBO based approach was benchmarked against PSO and GWO techniques [19] (Table 2-5) (Fig. 5-10).

The one-to-one based optimizer balanced and improved exploration and exploitation mechanism is responsible for the enhanced dynamic performance of the suggested optimization-based controller. The one to one update approach maintains the diversity through a number of iterations that lowers the risk of premature convergence in contrast to traditional population based algorithms that mainly depend on mean solution. As a result, the near global optimal controller parameters are reached more quickly that also makes the method fast. Also, better damping properties of the cascade tilted integral derivative structure are demonstrated by the decrease in the settling time and the overshoot. Transient

Table 2. When considering the target function as ISE, the comparison of controller parameters

Optimization Method Used (Algorithm)	Power System Area one			Power System Area two			ISE
	Tilted Parameter (K_t)	Integral Parameter (K_i)	Derivative Parameter (K_d)	Tilted Parameter (K_t)	Integral Parameter (K_i)	Derivative Parameter (K_d)	
OOBO	1.02	2.68	2.05	3.01	3.12	1.43	0.0042
GWO	1	1.52	2.34	2.52	2.14	2.62	0.0055
PSO	1.58	2.30	2.11	3.72	1.24	2.41	0.0061

Table 3. The description of dynamic performance through the application of four optimization methods (ISE)

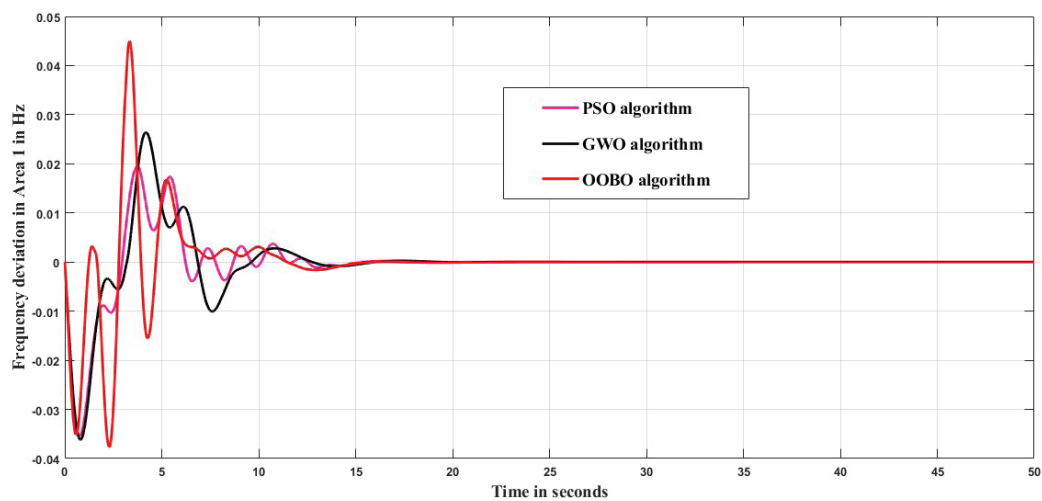
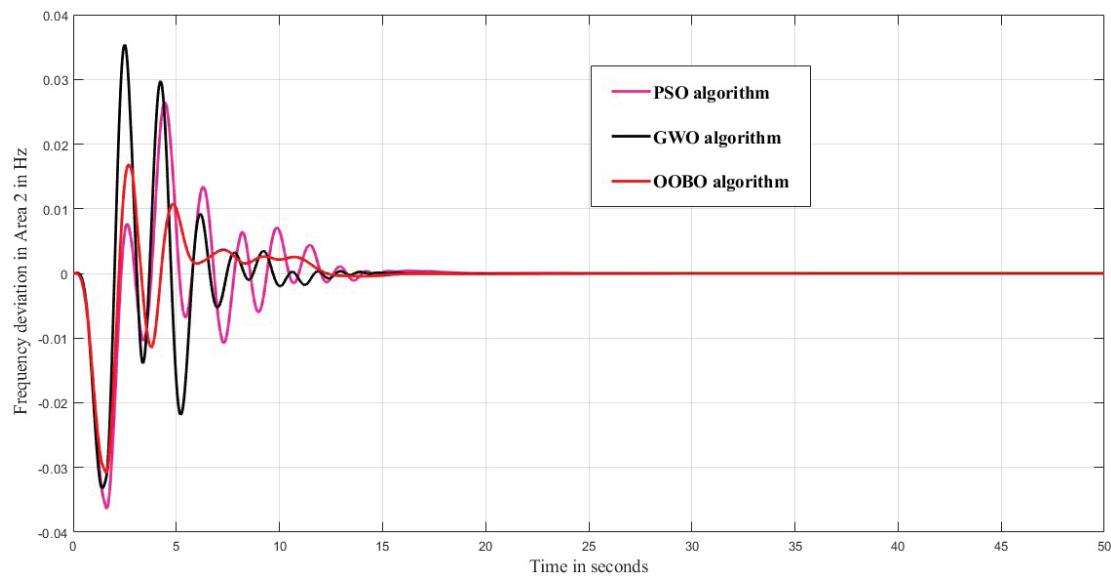
Optimization Method Used Algorithm	Parameter	Overshoot (Hz) of the system	Undershoot (Hz) of the system	Settling time (seconds) of the system	ISE
OOBO	Δf_1	0.018	0.030	18	0.0042
	Δf_2	0.020	0.032	17	
	ΔP_{tie}	0.001	0.006	20	
GWO	Δf_1	0.036	0.038	23	0.0055
	Δf_2	0.025	0.040	22	
	ΔP_{tie}	0.002	0.006	21	
PSO	Δf_1	0.026	0.033	17	0.0061
	Δf_2	0.020	0.036	18	
	ΔP_{tie}	0.0018	0.006	20	

Table 4. When considering the target function as ITAE, the controller parameters in the various optimization techniques

Optimization Method Used (Algorithm)	Power System Area one			Power System Area two			ITAE
	Tilted Parameter (K_t)	Integral Parameter (K_i)	Derivative Parameter (K_d)	Tilted Parameter (K_t)	Integral Parameter (K_i)	Derivative Parameter (K_d)	
OOBO	1.26	2.15	2.12	1.14	1.20	2.36	0.7822
GWO	1.42	1.09	2.60	1.23	1.48	2.16	1.125
PSO	2.20	3.12	2.95	3.10	1.99	3.05	0.9521

Table 5. The description of dynamic performance through the application of four optimization algorithms (ITAE)

Optimization Method Used Algorithm	Parameter	Overshoot (Hz) of the system	Undershoot (Hz) of the system	Settling time (seconds) of the system	ITAE
OOBO	Δf_1	0.017	0.032	15	0.7822
	Δf_2	0.022	0.031	13	
	ΔP_{tie}	0.002	0.005	16	
GWO	Δf_1	0.026	0.038	25	1.125
	Δf_2	0.038	0.038	26	
	ΔP_{tie}	0.002	0.006	22	
PSO	Δf_1	0.044	0.040	20	0.9521
	Δf_2	0.020	0.032	19	
	ΔP_{tie}	0.002	0.006	19	

**Figure 5.** Deviation in the frequency of Area 1 (ISE).**Figure 6.** Deviation in the frequency of Area 2 (ISE).

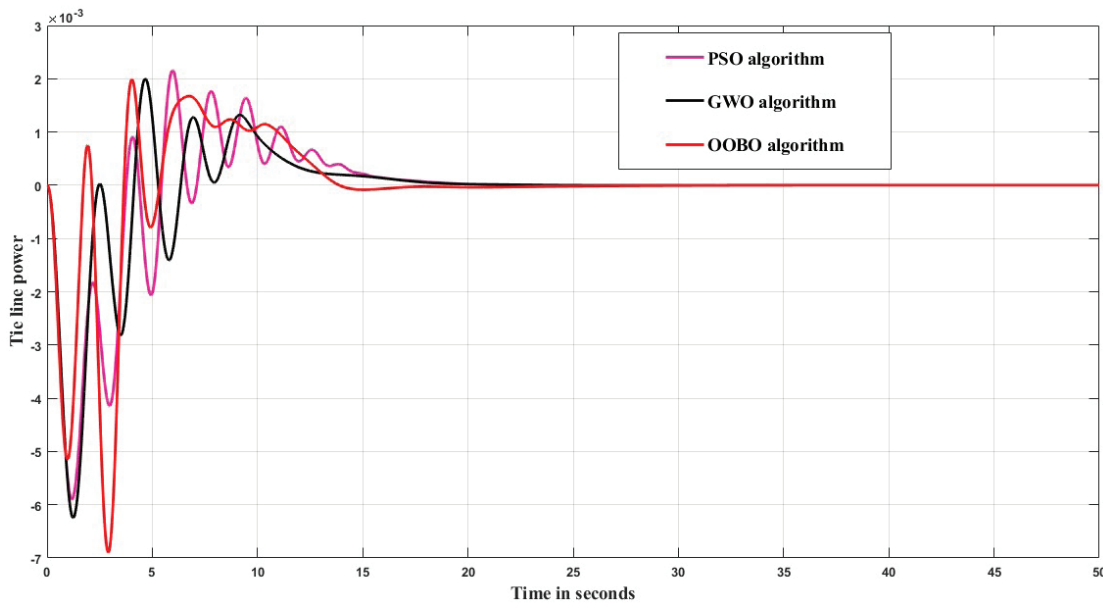


Figure 7. Deviation in the tie line power of Area 2 (ISE).

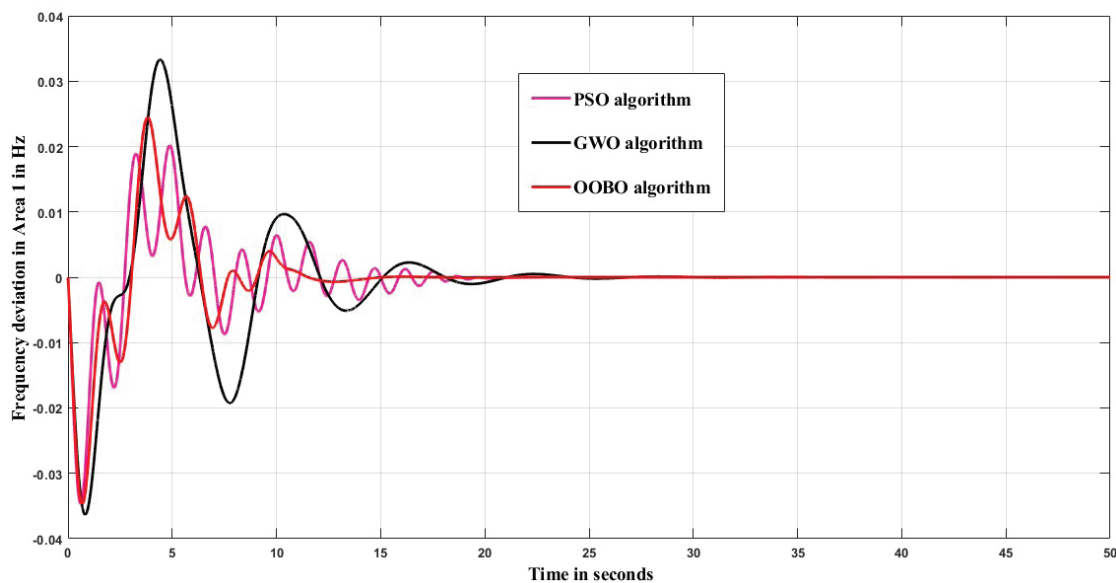


Figure 8. Deviation in the frequency of Area 1 (ITAE).

stability also gets improved by the tilting and derivative components of the controller while the steady state error is also eliminated by the integral component. For modern power system reliability, the suggested strategy delivers better suppression of tie line oscillations than grey wolf and particle swarm techniques. Additionally, the results show that while integral square error tuning decreases the peak deviations while integral time weighted absolute error tuning improves the settling time. This defines the flexibility

of the suggested design process and draws attention to the trade-off between response and control.

In comparison with the grey wolf optimization the suggested optimization-based controller stabilizes the frequency deviation more quickly under integral squared error criterion as shown in the Figure 11. In this particular instance the particle swarm optimization shows a shorter settling time but the associated objective function value is very large that shows that faster settling does not ensure the

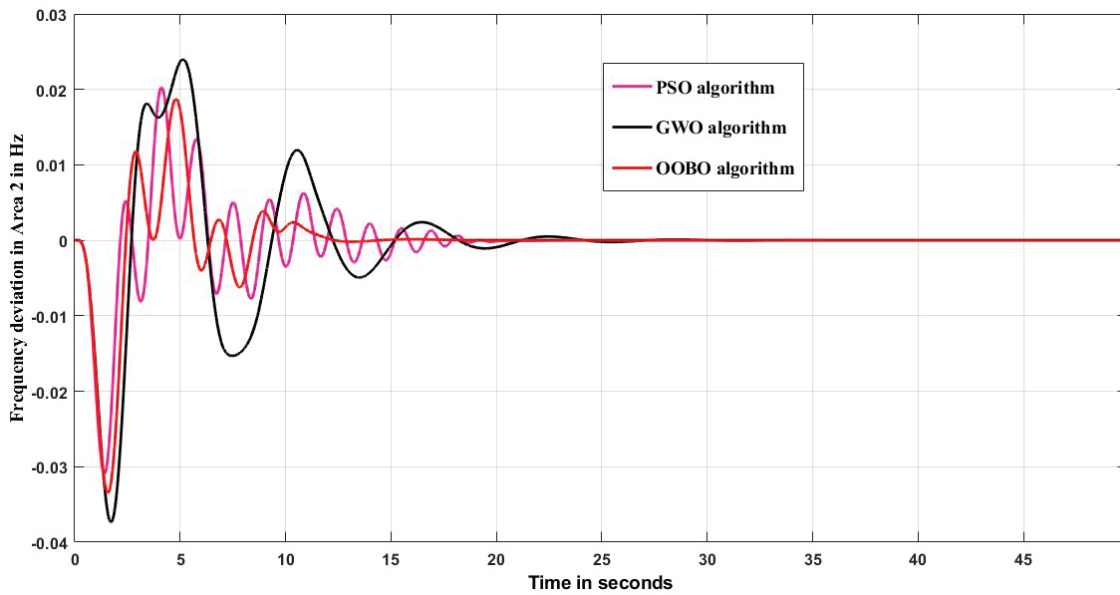


Figure 9. Deviation in the frequency of Area 2 (ITAE).

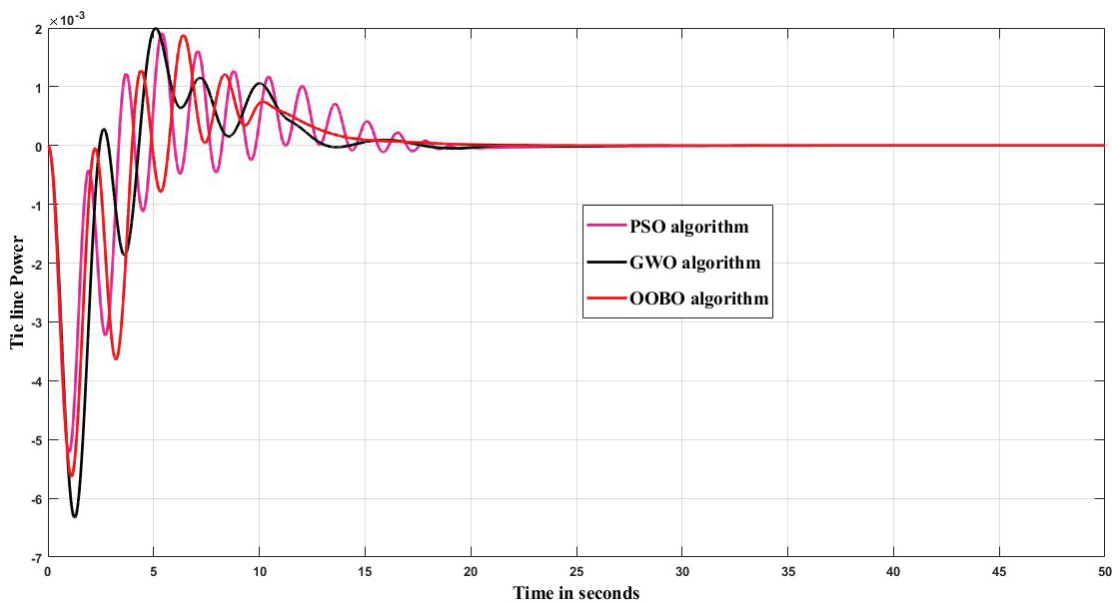


Figure 10. Deviation in the tie line power of Area 2 (ITAE).

better cumulative performance. This emphasise the importance of transient performance measurements.

The suggested approach has substantially less overshoot under integral square error tuning, as seen in Figure 12. When the one to one based technique is optimally set, the slanted integral derivative damping characteristics are improved as evidenced by the decrease in peak deviation. Also the controller performs better during load fluctuations.

Out of the all the strategies evaluated the suggested method produces the lowest integral square error as seen in

Figure 13. It indicates that the system has better dynamic stability and superior suppression of large transient excursions.

The advantage of the proposed method becomes more validating while considering the integral time weighted absolute error. When compared to both the optimization techniques the settling time is improved significantly as shown in Figure 14.

The proposed method has improved the stability behaviour and the tuning mechanism and the overshoot is minimised as shown in the Figure 15.

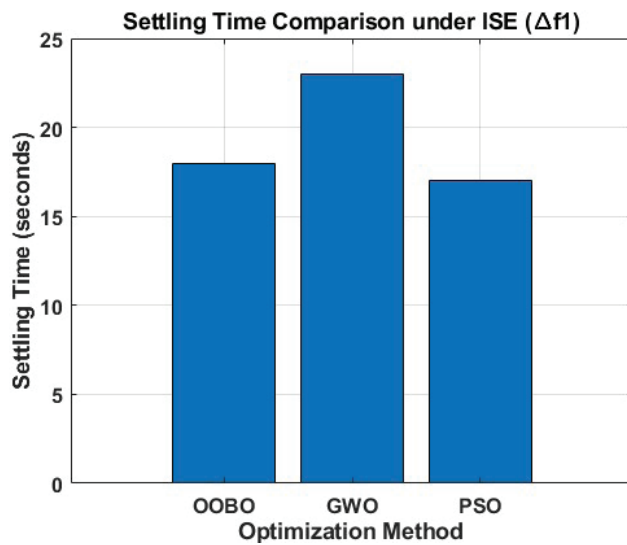


Figure 11. Comparative settling time of frequency deviation (Δf_1) under integral square error tuning.

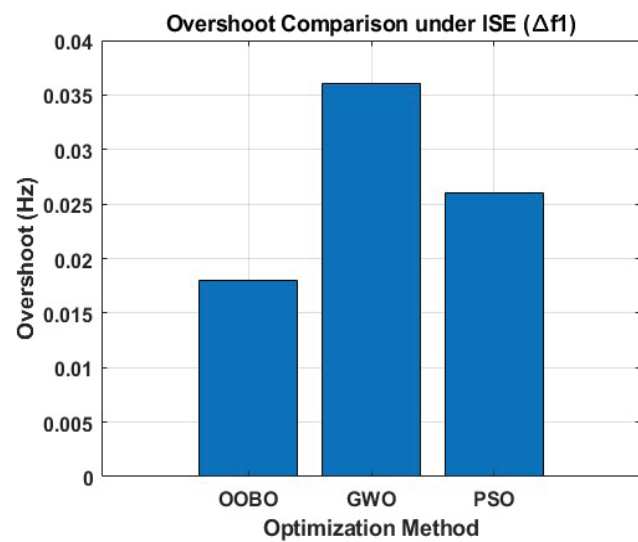


Figure 12. Comparative overshoot of frequency deviation (Δf_1) under integral square error tuning.

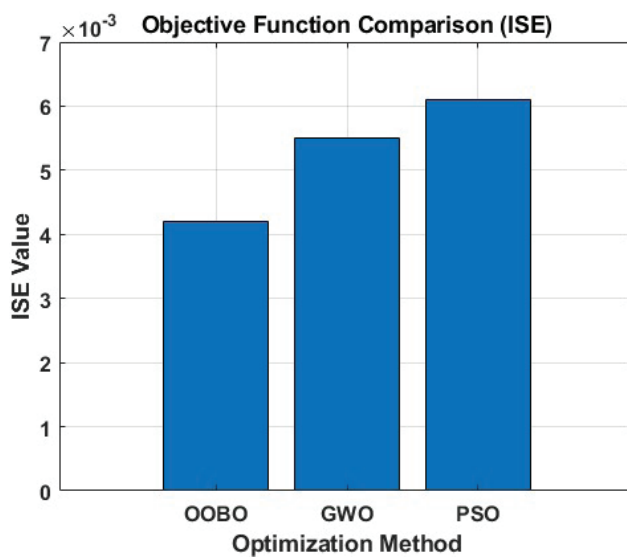


Figure 13. Comparison of integral squared error values for different optimization algorithms.

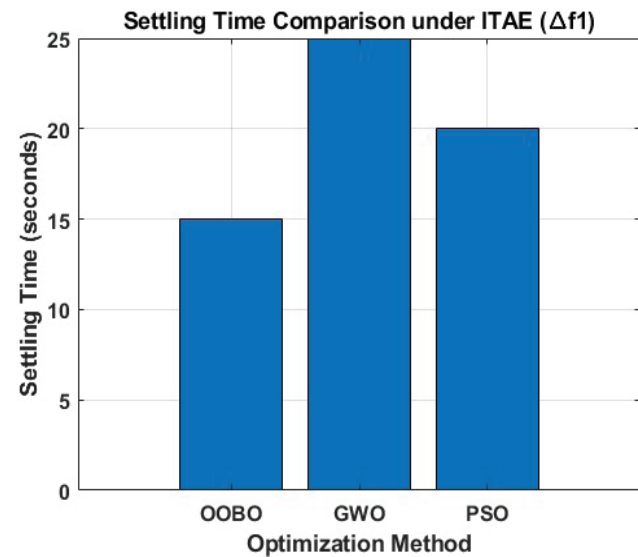


Figure 14. Comparative settling time of frequency deviation (Δf_1) under integral time weighted absolute error tuning.

These findings are further verified by the quantitative improvement analysis. The suggested method outperforms traditional optimization methods by a significant proportion under both integral squared error and integral time-weighted absolute error criteria, as illustrated in Figures 16 and 17. This verifies how well the one-to-one update method works to get more ideal controller parameters.

Limitations and Future Scope

There are still various restrictions even though the suggested controller performs better in a two area heterogeneous system. Hardware or real time implementation had

not been conducted and the study is limited to simulation based validation only. The model that has been analysed did not account for cyber security disturbances or communication delays. Furthermore, the only disturbance caused in the system was only due to step load was analysed. Further studies should consider looking into cyber resilient load frequency control structures, integration of communication delays and also expand the multi area system to large scale with the renewable penetration. Real time simulators for the validation can increase the applicability even more.

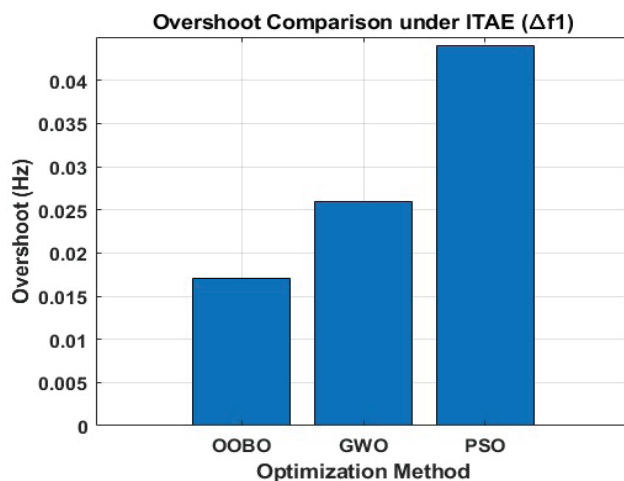


Figure 15. Comparative overshoot of frequency deviation (Δf_1) under integral time weighted absolute error tuning.

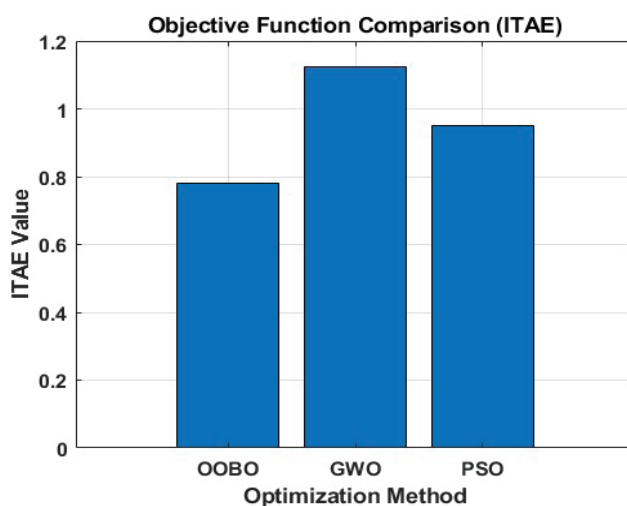


Figure 16. Comparative of frequency deviation (Δf_1) under integral time weighted absolute error tuning.

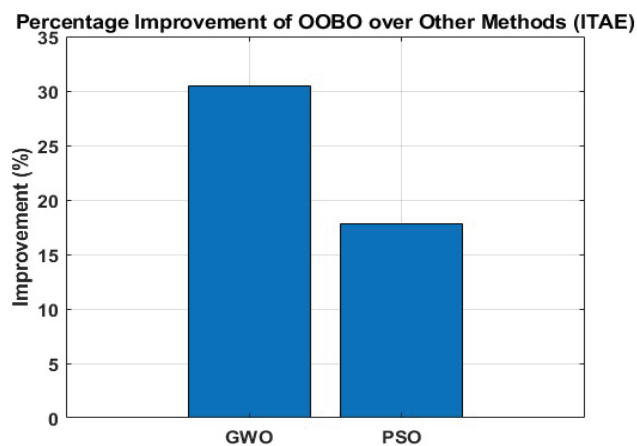


Figure 17. Comparison integral time weighted absolute error values for different optimization algorithms.

CONCLUSION

An enhanced tilted integral derivative controller for the frequency regulation of a heterogeneous interconnected power system was described in the study. It was adjusted using a population optimization approach that is based on a one to one ratio. In order to assess both transient and steady state behaviour the controller was optimised with the integral square error and integral time weighted absolute error performance parameters. In comparison to grey wolf and particle swarm optimisation strategies comparative analysis shows that the suggested strategy decreased overshoot by over 45 percent and settling time by up to 40 percent. The stable performance under generation rate constraints and governor dead band nonlinearities were observed along with the improved damping of tie line power oscillations. The outcome verifies that the suggested optimisation approach improves the controller robustness and convergence reliability. In low inertia power systems with a variety of generating units the proposed methodology presents a feasible solution for frequency regulation.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

REFERENCES

- [1] Amarendra K, Teeparthi K, Vamsi Y, Veeramsetty V, Thota V. Load frequency control of an interconnected microgrid using MGO-based 2DOF-PID controller. 2023. p. 1–6. [\[CrossRef\]](#)

- [2] Kumar A, Anwar MN. Decentralized load-frequency controller design for a single as well as multi-area power system. *Iran J Sci Technol Trans Electr Eng* 2020;44:309–326. [\[CrossRef\]](#)
- [3] Ahmed M, Magdy G, Khamies M, Kamel S. Modified TID controller for load frequency control of a two-area interconnected diverse-unit power system. *Int J Electr Power Energy Syst* 2022;135:107528. [\[CrossRef\]](#)
- [4] Qian J, Lv X. Load frequency control of renewable energy power systems based on adaptive global fast terminal sliding mode control. *Appl Sci* 2025;15:7030. [\[CrossRef\]](#)
- [5] Izci D, Ekinici S, Çelik E, et al. Dynamic load frequency control in power systems using a hybrid simulated annealing based quadratic interpolation optimizer. *Sci Rep* 2024;14:26011. [\[CrossRef\]](#)
- [6] Kumar A, Anwar MN, Kumar S. Sliding mode controller design for frequency regulation in an interconnected power system. *Prot Control Mod Power Syst* 2021. [\[CrossRef\]](#)
- [7] Anwar MN, Pan S. A new PID load frequency controller design method in frequency domain through direct synthesis approach. *Int J Electr Power Energy Syst* 2015. [\[CrossRef\]](#)
- [8] Verma A, Asim M, Mahboob R. Load frequency control in power systems using the most valuable player algorithm. *Indian J Sci Technol* 2023;16:3854–3861. [\[CrossRef\]](#)
- [9] Siddiqui MA, Anwar N, Laskar SH. A simple tuning approach for PID controller based on direct synthesis and rootlocus. In: 2019 3rd International Conference on Computing Methodologies and Communication (ICCMC); 2019; Erode, India. p. 466–470. [\[CrossRef\]](#)
- [10] Vasu G, Sivakumar M, Raju MR. A novel model reduction approach for linear time-invariant systems via enhanced PSO-DV algorithm and improved MPPA method. *Proc Inst Mech Eng I J Syst Control Eng* 2020;234:240–256. [\[CrossRef\]](#)
- [11] Patel NC, Agrawal R, Pradhan P, Satapathy S, Ahmed I, Debnath M. Two-staged (PDF+1PI) controller design for load frequency control. 2020. p. 1–6. [\[CrossRef\]](#)
- [12] Morsali J, Zare K, Tarafdar Hagh M. Comparative performance evaluation of fractional order controllers in LFC of two-area diverse-unit power system with considering GDB and GRC effects. *J Electr Syst Inf Technol* 2018;5:708–722. [\[CrossRef\]](#)
- [13] Topno PN, Chanana S. Tilt integral derivative control for two-area load frequency control problem. In: 2015 2nd International Conference on Recent Advances in Engineering & Computational Sciences (RAECS); 2015; Chandigarh, India. p. 1–6. [\[CrossRef\]](#)
- [14] Agrawal P, Asim M, Tariq M. Particle swarm optimization (PSO) for maximum power point tracking. 2022. p. 1–5. [\[CrossRef\]](#)
- [15] Mirjalili S, Mirjalili SM, Lewis A. Grey wolf optimizer. *Adv Eng Softw* 2014;69:46–61. [\[CrossRef\]](#)
- [16] Saremi S, Mirjalili S, Lewis A. Grasshopper optimization algorithm: Theory and application. *Adv Eng Softw* 2017;105:30–47. [\[CrossRef\]](#)
- [17] Trojovský P, Dehghani M. Pelican optimization algorithm: A novel nature-inspired algorithm for engineering applications. *Sensors (Basel)* 2022;22:855. [\[CrossRef\]](#)
- [18] Elkasem AHA, Kamel S, Korashy A, Nasrat L. Load frequency control design of two area interconnected power system using GWO. In: 2019 IEEE Conference on Power Electronics and Renewable Energy (CPERE); 2019; Aswan, Egypt. p. 278–283. [\[CrossRef\]](#)
- [19] Latif A, Hussain SMS, Das DC, Ustun TS, Iqbal A. A review on fractional order (FO) controllers' optimization for load frequency stabilization in power networks. *Energy Rep* 2021;7:4009–4021. [\[CrossRef\]](#)
- [20] Kumar A, Asim M, Shadab MM, Akhtar I. Review of various load frequency controllers. In: Iqbal A, Malik H, Riyaz A, Abdellah K, Bayhan S, editors. *Renewable power for sustainable growth. Lecture Notes in Electrical Engineering*. Vol. 723. Singapore: Springer; 2021. [\[CrossRef\]](#)
- [21] Azad MA, Tariq M, Sarwar A, Sajid I, Ahmad S, Bakhsh FI, Sayed AE. A particle swarm optimization-adaptive weighted delay velocity-based fast-converging maximum power point tracking algorithm for solar PV generation system. *Sustainability* 2023;15:15335. [\[CrossRef\]](#)
- [22] Sajid I, Sarwar A, Tariq M, Bakhsh FI, Ahmad S, Mohamed ASN. Archimedes optimization algorithm (AOA)-based global maximum power point tracking for a photovoltaic system under partial and complex shading conditions. *Energy* 2023;283:129169. [\[CrossRef\]](#)
- [23] Babu S, Sondi A. Load frequency controllers design and comparison for interconnected hydro-thermal systems. *Int J Innov Res Sci Eng Technol* 2017;6:17307–17315.
- [24] Tuan DH, Tran DT, Nguyen Ngoc Thanh V, Huynh VV. Load frequency control based on gray wolf optimizer algorithm for modern power systems. *Energies* 2025;18:815. [\[CrossRef\]](#)
- [25] Gupta P, et al. Impact of distributed energy resources on load frequency control: A review of 2025 trends. *Renew Sustain Energy Rev* 2025.
- [26] Chaudhari P, Siddhpura DM, Ranva J, Varu V, Katariya A. Real-time load frequency control for PV-integrated power systems. *Int J Eng Res Technol* 2025;14:110363.
- [27] Kumar S, et al. Virtual inertia support for load frequency control in low-inertia microgrids. *IEEE J Emerg Sel Top Power Electron* 2025.

- [28] Tungadio DH, Sun Y. Load frequency controllers considering renewable energy integration in power system. *Energy Rep* 2019;5:436–453. [\[CrossRef\]](#)
- [29] Wu Z, Gao W, Gao T, Yan W, Zhang H, Yan S, et al. State-of-the-art review on frequency response of wind power plants in power systems. *J Mod Power Syst Clean Energy* 2018;6:1–16. [\[CrossRef\]](#)
- [30] Yan Z, Xu Y. Data-driven load frequency control for stochastic power systems: A deep reinforcement learning method with continuous action search. *IEEE Trans Power Syst* 2018;34:1653–1656. [\[CrossRef\]](#)
- [31] Ramakrishna K, Bhatti T. Sampled-data automatic load frequency control of a single area power system with multi-source power generation. *Electr Power Compon Syst* 2007;35:955–980. [\[CrossRef\]](#)
- [32] Gautam SK, Goyal N. Improved particle swarm optimization based load frequency control in a single area power system. In: 2010 Annual IEEE India Conference (INDICON); 2010. p. 1–4. [\[CrossRef\]](#)
- [33] Gulzar MM, Iqbal M, Shahzad S, Muqet HA, Shahzad M, Hussain MM. Load frequency control (LFC) strategies in renewable energy-based hybrid power systems: A review. *Energies* 2022;15:3488. [\[CrossRef\]](#)
- [34] Tan W. Decentralized load frequency controller analysis and tuning for multi-area power systems. *Energy Convers Manag* 2011;52:2015–2023. [\[CrossRef\]](#)
- [35] Alhelou HH, Hamedani-Golshan ME, Zamani R, Heydarian-Forushani E, Siano P. Challenges and opportunities of load frequency control in conventional, modern and future smart power systems: A comprehensive review. *Energies* 2018;11:2497. [\[CrossRef\]](#)
- [36] Saleem MU, Shakir M, Usman MR, Bajwa MHT, Shabbir N, Ghahfarokhi PS, et al. Integrating smart energy management system with Internet of Things and cloud computing for efficient demand side management in smart grids. *Energies* 2023;16:4835. [\[CrossRef\]](#)
- [37] Asgharian P, Noroozian R. Modeling and model predictive control of a microturbine generation system for stand-alone operation. *Sigma J Eng Nat Sci* 2019;37:705–722.
- [38] Sobhanam AP, Mary PM, Mariasiluvairaj WI, Wilson RD. Automatic generation control using an improved artificial electric field in multi-area power system. *IETE J Res* 2023;69:4813–4825. [\[CrossRef\]](#)
- [39] Çolak ÖÜ, Çakır Y. Genetic algorithm optimization method for parameter estimation in the modeling of storage modulus of thermoplastics. *Sigma J Eng Nat Sci* 2019;37:981–988.
- [40] Gupta M, Walia A, Gupta S, Sikander A. Modelling and identification of single area power system for load frequency control. In: 2017 4th International Conference on Signal Processing, Computing and Control (ISPCC); 2017. p. 436–439. [\[CrossRef\]](#)
- [41] Mohammed AJ, Al-Majidi SD, Al-Nussairi MK, Abbod MF, Al-Raweshidy HS. Design of a load frequency controller based on artificial neural network for single-area power system. In: 2022 57th International Universities Power Engineering Conference (UPEC); 2022 Aug 30-Sep 2. p. 1–5. [\[CrossRef\]](#)
- [42] Bharat M, Dodakundi M, Dash R. Design and analysis of optimized hydro governor control action using GWO. In: 2023 IEEE 2nd International Conference on Industrial Electronics: Developments & Applications (ICIDEA); 2023. p. 615–619. [\[CrossRef\]](#)
- [43] Kunya AB, Abubakar AS, Yusuf SS. Review of economic dispatch in multi-area power system: State-of-the-art and future prospective. *Electr Power Syst Res* 2023;217:109089. [\[CrossRef\]](#)
- [44] Kunya AB. Hierarchical bi-level load frequency control for multi-area interconnected power systems. *Int J Electr Power Energy Syst* 2024;155:109600. [\[CrossRef\]](#)
- [45] Kiehbaddroudzeh M, Merabet A, Hosseinzadeh-Bandbafha H, Ghenai C. Environmental assessment of optimized renewable energy-based microgrids integrated desalination plant: Considering human health, ecosystem quality, climate change, and resources. *Environ Sci Pollut Res Int* 2023;30:29888–29908. [\[CrossRef\]](#)
- [46] Cetinkaya U, Bayindir R. Impact of increasing renewable energy sources on power system stability and determine optimum demand response capacity for frequency control. In: 2022 10th International Conference on Smart Grid (icSmartGrid); 2022. p. 396–400. [\[CrossRef\]](#)
- [47] Ali R, Mohamed TH, Qudaih YS, Mitani Y. A new load frequency control approach in an isolated small power systems using coefficient diagram method. *Int J Electr Power Energy Syst* 2014;56:110–116. [\[CrossRef\]](#)
- [48] Yusuf SS, Abubakar AS. A comprehensive review on grid-forming inverter: Potential and future trends. *Majlesi J Electr Eng* 2023;17:1–27.
- [49] Ahmed I, Rehan M, Basit A, Malik SH, Hong KS. Multi-area economic emission dispatch for large-scale multi-fueled power plants contemplating inter-connected grid tie-lines power flow limitations. *Energy* 2022;261:125178. [\[CrossRef\]](#)
- [50] Khujaev A, Ugurenver A. Centralized controller-based on optimal power flow (OPF) algorithm for power management in microgrid systems. *Sigma J Eng Nat Sci* 2025;43:2279–2293. [\[CrossRef\]](#)