

Enhancing Frequency Stability in Multi-Area Grids with High Penetration of Renewable Energy Sources

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Abstract

The increasing penetration of intermittent and uncertain renewable energy sources presents substantial challenges to frequency stability in modern power systems. This study aims to enhance frequency regulation in a two-area interconnected power system by comparing conventional and optimization-based control strategies. A detailed Load Frequency Control (LFC) model incorporating governor, turbine, generator, and tie-line dynamics was developed to evaluate system responses to load disturbances. Three control schemes were examined: an Integral controller, a conventional Proportional–Integral–Derivative (PID) controller, and a Particle Swarm Optimization (PSO)-tuned PID controller. PSO was used to optimize the PID parameters by minimizing the Integral of Time-Weighted Absolute Error (ITAE). MATLAB/Simulink simulations showed that the Integral controller produced an overshoot of 0.0164, a settling time of 29.22 seconds, and an ITAE value of 2.2190. The conventional PID controller reduced the overshoot and ITAE value to 0.0026 and 0.5194, respectively, although its settling time increased slightly to 29.98 seconds. The PSO-tuned PID controller achieved the best overall performance, with the lowest overshoot (0.0007), fastest settling time (29.21 seconds), and lowest ITAE value (0.0557). These findings demonstrate that PSO-based PID

tuning substantially improves damping and reduces frequency deviations following load disturbances. The study contributes a comparative evaluation of control strategies for multi-area frequency regulation and indicates that PSO-tuned PID control is a promising approach for strengthening the dynamic stability of renewable-integrated power systems, although further practical validation is required before full-scale implementation.

Keywords: Frequency Stability; Load Frequency Control; Multi-Area Power System; Particle Swarm Optimization; Renewable Energy Integration

INTRODUCTION

Modern electric power systems are complex networks designed to ensure reliable generation, transmission, and distribution of electricity while maintaining a continuous balance between supply and demand (Mohanty, 2023). This balance is critical for system stability, as any mismatch leads to frequency deviations. Load Frequency Control (LFC) plays a vital role in regulating this balance by maintaining system frequency within acceptable limits (Abdelghany et al., 2024). In practice, constant fluctuations in load and generation cause frequency variations which, if not properly controlled, can degrade power quality, damage equipment, and even result in system instability or collapse (Roy & Oo, 2024; Khalil et al., 2022).

The complexity of LFC increases significantly in multi-area power systems, where multiple interconnected regions with different load and generation characteristics must operate in coordination (Daood et al., 2024). Although tie-lines improve reliability by enabling power sharing, they also allow disturbances to propagate across areas. For example, a sudden load change in one region can affect the entire network's frequency, necessitating coordinated control strategies (Aditya et al., 2024).

Conventional PID controllers are widely used in LFC due to their simplicity, but their performance depends heavily on precise tuning under nominal conditions, which rarely reflect real-world dynamics (Ali et al., 2025; Ahmed et al., 2021). The increasing variability in load demand, system nonlinearities, and especially the integration of renewable energy sources (RES) further limit their effectiveness (Alnefaie et al., 2025). Intelligent control techniques such as fuzzy logic, neural networks, genetic algorithms, and particle swarm optimization provide improved adaptability by handling uncertainties and nonlinear

behaviors, thereby enhancing system stability and transient performance (Nath & Sambariya, 2023; Brahim et al., 2021; Reddy et al., 2024; Çavdar et al., 2024).

However, high penetration of RES introduces low-inertia conditions and power fluctuations that challenge traditional LFC methods (Rahman et al., 2023; Daood et al., 2024). Existing centralized and some AI-based approaches often lack practical validation in hybrid, multi-source systems, leaving gaps in their real-world applicability (Khalil et al., 2022; Das et al., 2021). Additionally, there is a lack of adaptive frameworks that integrate decentralized and coordinated control across multiple areas, while issues such as scalability, RES variability, and limited research on energy storage roles further hinder the development of robust LFC systems (Doan et al., 2021; Dev et al., 2021; Hamza et al., 2022; Elkasem et al., 2024).

MATERIALS AND METHODS

Materials

The materials used in this research include a personal computer, Power system data, and the MATLAB software.

Methods

Dynamics of the Power System

Load frequency control (LFC) is a crucial process for large-sized generators, aiming to maintain unvarying frequencies, distribute loads, and manage tie line power exchange according to scheduled values. Various components of the automatic load frequency control loop are given away in Figure 1.

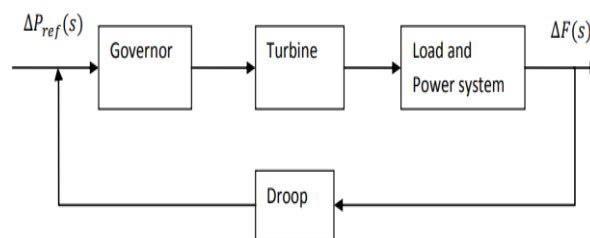


Figure 1: Block diagram of load frequency control (Doan et al., 2021).

Turbines

Turbines transform natural energy into mechanical power for generators and include three types: non-reheat, reheat, and hydraulic turbines (Wang et al., 2021). The model discussed illustrates how the power output of a non-reheat turbine reacts to variations in the steam valve's opening, incorporating a single gain factor K_T and a single time constant T . In the model, the representation of the turbine is,

$$\frac{\Delta P_T(s)}{\Delta P_v(s)} = \frac{K_T}{1+sT_T} \quad \dots(1)$$

Where, $\Delta P_v(s)$ = the input to the turbine; $\Delta P_T(s)$ = the output from the turbine

Generators

Generators convert mechanical power from turbines to electrical power, where the rotor speed is vital and directly proportional to the power system's frequency. It is crucial to balance generated power and load demands, as variations in load can lead to mechanical power exceeding generator power, resulting in frequency bias. Resistive loads (PL) can be fixed or can compensate for changes in load.

Mathematically,

$$\frac{\Delta P_v(s)}{\Delta P_g(s)} = \frac{K_T}{1+sT_g} \quad \dots(2)$$

Where, $\Delta P_v(s)$ = the output from the generator, $\Delta P_g(s)$ = the input to the generator, $T_g(s)$ = time constant of the generator

Governors

Governors in power systems detect frequency bias due to load changes and eliminate it by altering turbine inputs, like speed regulation and governor time constant. LFC aims to limit frequency deviation in active power load, using the load reference set point to adjust valve/gate positions.

Mathematically,

$$\Delta P_g(s) = \Delta P_{ref}(s) - \frac{1}{R} \Delta F(s) \quad \dots(3)$$

Where, $\Delta P_g(s)$ = governor output, $\Delta P_{ref}(s)$ = the reference signal, R = regulation constant or droop, $\Delta F(s)$ = frequency deviation due to speed

Load

The power systems load constitutes a diversity of electrical devices (Shouran, 2022). The resistive loads, for example, lighting and heating loads, are not dependent on frequency, but the motor loads are responsive to frequency, depending on the speed-load characteristics, as shown below:

$$\Delta P_e = \Delta P_L + D\Delta\omega \quad \dots(4)$$

Where, ΔP_L = non-frequency responsive load change, $D\Delta\omega$ = frequency responsive load change, $D = \frac{\%change \in load}{\%change \in frequency}$

Tie-lines

Tie-lines link different areas in a power grid, facilitating power exchange between regions with varying frequencies (Xu et al., 2022). This exchange involves tie-line trades and synchronizing torque coefficients, leading to potential power errors. Tie-lines are designed for cost-effective power trading among neighboring systems and are essential when generating units experience power loss, aiding in frequency restoration.

Let there be two control areas, and power is to be exchanged from area 1 to area 2. Mathematically,

$$P_{12} = \frac{|V_1||V_2|}{X_{12}} \sin(\delta_1 - \delta_2) \quad \dots(5)$$

Where, 1 stands for control area 1, and 2 stands for control area 2, X_{12} = series reactance involving areas 1 and 2, $|V_1|$ and $|V_2|$ = magnitude of voltages of area 1 plus area 2.

Area Control Error

LFC seeks to eliminate frequency errors across all areas and facilitate scheduled power exchanges via the tie-line. By correcting frequency errors to zero, it addresses steady-state tie-line power errors through area control error (ACE) signals, which each power-generating area employs (Masikana et al., 2024). To manage power interchange across various areas, LFC calculates real power flow through tie lines and subtracts predetermined interchange values to determine error levels (Roy & Oo, 2024). The total power exchange,

jointly with a gain, B (MW/0.1Hz), known as the bias in frequency, as a multiplier with the divergence in frequency, is known as the Area Control Error (ACE) specified by,

$$ACE = \sum_{k=1}^k P_k - P_s + B(f_{act} - f_0)MW \quad \dots(6)$$

Where, P_k = power in the tie line (if out of the area, then +ve), P_s = planned power exchange, f_0 = base frequency, f_{act} = actual frequency. Positive (+ve) ACE shows that the flow is out of the area.

Parallel Operation of Generators

A parallel generator can be utilized for power generation in specific regions, showcasing its inertia constant, damping constant, and frequency response. The tie line flows and frequency droop illustrate the interconnection of power areas with varying governor-speed-droop characteristics (Nath & Sambariya, 2023). Effective power exchange necessitates synchronization at a common frequency. Figure 2 shows the block diagram for the parallel operation of generators.

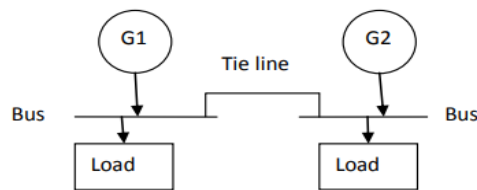


Figure 2: Block diagram for parallel operation of generators (Nath & Sambariya, 2023)

Modeling of LFC

This subsection covers the entire aspect of LFC design.

Modeling for the change in frequency

Let us consider a load frequency control loop of a system, which is isolated, intended for the examination of the steady state and dynamic responses, as shown in Figure 3.

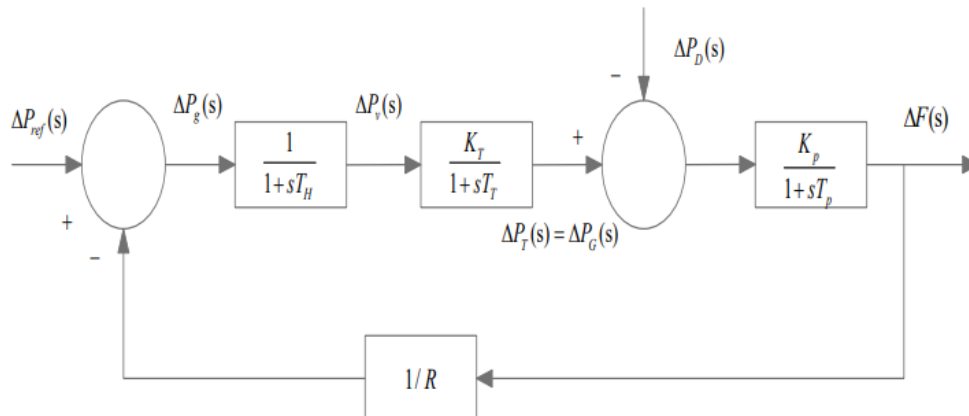


Figure 3: Load frequency control loop

Steady state analysis

Let ΔP_{ref} be the setting for the speed changer and ΔP_D be the alteration in demand of the load. Considering a simple situation where the speed changer might have a constant setting, i.e. $\Delta P_{ref} = 0$ as well as there is a change in the load demand. This may be known to be a free governor operation.

For such a process, the steady modification in the system frequency for a step change in load, i.e.

is obtained as follows:

$$\left[\left\{ \Delta P_{ref}(s) - \frac{1}{R} \Delta F(s) \right\} \frac{K_T}{(1+sT_H)(1+sT_T)} - \Delta P_D(s) \frac{K_p}{(1+sT_p)} = \Delta F(s) \right] \quad \dots(7)$$

This implies that,

$$\Delta F(s) = \frac{-K_p \Delta P_D(s) / s(1+sT_p)}{\left(\frac{K_T K_p}{R} \right) / (1+sT_H)(1+sT_T)(1+sT_p)} \quad \dots(8)$$

After simplification, we get,

$$\Delta F(s) = \frac{-\Delta P_D}{\beta} \quad \dots(9)$$

Where, β is the area frequency response characteristics

Dynamic analysis

For a step change in load,

$$\Delta F(s) = \frac{-K_p \Delta P_D(s) / s(1+sT_p)}{\left(\frac{K_T K_p}{R} \right) / (1+sT_H)(1+sT_T)(1+sT_p)} \quad \dots(10)$$

Assuming amplifier and turbine response to be instantaneous, i.e., $T_T = T_H = 0$ and $K_T = 1$, we have

$$\Delta F(s) = \frac{-K_p}{(1+sT_p) + \frac{K_p}{R} \frac{1}{s}} \frac{\Delta P_D}{s} \quad \dots(11)$$

After simplification, we get,

$$\Delta F(s) = \frac{-RsK_p(1+sT_H)(1+sT_p)}{Rs(1+sT_H)(1+sT_T)(1+sT_p) + (s+RK_i)K_p} \frac{\Delta P_D(s)}{s} \quad \dots(12)$$

Modeling of the Tie-Line

Let us consider that area 1 has surplus power and transfers power to area 2 by the tie-line. Figure 4 shows the Power transfer through the tie line

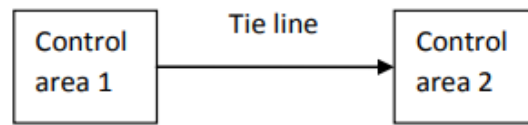


Figure 4: Power transfer through the tie line

where, P_{12} is the power exchanged from area 1 towards area 2 via tie lines.

Then, the power transfer equation, the tie-line is specified as follows:

$$P_{12} = \frac{|V_1||V_2|}{X_{12}} \sin(\delta_1 - \delta_2) \quad \dots(13)$$

$$\Delta P_{12} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1 - \delta_2) (\Delta\delta_1 - \Delta\delta_2) \quad \dots(14)$$

Where, δ_1 and δ_2 are the power angles of end voltages and corresponding machines of the two Areas, X_{12} = reactance of the tie line, $|V_1|$ and $|V_2|$ = magnitude of voltages of area 1 plus area 2

The sequence of the subscripts depicts that the flow of power due to the tie lines is positive in the direction from 1 to 2.

For a little deviation in the angles δ_1 and δ_2 changes by $\Delta\delta_1$ and $\Delta\delta_2$, the tie line power changes as follows:

$$\Delta P_{12} = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1 - \delta_2) (\Delta\delta_1 - \Delta\delta_2) \quad \dots(15)$$

i.e.

$$\Delta P_{12} = T^0 (\Delta\delta_1 - \Delta\delta_2) \quad \dots(16)$$

i.e.

$$\Delta P_{12}(s) = \frac{2\pi T^0}{s} (\Delta F_1(s) - \Delta F_2(s)) \quad \dots(17)$$

$$\text{Where, } T^0 = \frac{|V_1||V_2|}{X_{12}} \cos(\delta_1 - \delta_2) = \text{Torque produced} \quad \dots(18)$$

In a control area that is isolated, the incremental power ($\Delta P_G - \Delta P_D$) is the rate of rise of preserved kinetic energy due to a rise in the load, followed by a rise in the frequency. The power due to the tie-lines for each area is as follows:

$$\Delta P_1(s) = \Delta P_{12}(s) + a_{31}\Delta P_{31}(s) \quad \dots(19)$$

$$\Delta P_2(s) = \Delta P_{23}(s) + a_{12}\Delta P_{12}(s) \quad \dots(20)$$

Control of tie line bias is utilized to get rid of the steady state error due to frequency, plus the exchange of power due to tie lines. This shows that all of the control areas should put in their share in frequency control, besides dealing with their particular total interchange of power.

Let ACE_1 = area control error of area 1, ACE_2 = area control error of area 2.

ACE_1 , and ACE_2 are shown as linear arrangements of frequency along with tie-line power error as follows:

$$ACE_1 = \Delta P_{12} + b_1\Delta f_1 \quad \dots(21)$$

$$ACE_2 = \Delta P_{23} + b_2\Delta f_2 \quad \dots(22)$$

Where, b_1 and b_2 , are known as biases in the area frequency of area 1, and area 2, respectively.

Area control error (ACE) is negative when the net power flow output from an area is very small or when the frequency has dropped, or both. During such situations, we need to increase the generation.

Modelling of a Single Area System

Figure 5 shows the Load Frequency Control (LFC) loop. The frequency, which changes with load, is contrasted with the reference speed setting. The frequency can be set to the desired value by making generation and demand equal with the help of a steam valve controller, which regulates the steam valve and increases power output from generators. It serves the primary/basic purpose of balancing the real power by regulating turbine output according to the variation in load demand (ΔP_θ).

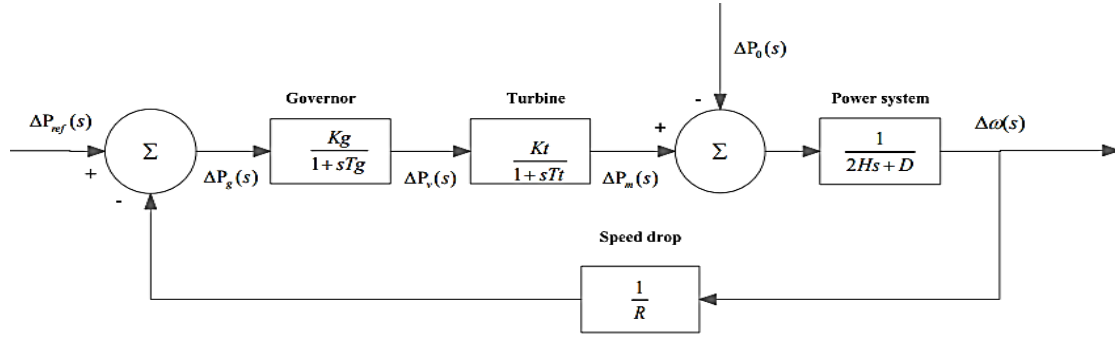


Figure 5: Model of a single-area LFC without using secondary control

The transfer function of the model of the single area system, as shown in Eqn. (23):

$$KG(s)H(s) = \frac{1}{R} \frac{1}{(2Hs + D)(1 + \tau_g s)(1 + \tau_T s)} \quad \dots(23)$$

$$\frac{\Delta\omega(s)}{-\Delta P_L(s)} = \frac{(1 + \tau_g s)(1 + \tau_T s)}{(2Hs + D)(1 + \tau_g s)(1 + \tau_T s) + \frac{1}{R}} \quad \dots(24)$$

$$\Delta\omega(s) = -\Delta P_0(s)T(s) \quad \dots(25)$$

For the case with a load that is not sensitive to frequency load (D=0):

$$\Delta\omega_{ss} = (-\Delta P_0)R \quad \dots(26)$$

The integral controller, which is responsible for making the frequency deviation zero, is put in the secondary loop as shown in Figure 6.

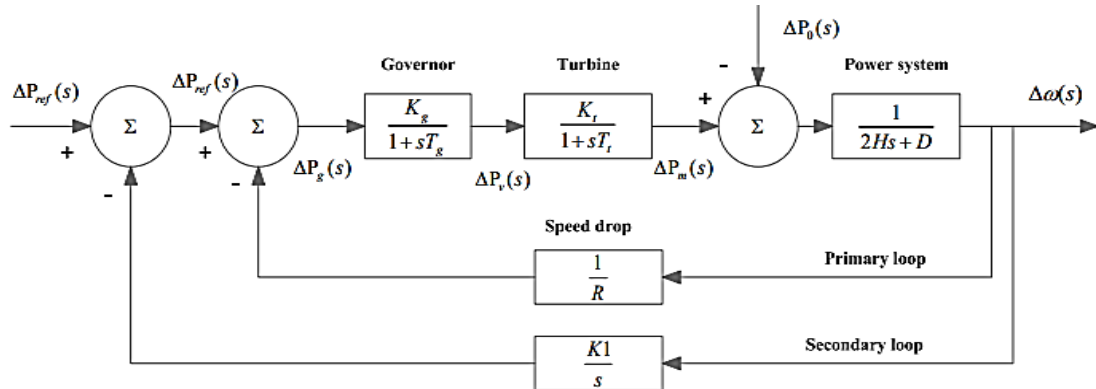


Figure 6: Model of single-area LFC using secondary control

$$\omega = \frac{1}{D + \frac{1}{R}} [\Delta P_{ref} - \Delta P_0] \quad \dots(27)$$

Modelling of Two-Area System

Two area-interconnected systems, which are joined using tie-lines for the flow of tie-line power, may be described in the following equations. Let the additional input be ΔP_{12} , ΔP_{01} be the load change in area 1 and the respective frequencies of the two areas be

$$\Delta\omega = \Delta\omega_1 = \Delta\omega_2 \quad \dots(28)$$

Let X_{12} be the reactance of the tie line, then the power delivered from area 1 to area 2 is

$$P_{12} = \frac{|E_1||E_2|}{X_{12}} \sin\delta_{12} \quad \dots(29)$$

The equation can be linearized as:

$$\Delta P_{12} = \frac{dP_{12}}{d\delta_{12}} \delta_{12} \quad \dots(30)$$

$$\Delta\delta_{12} = P_s \Delta\delta_{12} \quad \dots(31)$$

The tie-line power deviation:

$$\Delta P_{12} = P_s (\Delta\delta_1 - \Delta\delta_2) \quad \dots(32)$$

Let $\Delta\omega = \Delta\omega_1 = \Delta\omega_2$

For area 1,

$$\Delta P_{m1} - \Delta P_{12} - \Delta P_{01} = \Delta\omega D_1 \quad \dots(33)$$

$$\Delta P_{m1} = -\Delta P_{m2} = \Delta P_{12} = \Delta\omega D_2 \quad \dots(34)$$

For area 2,

$$\Delta P_{m1} = \frac{-\Delta\omega}{R_1} \quad \dots(35)$$

$$\Delta P_{m2} = \frac{-\Delta\omega}{R_2} \quad \dots(36)$$

For an entire load change of the steady state, frequency deviation in two areas is as shown;

$$\Delta\omega = \frac{-\Delta P_{L1}}{\left(\frac{1}{R_1} + D_1\right)\left(\frac{1}{R_2} + D_2\right)} = \frac{-\Delta P_{L1}}{\beta_1 + \beta_2} \quad \dots(37)$$

There can be one LFC for every control area in an interrelated multi-area system. ACEs are the actuating signals that stimulate modifications in reference power set points, such that $\Delta\omega$ becomes zero as soon as the steady-state is attained.

Each area ACE is a combination of frequency as well as tie-line error.

$$ACE_i = \sum nj = \Delta P_{ij} + K_i \Delta \omega \quad \dots(38)$$

Controller Design

The PID controller output is given as:

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \quad \dots(39)$$

Where:

K_p = proportional gain, K_i = integral gain, K_d = derivative gain, $e(t)$ = Area Control Error (ACE)

Particle Swarm Optimization (PSO) for Controller Tuning

Particle Swarm Optimization (PSO) is a population-based optimization technique inspired by the social behavior of birds flocking or fish schooling. It is used in this study to optimally tune the PID controller parameters (K_p, K_i, K_d) to achieve improved system stability.

PSO Mathematical Formulation

Each particle represents a candidate solution defined as:

$$X_i = [K_p, K_i, K_d] \quad \dots(40)$$

The velocity and position of each particle are updated using:

$$v_i^{k+1} = wv_i^k + c_1 r_1 (pbest_i - x_i^k) + c_2 r_2 (gbest - x_i^k) \quad \dots(41)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad \dots(42)$$

Where:

w = inertia weight, c_1, c_2 = cognitive and social coefficients, r_1, r_2 = random numbers in [0,1], $pbest_i$ = best position of particle i , $gbest$ = global best position

Objective (Fitness) Function

The performance of each particle is evaluated using the Integral of Time-weighted Absolute Error (ITAE):

$$J = \int_0^T t \cdot (|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|) dt \quad \dots(43)$$

The goal is to:

$$\min J \quad \dots(44)$$

This ensures reduced overshoot, faster settling time, and improved damping.

RESULTS

Results of Frequency Deviation (Δf_1) in Area I

Figure 7 demonstrates the frequency deviation (Δf_1) responses in Area 1 for three controllers: Integral, classical PID, and PSO-optimized PID.

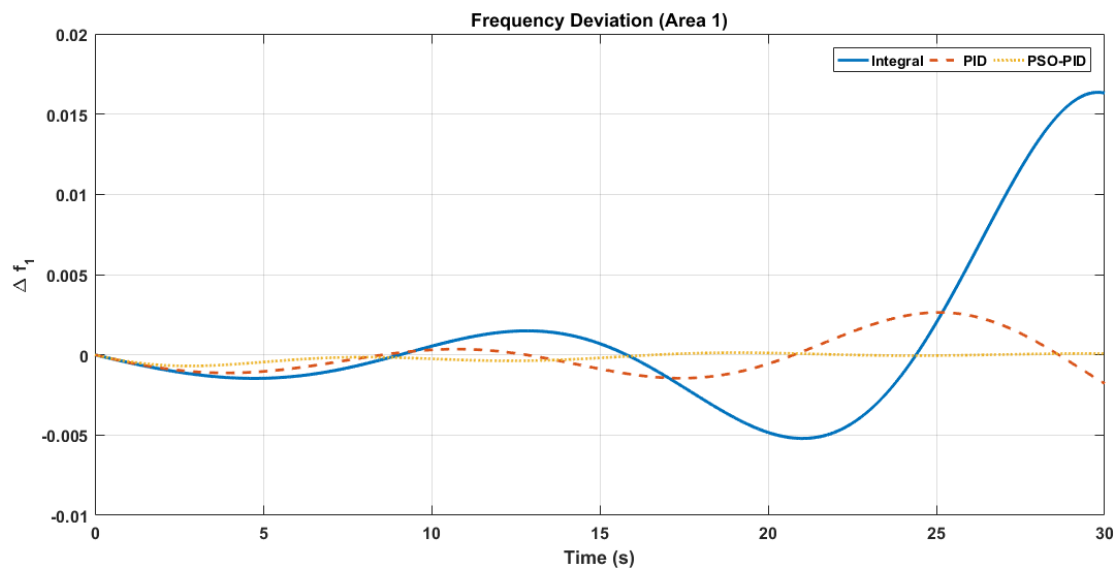


Figure 7: Area I Frequency Deviation (Δf_1)

Initially, all controllers show minor negative deviations due to load disturbances, but their performances diverge significantly. The Integral controller has the weakest performance, leading to instability with increasing oscillations. The classical PID controller performs better with smaller undershoot and controlled oscillations but fails at complete stabilization. The PSO-optimized PID controller exhibits the most effective response, with minimal deviation and quick stabilization near zero, indicating robust resistance to disturbances. The analysis emphasizes the Integral controller's deficiencies and highlights the PSO-PID's effectiveness amid renewable energy challenges.

Results of Frequency Deviation (Δf_2) in Area II

Figure 8 analyzes the frequency deviation response (Δf_2) in Area II, influenced indirectly by tie-line interactions rather than direct load disturbances.

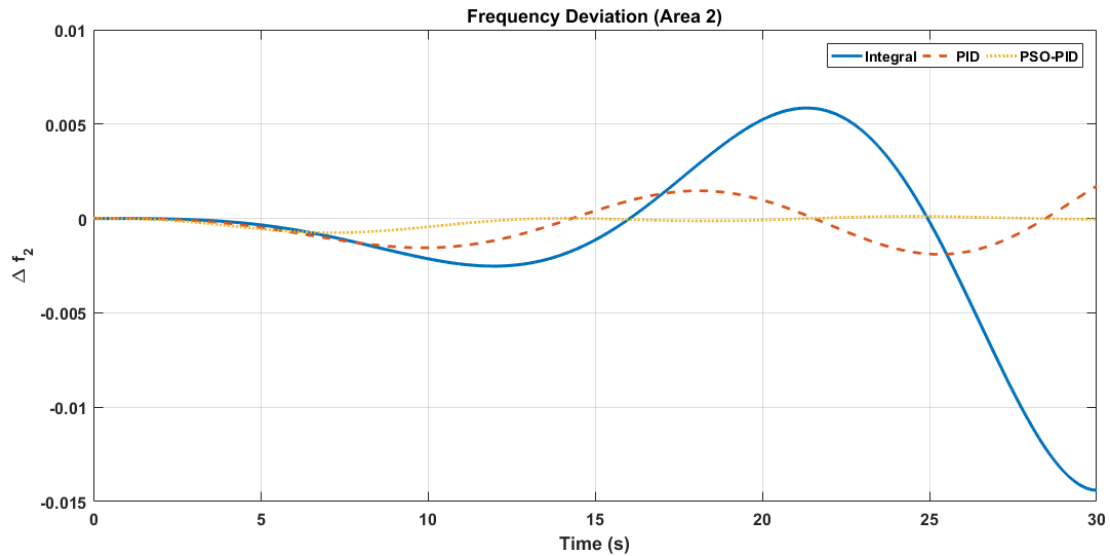


Figure 8: Area II Frequency Deviation (Δf_2)

Initial deviations in Area II are smaller than in Area I, indicating its stability. The Integral controller is ineffective, exhibiting increased oscillations and a significant negative peak of -0.014 Hz. In contrast, the classical PID controller performs better with reduced deviations and oscillations between -0.002 Hz and $+0.0015$ Hz, yet it still fails to stabilize fully. The PSO-optimized PID controller significantly outperforms others with near-zero frequency deviation and rapid stabilization, effectively managing disturbances, including those from renewable sources. The findings highlight the importance of coordinated control in interconnected power systems, especially as instability in Area I adversely impacts Area II.

Results of Tie-line power deviation (ΔP_{tie})

Figure 9 illustrates the tie-line power deviation (ΔP_{tie}) between Area I and Area II.

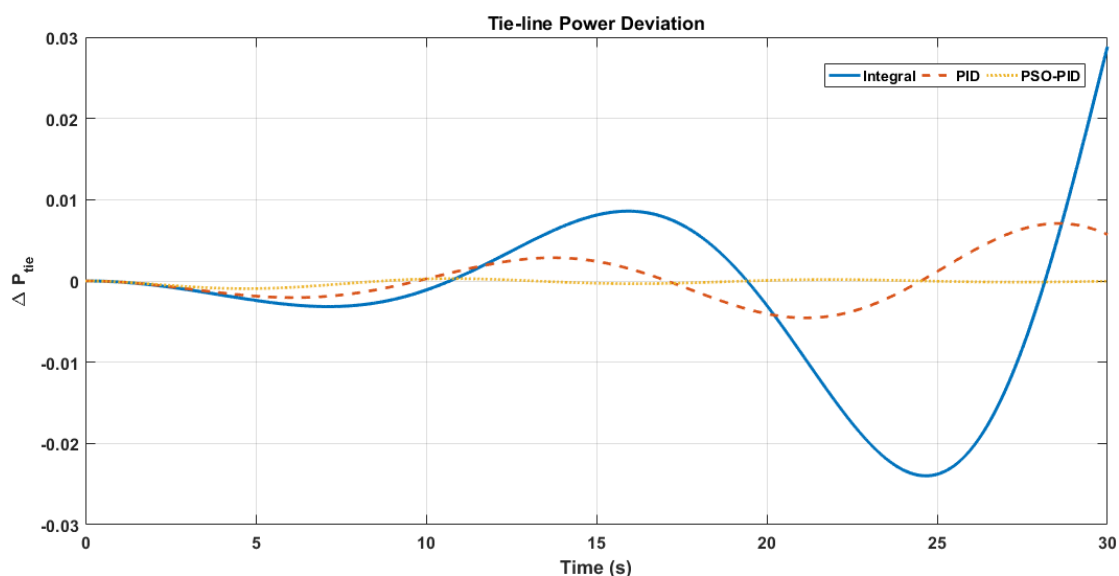


Figure 9: Tie-line power deviation (ΔP_{tie})

This response highlights the coordination of power exchange in maintaining system stability after a disturbance. Initially, controllers show small deviations due to disturbances in Area 1. The Integral controller performs poorly, with significant oscillations in tie-line power, indicating inadequate control and potential system issues. The classical PID controller improves performance, reducing oscillations but still facing fluctuations. The PSO-optimized PID controller excels, maintaining near-zero response with quick damping of deviations, ensuring optimal power regulation and enhancing system reliability. While the Integral controller's instability risks power transfer and reliability, the PSO-PID controller effectively manages disturbances, including variability from renewable energy sources.

Performance comparison

Figure 10 shows the performance comparison of the three controllers using the selected key performance indicators.

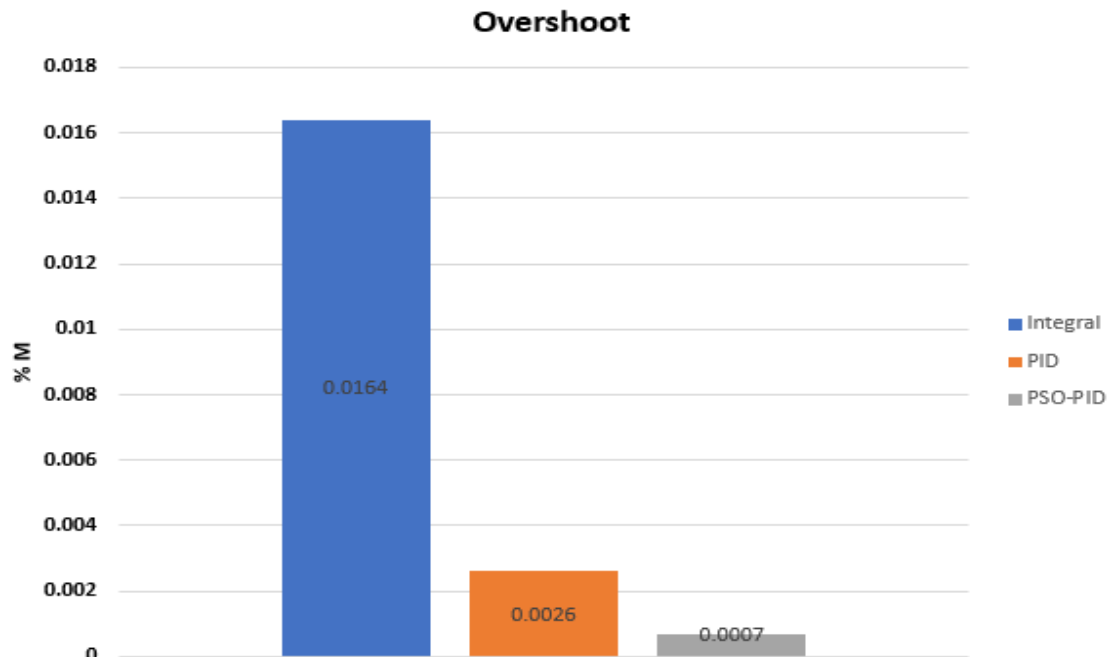


Figure 10: Overshoot ITAE of the controllers

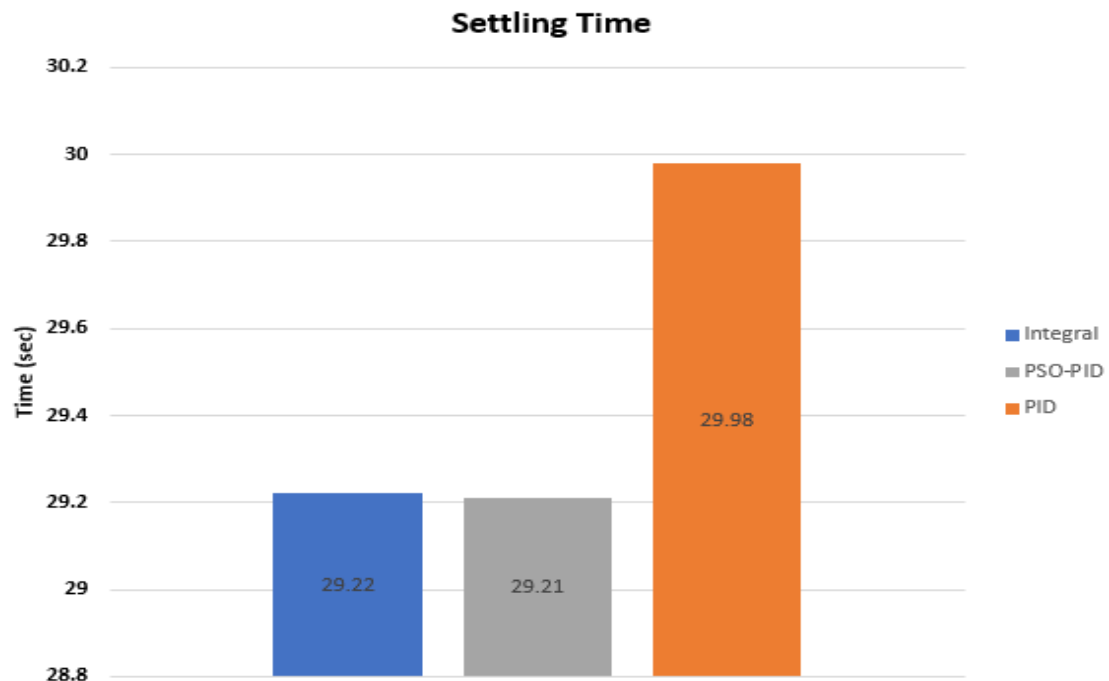


Figure 11: Settling time ITAE of the controllers

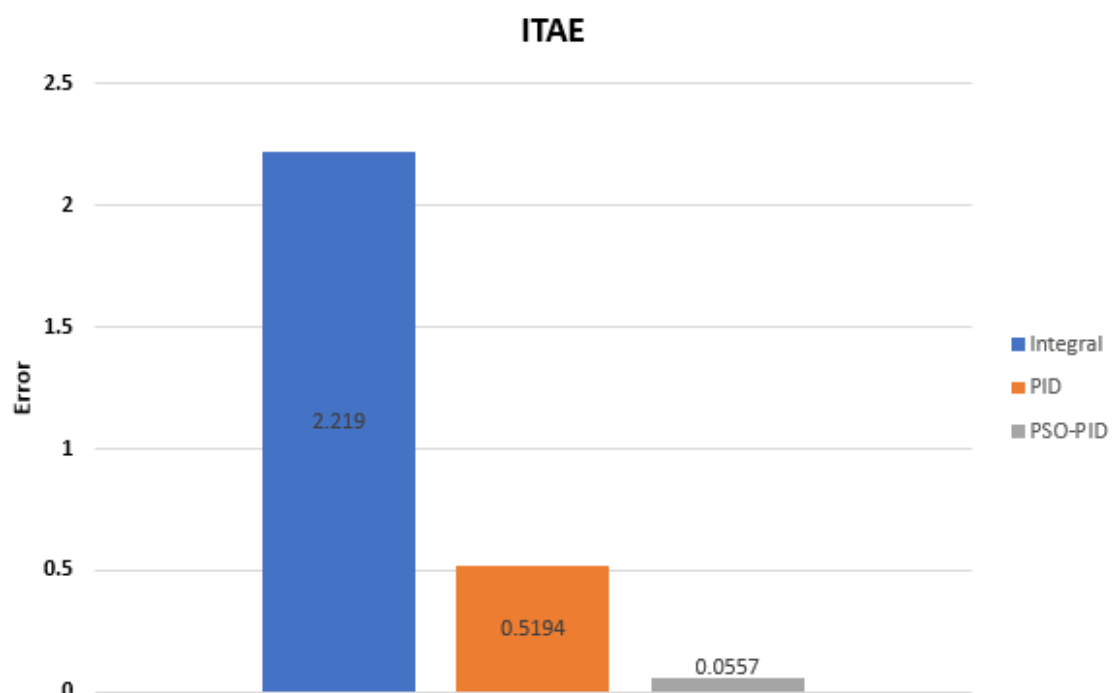


Figure 12: ITAE of the controllers

From figure 10-12, the Integral controller demonstrates the weakest dynamic performance compared to the other controllers, with a notable overshoot of 0.0164 and a long settling time of 29.22 seconds, indicating a sluggish response. Additionally, it has the highest ITAE value of 2.2190, reflecting its difficulty in effectively dampening oscillations

and addressing steady-state errors. This inefficiency results in extended deviations in system frequency, which is particularly problematic in applications like Load Frequency Control (LFC) where rapid stabilization is essential.

The PID controller outperforms the Integral controller, significantly reducing overshoot to 0.0026, indicating better damping and less oscillation. Although its settling time is slightly longer at 29.98 seconds, the ITAE value is much lower at 0.5194, showing effective minimization of time-weighted error. This enhancement is due to the integration of proportional, integral, and derivative components, improving both transient and steady-state performance.

The PSO-optimized PID (PSO-PID) controller shows superior performance, characterized by the lowest overshoot (0.0007) and the shortest settling time (29.21 s). Its ITAE value (0.0557) is significantly reduced, indicating effective error minimization. This demonstrates that Particle Swarm Optimization (PSO) enhances PID parameter optimization, balancing speed, stability, and accuracy.

DISCUSSION

The evaluation of controller performance is based on key metrics such as overshoot, settling time, and Integral of Time-weighted Absolute Error (ITAE). The Integral controller displays poor performance with an overshoot of 0.0164, a settling time of 29.22 seconds, and a high ITAE of 2.2190, indicating inefficiency in fast disturbance response. The PID controller significantly improves these metrics, achieving an overshoot of 0.0026, a slight increase in settling time to 29.98 seconds, and a reduced ITAE of 0.5194, showcasing balance in transient and steady-state performance. The PSO-PID controller outperforms both with an almost negligible overshoot of 0.0007, the fastest settling time at 29.21 seconds, and an ITAE of 0.0557, indicating exceptional efficiency in error minimization and disturbance rejection. Overall, transitioning from Integral to PID and further to PSO-PID controllers reflects substantial enhancements in system damping and stability, with the PSO-PID achieving the best overall performance.

CONCLUSION

In conclusion, the results clearly demonstrate that while conventional controllers such as Integral and PID provide acceptable performance, the adoption of intelligent optimization techniques like PSO leads to substantial improvements. The PSO-PID controller emerges as the most effective control strategy, offering superior dynamic response, enhanced stability, and optimal error minimization, making it a preferred choice for advanced Load Frequency Control applications in modern power systems.

Recommendation

The use of real-time simulators or hardware-in-the-loop platforms to test and validate control strategies under realistic operating conditions is recommended.

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