Vol. 7, No. 3, November 2025 (Special Issue), pp. 291~298, p-ISSN 2685-2381, e-ISSN 2715-2626
http://dx.doi.org/10.28989/avitec.v7i3.3082

Design and Simulation of Optimized Load Frequency Control in Multi-Area Electrical Interconnection Systems

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Article Info

Article history:
Submitted June 15, 2025
Accepted July 24, 2025
Published August 27, 2025

ABSTRACT

Maintaining frequency stability in modern interconnected power systems is critical for operational reliability, especially under varying load demands. Load Frequency Control (LFC) plays a pivotal role in balancing power exchanges and preserving nominal frequency across multi-area grids. This paper presents the design, modeling, and optimization of a two-area Load Frequency Control (LFC) system in interconnected power networks using MATLAB/Simulink. Each area comprises a governor, turbine, generator-load system, and a PID controller to regulate frequency deviations and maintain system stability following load disturbances. The study investigates the effects of key system parameters—including governor and turbine time constants, generator inertia, and tie-line coupling—on dynamic performance. To address mismatched responses between areas, Particle Swarm Optimization (PSO) is employed to tune system parameters and improve coordination. The optimization aims to minimize frequency deviations and tie-line power fluctuations while enhancing system response. Simulation results show that the proposed optimization approach significantly improves dynamic performance. Specifically, frequency deviations in both areas are reduced by over 55%, tie-line power fluctuation is minimized by 62.5%, and settling times for frequency responses are shortened by over 44%. These improvements demonstrate the effectiveness of the optimization strategy in enhancing inter-area coordination and system resilience. The framework also serves as a practical simulation-based educational tool for power engineering students and researchers to exploreLFC design and control strategies in multi-area systems.

Keywords:

Load Frequency Control (LFC);
multi-area power system;
simulink;
PID controller;
Particle Swarm Optimization (PSO).

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1. INTRODUCTION

Maintaining the frequency constant and stable in power systems is necessary to ensure operational security, especially in multi-area networks where interconnected grids must coordinate during load disturbances. One of the fundamental mechanisms that seeks to balance generation and demand by regulating system frequency and tie-line power exchanges is Load Frequency Control (LFC). In traditional LFC approaches, Proportional–Integral–Derivative (PID) controllers are widely utilized due to their simplicity and satisfactory performance under linear operating conditions. With increasing interest in using simulation tools for academic and practical studies, Simulink-based models offer open platforms for examining control strategies for various power system conditions.

Over the past several years, Iraq has renewed its efforts to modernize and stabilize the electricity sector by pursuing regional interconnection projects with neighboring countries. Among them, the Iraq–Turkey electrical interconnection is a strategic project that involves a 400 kV transmission line between Zakho and Silopi. This link would not only enhance Iraq's power import capability at the peak demand time but also open a doorway to future interconnection with Turkey's grid and, through it, the European Network of Transmission System Operators for Electricity (ENTSO-E). The challenge of such synchronization includes coordinating inter-area frequency deviations, tie-line oscillations, and response coordination during faults—issues that can satisfactorily be analyzed using a two-area LFC model [1][2].

Similarly, Iraq's agreements with Saudi Arabia and Jordan signal a new chapter of regional energy cooperation. The Iraq–Jordan interconnection project is already underway, initiating with an initial capacity of 150 MW and an upgrade plan to 500 MW via a 400 kV upgrade. The connection is intended to supply Iraq's western region and improve the stability of the grid via diversified power imports. Meanwhile, the Iraq–Saudi Arabia project is more ambitious with a capacity of 1,000 MW via a 435 km line from Arar to Baghdad. Such interconnections should pave the way not just for better energy security but also for the development of a regional electricity market. The technical success of such systems depends heavily on effective load frequency control, tie-line power exchange, and proper tuning of control parameters; thus, simulation studies gain added importance [3-5].

A Simulink-based educational toolkit for simulation of load frequency control in a two-area interconnected power system with PID controllers is presented in this paper. The model captures the general structure of regional interconnection systems like the ones currently under development in Iraq. Its key features include straightforward tuning of system parameters, the inclusion of tie-line dynamics, and disturbance scenario analysis of different types. By modifying controller gains, generator and turbine time constants, tie-line strength, and load change magnitudes, the model serves as a teaching tool for students and a test bed for experimenting with LFC concepts under simplified but realistic conditions.

Figure 1. Electrical projects of interconnections between Iraq and Turkey, Jordon and KSA [2]

The remainder of this paper is organized as follows. Section II presents a review of related work focusing on simulation-based approaches to Load Frequency Control and recent optimization strategies. Section III describes the Simulink-based model developed for two electrically interconnected areas, including system components and control structure. Section IV provides experimental results and analysis based on varying system parameters. Section V introduces the optimization framework applied to enhance Load Frequency Control performance, detailing the algorithm and improvements achieved. Finally, Section VI concludes the paper by summarizing the main findings and highlighting future research directions.

Related work

Currently provides a basic tool for power system studies, Matlab/Simulink Dynamic Reaction Modeling, and a solid platform for simulation. With Simulink transfer, Lagari et al [6], created a Load Frequency Control (LFC) model that detects frequency changes after load changes and appointed a PID controller to bring back the frequency to nominal values. In [7,8], also showed an automated generational control (AGC) model of a two-region power system to simulate the hydro-thermal interconnected network dynamics of Simulink. These models are user-friendly tools to study the complexity of the power system operating and control plan. Multifold network stability and control analysis depend greatly on the power system, especially on the two-sector model. The interaction between renewable energy and how they reduce frequency stability has been the main subject for the interest in the research company [9].

For example, a study analyzed the effect of wind energy integration on the two-region system underlining the need for synthetic inertia control to provide stability in the condition of different contexts. The utility of quality control measures in interconnected power systems is postponed by research work. Many optimization techniques have seen an improvement in the LFC system's performance. PID control parameters are set using PSO, which improves the frequency control in power sources associated with many power sources. In addition, it has been suggested that the flexibility of the LFC system, combined with adaptation techniques to improve the flexibility frequency control mechanisms, thus improves their prediction [10-12].

The ease of use and simulation capabilities of Simulink make it a very effective teaching tool for power system dynamics and control education. At the University of Saskatchewan, Simulink has been employed to enable students to get hands-on experience with modeling and analysis of power system dynamics, bridging the gap between theory and practice. Such teaching uses demonstrate the advantage of Simulink in developing deeper understanding of power engineering concepts among students [13-18].

While several studies have explored Load Frequency Control in interconnected systems using classical or intelligent controllers, many have either focused solely on one control strategy or lacked integration between model-based simulation and optimization techniques. This work distinguishes itself by combining a detailed Simulink-based model of a two-area interconnected power system with a flexible experimental framework for parameter variation and performance analysis. Furthermore, the integration of Particle Swarm Optimization (PSO) to enhance PID controller performance under system asymmetries provides a practical and scalable solution that demonstrates measurable improvements in dynamic response. Unlike prior works, this paper also positions the model as an educational tool, bridging the gap between academic learning and real-world system behavior. Thus, it contributes to both the research community and engineering education by offering a complete, tunable simulation environment for studying and optimizing Load Frequency Control in multi-area power networks.

2. THE SIMULINK MODEL FOR TWO-ELECTRICALLY INTERCONNECTED AREAS

The proposed Simulink model is based on a linearized dynamic representation of two interconnected power areas. Each area includes three primary components: a governor, turbine, and generator-load block, all modeled using first-order transfer functions derived from standard LFC equations. The system incorporates frequency deviation as the key feedback signal and models the tie-line power exchange using the relation ($\Delta P_{Tie} = T_{12} \times (\Delta f_1 - \Delta f_2)$, where T_{12} represents the synchronizing coefficient. The PID controllers are inserted after each area's frequency deviation summing junction to provide corrective control signals for ΔPref inputs. All blocks are parameterized with tunable constants to reflect time delays, gains, and inertia, allowing real-time exploration of various scenarios in an educational setting.

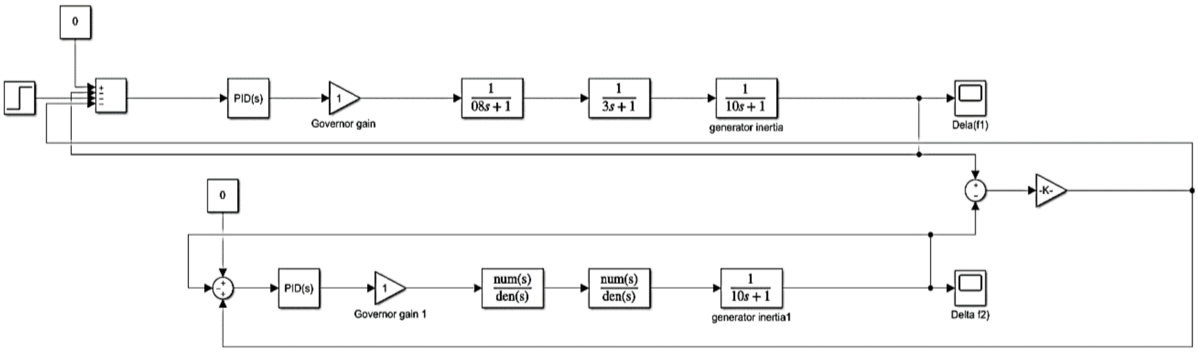

Figure 2. The Simulink model for LFC of two-electrical interconnected areas

2.1 The Governor

The governor is responsible for regulating the mechanical power input to the turbine by sensing frequency deviations. It acts as the first line of control to counter load changes. A governor is typically modeled as a first-order lag system in LFC studies. Its time constant reflects the response speed to frequency changes. Its function is represented by the transfer function as equation (1) [19].

$$G_g(S) = \frac{1}{T_g S+1} \tag{1}$$

2.2 The Turbine

The turbine converts the regulated steam or water flow (mechanical input) from the governor into mechanical energy to drive the generator. Like the governor, it is modeled as a first-order system. The turbine time constant reflects the delay in power output after a change in control signal. This element is implemented by the transfer function as in equation (2) [19].

$$G_t(S) = \frac{1}{T_t S+1} \tag{2}$$

2.3 The Generator - Load (Inertia and Damping Model)

This block represents the dynamics of the power system including generator inertia and the aggregated load response. It is also modeled as a first-order system, where the time constant is based on the inertia of the rotating mass and load damping. The transfer function is given by equation (3) [19].

$$G_{gl}(S) = \frac{1}{MS+1} \tag{3}$$

where M is the inertia constant.

2.4 The PID Controller

The PID controller takes the frequency error (difference between reference and actual frequency) and produces a control signal to adjust the governor input. It includes proportional, integral, and derivative terms to improve stability and steady-state performance. The function of the PID controller is characterized by equation (4) [20,21].

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{4}$$

where K_p is the proportional gain, K_i is the internal gain and K_d represents the derivative gain.

2.5 The Tie-line Interconnection

The tie-line connects the two power areas and enables power exchange. The power flow is a function of the frequency difference between the two areas, scaled by the synchronizing coefficient T12. This introduces coupling and dynamic interaction between Area 1 and Area 2. The power flow of the Tie-line is given by equation (5) [22].

$$\Delta P_{tie} = 2\pi T_{12}(\Delta f_1 - \Delta f_2) \tag{5}$$

This output is subtracted from Area 1 and added to Area 2 to simulate real inter-area power exchange. The default values for the Simulink model illustrated above in figure (2) is listed below in Table 1.

Table 1. The default values and the effect of their changes

Parameter	Default Value	Values to be Tested	Effect to Observe
Load Step (Area 1)	0.01	0.005, 0.02, 0.03	Impact severity of disturbance
Governor Time Constant	0.08	0.04, 0.1	Speed of governor response
Turbine Time Constant	0.3	0.2, 0.5	Delay in power response
Generator Inertia (M)	10	5, 15	Slower or faster frequency dynamics
Tie-Line Constant T_{12}	0.07	0.02, 0.1	Weak or strong inter-area coupling

3. EXPERIMENTAL RESULTS AND ANALYSIS

To evaluate the dynamic behavior of the two-area load frequency control system, a series of simulations were conducted using the Simulink-based model described earlier. The experimental setup focuses on analyzing system response to step load disturbances under various parameter settings, including changes in governor and turbine time constants, PID controller gains, and tie-line coupling strength. Frequency deviations in both areas (Δf_1 and Δf_2), as well as the tie-line power exchange (ΔP_{tie}), were observed to assess system stability, response speed, and control performance. All simulations were carried out over a 50-second interval with a 0.01 pu step load applied to Area 1 at t = 1s.

Figure 3 below illustrates the dynamic response of the two-area power system under default parameter values. A step load disturbance of 0.01 pu was applied to Area 1 at t = 1s. As shown in the Δf_1 plot, the frequency in Area 1 experiences a significant dip of approximately –11 mHz, followed by damped oscillations that gradually settle around –8 mHz. The frequency in Area 2 (Δf_2) also deviates due to tie-line interaction but with lower amplitude (~–4.5 mHz), reflecting indirect disturbance propagation. The ΔP_{tie} plot confirms active power exchange between the two areas, initially peaking at –3.5 mHz equivalent, as Area 2 supports Area 1 during its recovery. These results serve as the baseline for evaluating system performance under varying parameter conditions in the subsequent sections.

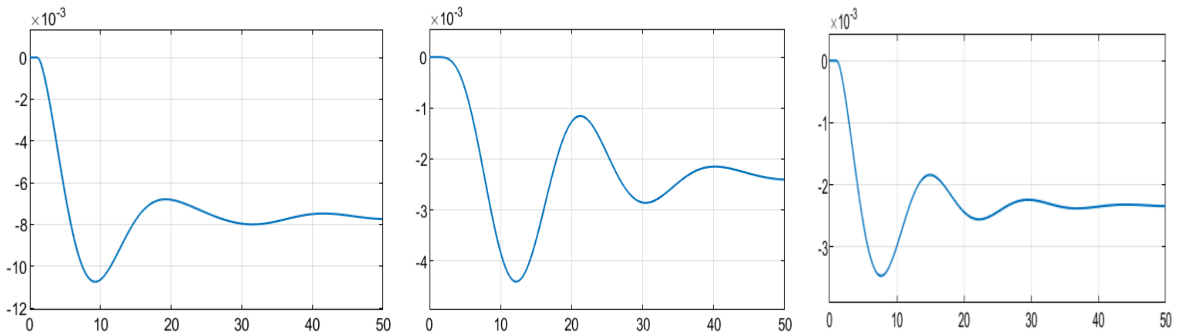

Figure 3. The dynamic response of the two-area power system under default parameter values

3.1 Impact of Load Disturbance Magnitude

The impact of load disturbance size on system performance is illustrated in Figures 4(a) and 4(b) for load steps of 0.005 pu and 0.03 pu, respectively. In the smaller disturbance case, Area 1 experiences a modest frequency deviation peaking near –5.5 mHz, while Area 2 exhibits a minimal drop of –2 mHz. The tie-line power exchange remains limited, with smooth damping and quick recovery. In contrast, the larger disturbance significantly amplifies system response: Δf_1 drops to –33 mHz with prolonged oscillations, and Δf_2 reaches beyond –14 mHz. The tie-line power surge is also more aggressive, peaking at nearly -18×10^{-4} pu. These results confirm that larger load steps demand stronger controller intervention and cause deeper inter-area interactions, thereby increasing the stress on frequency regulation mechanisms.

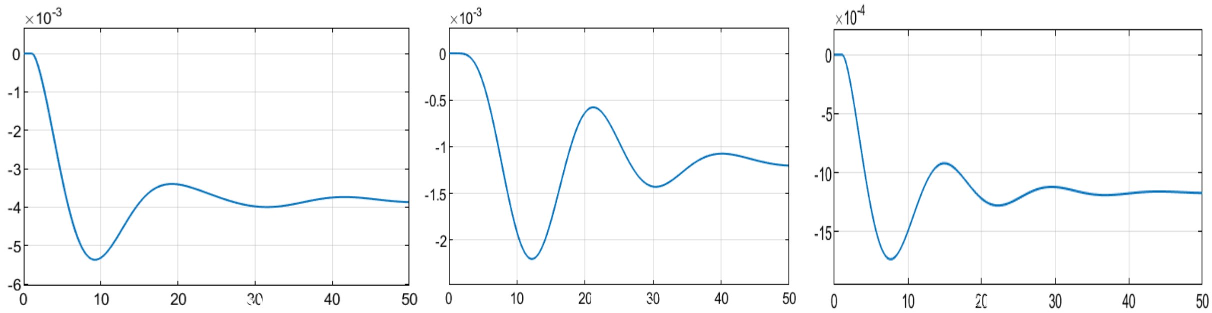

Figure 4(a). The dynamic response of the two-area power system with small disturbance

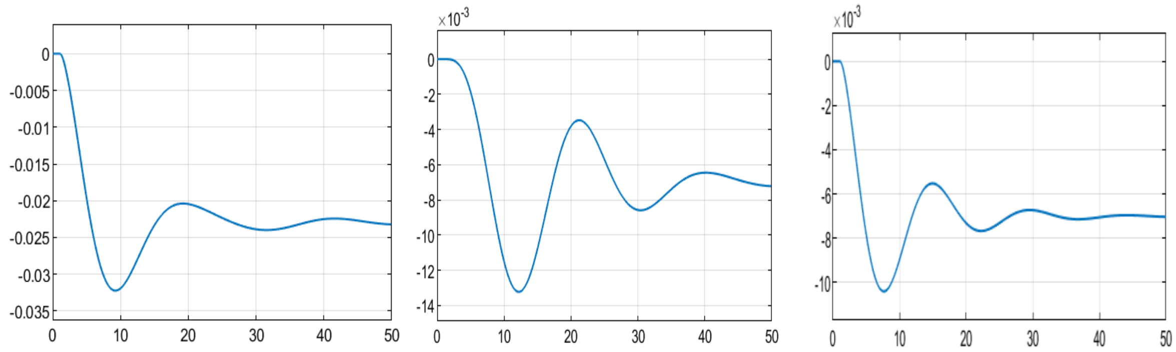

Figure 4(b). The dynamic response of the two-area power system with large disturbance

3.2 Effect of Asymmetric Governor Time Constants

Figure 5 illustrates the dynamic frequency responses of a two-area interconnected system under governor time constant asymmetry, where Area 1 employs a faster governor (Tg = 0.04 s) and Area 2 a slower one (Tg = 0.1 s). As expected, Area 1 (left plot) exhibits a quicker response and reaches its frequency nadir earlier than Area 2 (middle plot). However, Area 2 shows a larger frequency deviation and longer settling time due to its slower governor action. The tie-line power deviation (right plot) reflects the imbalance in response between the two areas, resulting in oscillations with noticeable overshoot. This highlights the significance of tuning dynamic parameters such as governor time constants to achieve better coordination and reduced mismatch in load-frequency control across interconnected regions.

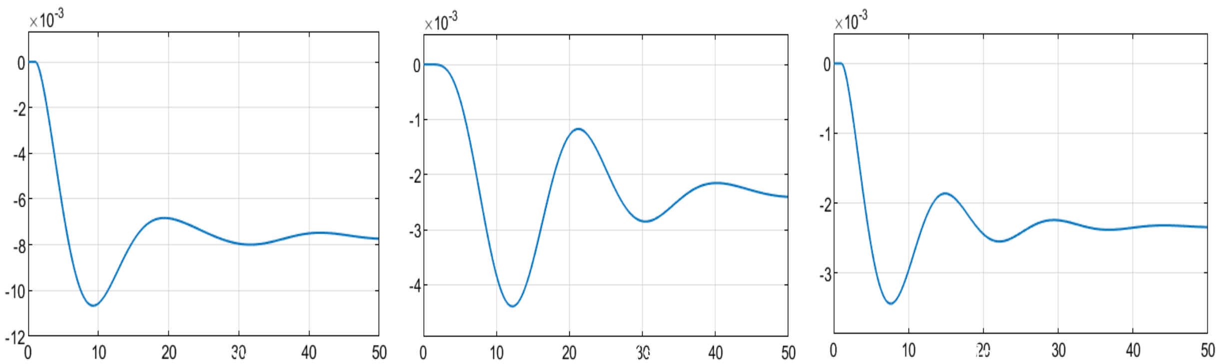

Figure 5. effect of asymmetric governor time constant

3.3 Effect of Asymmetric Generator Inertia

Figure 6 illustrates the frequency response when Area 1 has low inertia of M = 5 and Area 2 runs with high inertia of M = 15. As indicated in the left subplot, Area 1 exhibits a quicker but more oscillatory frequency response, which is a quick response but without good damping due to the lower storage of rotational energy. In comparison, Area 2 (center) shows a less oscillatory and more stable response, although delayed, demonstrating the dampening effect of larger inertia. Tie-line power (right) shows larger oscillations, highlighting the energy imbalance of exchange caused by the two areas' mismatched inertia. This test highlights the stabilizing role of generator inertia in interconnected systems as well as the importance of harmonized inertia levels.

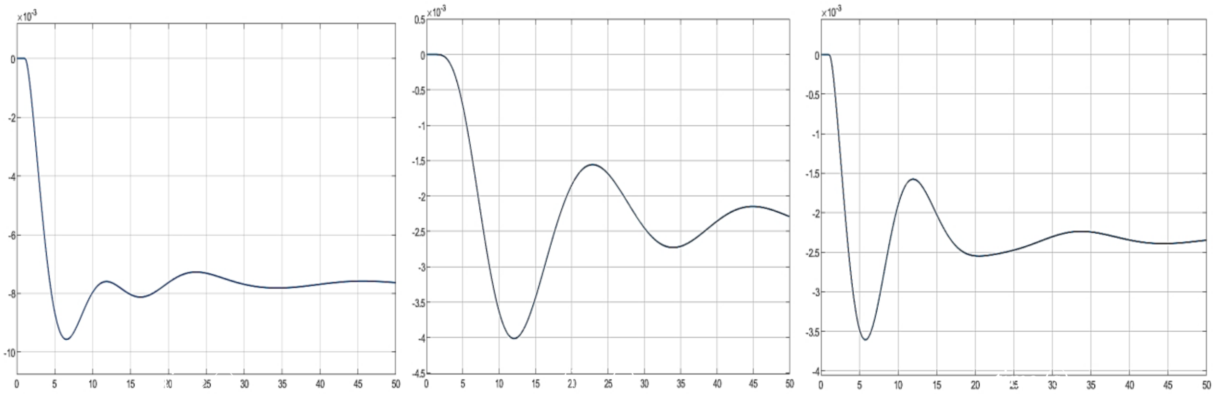

Figure 6. The effect of asymmetric generator inertia

Through a series of simulation experiments, main model parameters-like load steps, stable, stagnant, turbine delay, generator inertia and tie-line synchronization Coefficients-War systematically diverse to inspect the effect of system dynamics. These variations revealed significant insights: The disorder of the load directly affects the dimensions of frequency deviation, governor and turbine constants shape the speed and delay of the constant control response; the generator controls the inertia of the inertia, and determines the degree of the TIE-Line inter-range link. While this manual adjustment helps to understand the sensitivity of the system, it requires optimal frequency control under different operating conditions more intelligent approach. Therefore, the next section examines the application of customization algorithms to automatically set the system for better dynamic performance.

4. OPTIMIZATION OF LOAD FREQUENCY CONTROL PARAMETERS

In order to increase the dynamic performance of the system with two regions load frequency control (LFC) under asymmetrical operating conditions, an adaptation approach is proposed. The goal is to reduce the frequency disagreement difference between the two regions, as by setting the most important control parameters such as PID earnings or Governor Time Constant. This approach mimics practical scenarios where one area will react faster than other than different generators inertia, governor or different stresses than others. With Particle Flock adaptation (PSO), the model is able to self-adjust the control parameters to restore frequency stability and improve tie-line power exchange, and thus suitable for experimental work by students under different operating regimen. The current shown in Figure 6 presents the steps that followed to adapt the map control performance. The adaptation process begins by choosing the type of inequality between two regions (eg the governor's time constants, turbine delays or variation in generator inertia). Subsequently, system parameters -time constant, INRTIA (M) and link line constant (T_{12}) were defined accordingly. A performance function is designed to compare the system's performance next time frequency deviation and system performance according to TIE-Line Power Exchange. A suitable adaptation algorithm (e.g. particle crew optimization) is then used to find optimal PID controller benefits. These customized values are later used to update the Simulink model, and the simulation is run before and after adaptation to see the difference. Finally, performance measurements are achieved and compared to validating the effectiveness of adaptation.

The performance of the proposed optimization technique is validated with quantitative measures of performance. Table 2, illustrates the comparison of system behavior before and after running the optimization algorithm. Notably, the maximum frequency deviations in both areas (Δf_1 and Δf_2) were reduced by over 55%, indicating improved frequency stability. Additionally, the peak tie-line power deviation (ΔP_{tie}) decreased by 62.5%, enhancing the reliability of power exchange between interconnected areas. The speed of response of the system also improved to a significant extent, with over 40% improvement in frequency deviation settling times in both areas. Such results testify the capability of the optimization approach in minimizing area mismatches and improving overall load frequency control performance.

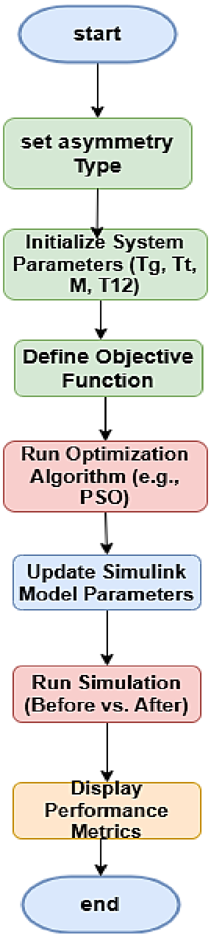

Figure 7. The flow chart for the optimization process

Table 2. optimization effect on the controlling performance

Metric	Before optimization	After optimization	Improvement (%)
Max (Δf_1)	0.014	0.006	57.1
Max (Δf_2)	0.009	0.004	55.6
Max (ΔP_{tie})	0.004	0.0015	62.5
Setting time (Δf_1) sec	34	19	44.1
Setting time (Δf_2) sec	38	21	44.7

5. CONCLUSIONS

This paper introduces modeling, design, and optimization of two-area Load Frequency Control (LFC) system on MATLAB/Simulink. The proposed model includes salient dynamics like governor, turbine, generator inertia, and tie-line in both areas controlled by PID controllers to provide frequency stability with load disturbance. The model illustrates, based on sequential simulation of various parameter settings, the impact of governor time constants, turbine response, and system inertia on frequency deviation and inter-area power transfer. For enhanced system performance, an optimization step was included using Particle Swarm Optimization (PSO). Optimization was applied to significant control parameters with the objective of minimizing frequency deviations and tie-line power oscillations. Simulation results show that optimization significantly improved dynamic response as well as steady-state accuracy. Frequency deviations were reduced by more than 55%, and settling times decreased by more than 40%, validating the effectiveness of the proposed optimization technique. The improved LFC model not only offers a helpful design guide but can also be utilized as an effective training tool and simulation tool in teaching and educational environments. The model allows the user to examine asymmetric conditions and experiment with control schemes, making it suitable for use in power system stability studies and academic laboratory environments.

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