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Enhanced Load Frequency Control of Renewable Integrated Power Systems Using PSO-Optimized PID Controller

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Load Frequency Control (LFC), Particle Swarm Optimization (PSO), System, Integral Time Absolute Error (ITAE), Frequency Stability, Swarm Intelligence, Controller Optimization, Dynamic Response Improvement, Thermal and Hydro-Thermal Systems.

ABSTRACT

Load Frequency Control (LFC) plays a crucial role in maintaining system stability in modern power systems, especially with the increasing penetration of renewable energy sources (RES). This paper presents an enhanced LFC strategy for renewable-integrated multi-area power systems using a Particle Swarm Optimization (PSO)-based controller. In the existing approach, a cascade (1+PDn)-FOPI controller tuned via Sand Cat Swarm Optimization (SCSO) is employed to minimize the Integral Time Absolute Error (ITAE) and improve dynamic response under load disturbances and system nonlinearities. Although SCSO provides satisfactory performance, it suffers from higher computational complexity. To overcome this limitation, the proposed method utilizes PSO for optimal tuning of controller parameters. PSO, inspired by swarm intelligence, offers faster convergence and requires fewer tuning parameters compared to SCSO. The effectiveness of the proposed PSO-based LFC strategy is validated on two-area thermal and hydro-thermal power systems integrated with renewable energy sources. Simulation results demonstrate that the PSO-optimized controller significantly improves frequency regulation, reduces settling time and overshoot, and enhances overall system dynamic stability under varying load conditions and renewable energy fluctuations. Hence, the proposed method provides a computationally efficient and robust solution for modern power system control.

1. Introduction

The increasing demand for electrical energy and the rapid integration of renewable energy sources (RES) have significantly transformed the structure and operation of modern power systems. Renewable resources such as wind and solar photovoltaic (PV) generation offer environmental and economic benefits by reducing greenhouse gas emissions and dependence on fossil fuels [1]. However, the intermittent and stochastic nature of renewable generation introduces substantial challenges to power system operation, particularly in maintaining frequency stability under varying load and generation conditions [2]. Consequently, Load Frequency Control (LFC) has become an essential control mechanism for ensuring reliable and secure operation of interconnected power systems. Load Frequency Control, also known as Automatic Generation Control (AGC), is responsible for maintaining the balance between power generation and load demand while regulating tie-line power exchanges between interconnected areas [3]. Any mismatch between generated and consumed power results in frequency deviations that can adversely affect system stability, power quality, and equipment performance [4]. Therefore, effective frequency regulation is crucial for maintaining nominal system frequency and ensuring stable operation of interconnected networks [5]. In conventional power systems dominated by thermal generating units, frequency control is relatively straightforward because synchronous generators inherently provide rotational inertia that helps damp frequency oscillations [6]. However, the increasing penetration of renewable energy sources, particularly wind and solar power, has reduced overall system inertia due to the replacement of conventional synchronous generators with power electronic interfaced generation units [7]. As a result, frequency deviations become more severe and system dynamics become increasingly complex, necessitating the development of advanced LFC strategies [8]. Multi-area interconnected power systems further complicate frequency regulation because disturbances occurring in one area can affect neighboring areas through tie-line connections [9]. Therefore, an effective LFC scheme must not only restore frequency deviations within individual areas but also maintain scheduled tie-line power exchanges between interconnected regions [10]. This requirement becomes even more challenging in renewable-integrated systems where generation fluctuations and load uncertainties occur simultaneously.

Traditionally, Proportional-Integral-Derivative (PID) controllers have been widely employed for LFC applications due to their simple structure, ease of implementation, and satisfactory performance under nominal operating conditions [11]. The proportional term provides immediate corrective action, the integral term eliminates steady-state error, and the derivative term improves damping characteristics and transient response. Despite these advantages, conventional PID controllers often exhibit degraded performance when subjected to nonlinearities, parameter variations, renewable generation fluctuations, and large load disturbances [12]. Consequently, achieving optimal PID parameter settings has become a major research focus in modern AGC applications. To enhance controller performance, numerous advanced control techniques have been proposed, including robust control, adaptive control, fuzzy logic control, neural network-based control, and fractional-order controllers [13]. Among these approaches, Fractional Order Proportional Integral (FOPI) controllers have attracted significant attention because of their additional tuning flexibility and improved dynamic performance [14]. Recently, cascade control structures such as the (1+PDn)-FOPI controller have been developed to further improve disturbance rejection capability and system robustness [15]. These controllers have demonstrated superior frequency regulation performance compared with conventional PID controllers in interconnected power systems.

The effectiveness of advanced controllers largely depends on the proper selection of controller parameters. Therefore, various optimization algorithms have been employed to determine optimal controller gains. Metaheuristic optimization techniques such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), Artificial Bee Colony (ABC), Ant Colony Optimization (ACO), and Grey Wolf Optimization (GWO) have shown promising results in LFC applications [16]. These optimization methods aim to minimize performance indices such as Integral Absolute Error (IAE), Integral Square Error (ISE), and Integral Time Absolute Error (ITAE), thereby improving frequency regulation performance [17]. Recently, Sand Cat Swarm Optimization (SCSO) has been introduced as an effective optimization technique inspired by the hunting behavior of sand cats [18]. SCSO has been successfully applied for tuning cascade (1+PDn)-FOPI controllers in renewable-integrated power systems, resulting in improved dynamic response and reduced frequency deviations [19]. Although SCSO demonstrates satisfactory optimization capability, it often involves relatively high computational complexity and increased execution time, particularly for large-scale power system applications [20]. These limitations may restrict its suitability for practical and real-time implementation. Particle Swarm Optimization (PSO), originally proposed by Kennedy and Eberhart, has emerged as one of the most popular optimization techniques due to its simplicity, fast convergence characteristics, and computational efficiency [21]. Inspired by the social behavior of bird flocks and fish schools, PSO utilizes cooperative interactions among particles to search for optimal solutions within the solution space. Unlike many other metaheuristic algorithms, PSO requires fewer control parameters and exhibits excellent global search capability, making it highly suitable for controller parameter optimization problems [22].

In power system control applications, PSO has been successfully employed for tuning PID controllers, excitation systems, power system stabilizers, and AGC parameters [23]. The algorithm effectively identifies optimal controller gains that improve transient response, reduce overshoot, minimize settling time, and enhance overall system stability. Furthermore, PSO demonstrates strong robustness against nonlinearities and uncertainties, making it particularly attractive for renewable-integrated power systems characterized by fluctuating generation and dynamic operating conditions [24]. Motivated by these advantages, this paper proposes a PSO-optimized PID controller for enhanced load frequency control of renewable-integrated multi-area power systems. The controller parameters are optimally tuned using the PSO algorithm based on an ITAE performance criterion to achieve improved frequency regulation and tie-line power control. The proposed method is evaluated on two-area thermal and hydro-thermal power systems integrated with renewable energy sources under various disturbance scenarios. Simulation results demonstrate that the PSO-based controller significantly improves dynamic performance by reducing frequency deviations, minimizing overshoot, shortening settling time, and enhancing overall system stability compared with existing control approaches. Therefore, the proposed PSO-optimized PID controller provides an effective, computationally efficient, and robust solution for modern renewable-integrated power system frequency regulation [25].

2. Motivations and Contributions

A. Motivations

The increasing integration of renewable energy sources (RES) such as wind and solar power into interconnected power systems has introduced significant challenges to load frequency control due to their intermittent and unpredictable nature. The reduced system inertia associated with renewable generation increases the sensitivity of power systems to load disturbances and generation fluctuations, resulting in larger frequency deviations and tie-line power oscillations. Although advanced controllers such as cascade (1+PDn)-FOPI controllers optimized using Sand Cat Swarm Optimization (SCSO) have demonstrated improved performance, their implementation is often associated with higher computational complexity and increased optimization time. Therefore, there is a need for a computationally efficient optimization technique that can provide fast convergence while maintaining effective frequency regulation and system stability in renewable-integrated power systems.

B. Contributions

The major contributions of this work are summarized as follows:

1. A PSO-optimized PID controller is proposed for load frequency control of renewable-integrated interconnected power systems.
2. The Particle Swarm Optimization (PSO) algorithm is employed to optimally tune the PID controller parameters, enabling improved dynamic performance and faster convergence compared to conventional tuning approaches.
3. The proposed controller is implemented in multi-area renewable-integrated thermal and hydro-thermal power systems to evaluate its effectiveness under varying load disturbances and renewable generation fluctuations.
4. The optimization process is formulated using an Integral Time Absolute Error (ITAE) performance index to minimize frequency deviations and tie-line power oscillations.
5. Simulation studies demonstrate that the proposed PSO-based controller significantly reduces overshoot, minimizes settling time, improves damping characteristics, and enhances frequency stability compared with conventional control methods.

6. The proposed approach provides a simple, robust, and computationally efficient solution for modern interconnected power systems with high penetration of renewable energy sources.

3. Test Systems

To evaluate the effectiveness of the proposed PSO-optimized PID controller, two interconnected renewable-integrated power system models are considered. These test systems are selected to analyze the controller performance under varying load disturbances and renewable energy fluctuations.

A. Test System 1

The first test system consists of a two-area interconnected power system with two non-reheat thermal generating units, as shown in Fig. 1. Each control area includes a speed governor, a non-reheat steam turbine, and a generator-load model. The generating capacity of each area is 2000 MW with a nominal load demand of 1000 MW. To represent renewable energy penetration, a solar photovoltaic (PV) unit is connected to Area 1, while a wind power generation unit is integrated into Area 2. The transfer function models and system parameters of the thermal units are adopted from the literature, whereas the renewable energy source models are incorporated to capture the effects of renewable generation variability on system frequency regulation.

B. Test System 2

The second test system is a two-area interconnected hydro-thermal power system comprising four generating units, as depicted in Fig. 2. Each area consists of both thermal and hydro generating plants operating in coordination to satisfy load demand. Similar to Test System 1, renewable energy integration is considered by connecting a solar PV unit to Area 1 and a wind generation unit to Area 2. This configuration provides a more realistic representation of modern power systems with diverse generation resources and varying dynamic characteristics.

The solar and wind generation units are represented using first-order transfer function models. These renewable energy sources introduce additional power fluctuations and uncertainties into the system, making load frequency control more challenging. The proposed PSO-based PID controller is therefore evaluated under these operating conditions to assess its capability in maintaining frequency stability and minimizing tie-line power deviations in renewable-integrated interconnected power systems.

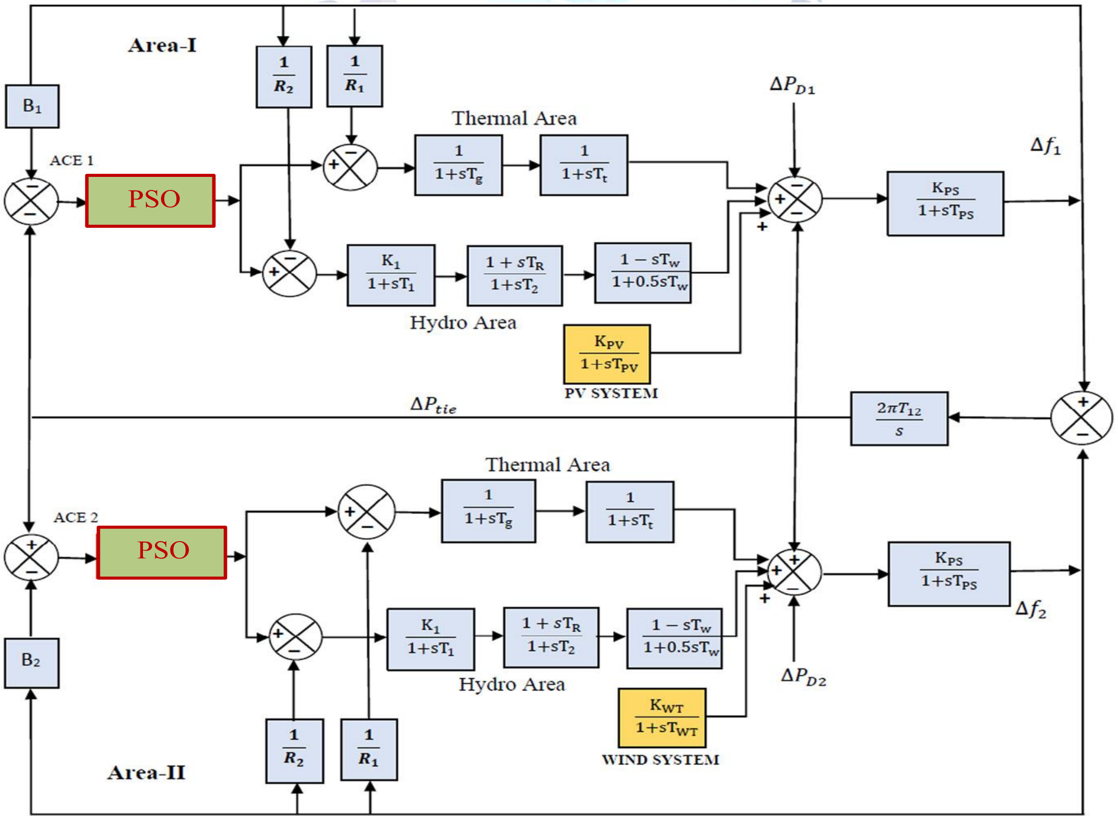


Fig. 1 Proposed PSO optimized PID controlled Two-area four-unit hydro thermal PS with RE sources.

C. Wind Turbine Generator Modelling

The wind turbine generator (WTG) is modeled by combining turbine and generator dynamics. The relationship between wind speed input and output power is given by:

$$T_{wind}\frac{dP_{wind}}{dt} + P_{wind} = K_{wind}V_{wind} \qquad (1)$$

where Pwind is wind power output, Vwind is wind speed, Twind is the time constant, and Kwind is the gain.

Taking Laplace transform:

$$T_{wind}sP_{wind}(s) + P_{wind}(s) = K_{wind}V_{wind}(s) \qquad (2)$$

$$P_{wind}(s)(1 + sT_{wind}) = K_{wind}V_{wind}(s) \qquad (3)$$

The transfer function is obtained as:

$$\frac{P_{wind}(s)}{V_{wind}(s)} = G_{wind}(s) \qquad (4)$$

$$G_{wind}(s) = \frac{K_{wind}}{1+sT_{wind}} \qquad (5)$$

D. Photovoltaic (PV) System Modeling

The PV system is modeled as a first-order system representing the combined dynamics of the PV array, converters, and controller:

$$T_{PV}\frac{dP_{PV}}{dt} + P_{PV} = K_{PV}U_{PV} \qquad (6)$$

where PPV is solar power output, UPV is solar irradiance, TPV is the time constant, and KPV is the gain.

Applying Laplace transform:

$$T_{PV}sP_{PV}(s) + P_{PV}(s) = K_{PV}U_{PV}(s) \qquad (7)$$

$$P_{PV}(s)(1 + sT_{PV}) = K_{PV}U_{PV}(s) \qquad (8)$$

The transfer function is given by:

$$\frac{P_{PV}(s)}{U_{PV}(s)} = G_{PV}(s) \qquad (9)$$

$$G_{PV}(s) = \frac{K_{PV}}{1+sT_{PV}} \qquad (10)$$

E. Existing Controller Structure

This section describes the structure of the existing cascade controller, which combines an integral-derivative controller with filter (1+PDn) and a fractional-order integral (FOPI) controller.

The controller follows a two-loop cascade architecture:

- Inner loop → fast disturbance rejection and precise tracking
- Outer loop → overall system regulation and stability

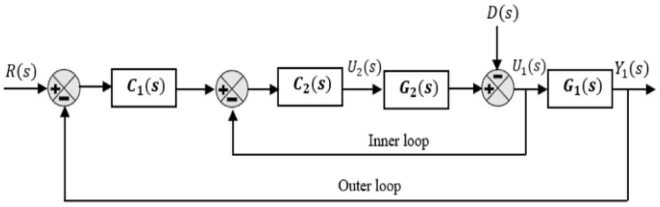
Let:

- R(s): reference input
- D(s): disturbance input
- G1(s),G2(s): plant transfer functions
- C1(s): outer controller
- C2(s): inner controller

F. Closed-Loop System Output

$$Y(s) = \frac{G_1(s)G_2(s)C_1(s)C_2(s)}{1+G_2(s)C_2(s)+G_1(s)G_2(s)C_1(s)C_2(s)}R(s) - \frac{G_1(s)}{1+G_2(s)C_2(s)+G_1(s)G_2(s)C_1(s)C_2(s)}D(s) \quad (11)$$

The structure of the suggested (1+PDn)-FOPI controller, applied to both areas of the PSs under study, is depicted in Fig. 4. In this configuration, the (1+PDn) controller functions as the outer controller $C1(s)$, and the FOPI controller serves as the inner controller $C2(s)$. The ACE signal is input to the cascade (1+PDn)-FOPI controller, where the output of the (1+PDn) controller is subtracted



Fig,2 General structure of close loop cascade controller

G. Objective function

The primary objectives of LFC are to bring the steady-state frequency back to zero and to maintain power transfer at a specified level. These objectives can be accomplished by carefully tuning the controller gains with the most appropriate objective function. Several OFs have been reported in the literature, but ITAE is chosen for its significant advantages, including rapid response, fewer oscillations, and shorter settling time. Other functions, such as IAE, ISE, and ITSE, are also calculated to assess performance and verify the effectiveness of the suggested controller. The expressions for these OFs in a two-area PS are shown below:

$$ITAE = \int_0^t (|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|).t.\,dt \qquad (12)$$

$$ITSE = \int_0^t ((\Delta f_1)^2 + (\Delta f_2)^2 + (\Delta P_{tie})^2).t.\,dt \qquad (13)$$

$$IAE = \int_0^t (|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|).\,dt \qquad (14)$$

$$ISE = \int_0^t ((\Delta f_1)^2 + (\Delta f_2)^2 + (\Delta P_{tie})^2).\,dt \qquad (15)$$

where the frequency deviations in areas 1 and 2 are represented by $\Delta f1$ and $\Delta f2$, respectively, with power deviation denoted as $\Delta P\ tie$ and total simulation time as t. The Optimal performance is achieved at the minimum value of the objective function ITAE, subject to the following constraints:

$$K_{Pi_{min}} < K_{Pi} < K_{Pi_{max}}$$
$$K_{Ii_{min}} < K_{Ii} < K_{Ii_{max}}$$
$$K_{Di_{min}} < K_{Di} < K_{Di_{max}}$$
$$N_{i_{min}} < N_i < N_{i_{max}}$$

$$\lambda_{i_{min}} < \lambda_i < \lambda_{i_{max}}$$
$$\mu_{i_{min}} < \mu_i < \mu_{i_{max}}$$

where min and max denote the minimum and maximum values of the PID, FOPID, PIDDμ, PI-PDn, and PI-(1+DD), and (1+PDn)-FOPI controller gains. In this study, the proportional gain (*KPi*), integral gain (*KIi*), and derivative gain (*KDi*) are set within the range of −1 to 1. The order of differentiation (*μ*) and order of integration (*λ*) are chosen from 0 to 1, while the coefficient 36 *N* ranges from 0 to 200.

4. Proposed Control algorithm of Particle Swarm Optimization

Particle swarm optimization (PSO) is an intelligent evolutionary algorithm inspired by the social behavior of flocking birds or schooling fish. Kennedy and Eberhart presented the PSO approach for the first time in 1997. The PSO algorithm can provide high-quality solutions in less time and with more steady convergence characteristics than other stochastic approaches, such as genetic algorithm.

In an *n*-dimensional space, let the position and individual *i* be represented as vectors Xi = (xi,...,xin) and Vi = (vi,...vin) in a PSO algorithm. Let

$$Pbest_i = \left(x_i^{Pbest}, \ldots\ldots x_{in}^{Pbest}\right) \qquad (17)$$

$$Gbest_i = \left(x_i^{gbest}, \ldots\ldots x_n^{gbest}\right) \qquad (18)$$

Equations (17) and (18) are individual igbest positions so far and their neighbors' best position so far, respectively. Utilizing this information, the PSO algorithm modifies the updated velocity of individual *i* using Equation (19):

$$V - i^k + 1 = \omega V_i^k + c_1 r_1 \times \left(Pbest_i^k - X_i^k\right) + c_2 r_2 \times \left(Gbest_i^k - X_i^k\right) \qquad (19)$$

Where

Vik is the velocity of individual *i* at an iteration *k*;

ω is the inertia weight parameter;

c1,c2 is the acceleration coefficients;

r1,r2 represents the ransom numbers between 0 and 1;

Xik is the position of individual *i* until iteration *k*;

Pbestik is the best position of individual iteration and Gbestik is the position of the group iteration.

The values of c1, c2, and ωω are predetermined and, generally, the weight ωω is shown as in Equation (4):

$$\omega = \omega_{max} - (\omega_{max} - \omega_{min}) \times \frac{iter}{Iter_{max}} \qquad (20)$$

where

ωmax,ωmin are the initial and final weights;

Itermax is the maximum iteration number;

iter is the current iteration number.

The moves from the individual position of the current to the next velocity modified in Equation (3) is shown in Equation (5):

$$Xi^{(k+1)} = Xi^k + Vi^{(k+1)} \qquad (21)$$

PSO's improved PID controller is intended for LFC and tie-power control. The objectives are to manage the frequency and inter-area tie-power with adequate oscillation damping while achieving good performance. The optimal values of the KP, KI, and Kd parameters for a PID controller are quickly and precisely determined in this work utilizing a PSO. In a typical PSO run, an initial population is produced at random. The original population is known as the 0th generation. Each member of the initial population has a unique performance index value. The PSO then generates a new population based on the performance index information. The system must be simulated to acquire the performance index value for each person in the present population. The PSO then uses the reproduction crossover and mutation operators to create the next generation of humans. These methods are continued until the population has converged and the optimal parameter value has been identified. Figure 2 represents a flowchart model of the PSO step-by-step algorithm implementation. We set the parameters for the PSO algorithm, such as the number of particles, maximum iterations, and inertia weight. Then, we set the particle positions and speeds at random inside the search space. We estimate the fitness function for each particle using the LFC problem, and the fitness function should represent the system's performance, such as frequency deviation and tie-line power deviation. Then update each particle's own best position and fitness. We then update the swarm's overall best position and fitness, and the PSO method is used to update the velocity and location of each particle. The new velocity and location should fall inside the scope of the search. This system is repeated until the maximum number of iterations is achieved or a good solution is discovered by using the best control action for the power system to keep frequency and tie-line power variations within acceptable limits.

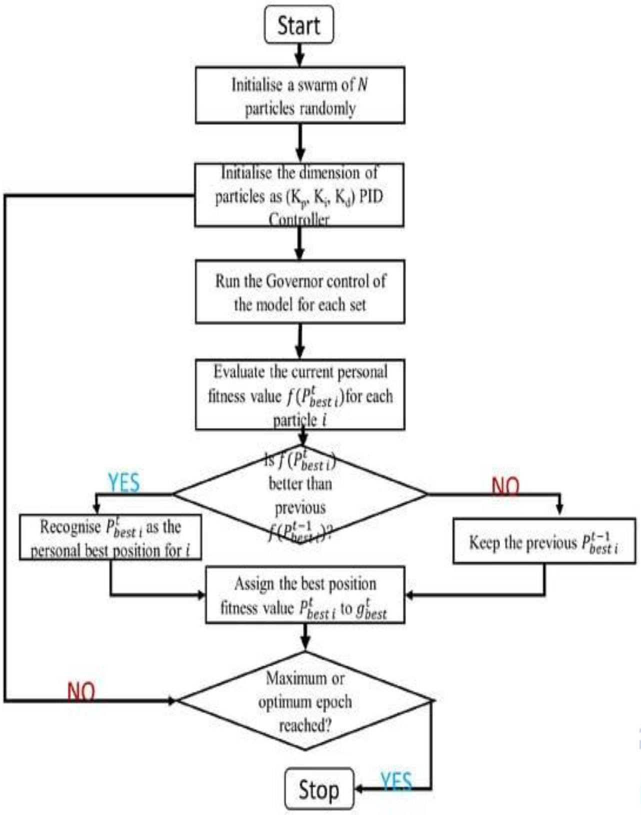


Figure 3. The flow chart model for the PSO-PID algorithm

5. Simulation Results and Discussion

The performance of the proposed PSO-optimized PID controller is evaluated on a renewable-integrated two-area interconnected power system under load disturbance conditions. The controller is designed to minimize frequency deviations and tie-line power oscillations while maintaining overall system stability. The dynamic responses of Area 1 frequency, Area 2 frequency, and tie-line power deviation are presented in Fig. X (a)–Fig. X(c).

a. Frequency Response of Area 1

Fig. 4 illustrates the frequency response of Area 1 under the action of the PSO-optimized PID controller. Following the disturbance, a small transient overshoot is observed, after which the frequency rapidly converges to its nominal value of 50 Hz. The oscillations are well damped and disappear within a short period, indicating effective frequency regulation. The fast settling behavior demonstrates the capability of the PSO algorithm to optimally tune the PID parameters for improved dynamic performance.

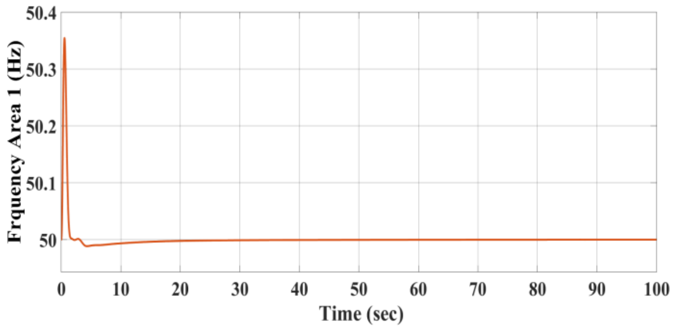


Fig.4 Area 1 Frequency Deviation Response (Δf1)

b. Frequency Response of Area 2

The frequency response of Area 2 is shown in Fig. 5. Similar to Area 1, the frequency experiences a brief transient deviation immediately after the disturbance. The controller effectively suppresses oscillations and restores the frequency to its nominal value with minimal settling time. The smooth and stable response confirms the robustness of the proposed control strategy under varying operating conditions and renewable power fluctuations.

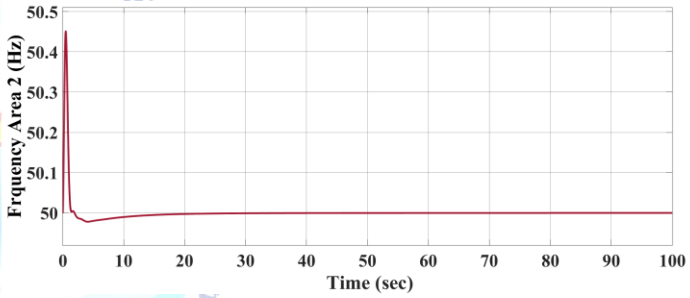


Fig.5 Area 2 Frequency Deviation Response (Δf2)

c. Tie-Line Power Response

Fig. 6 presents the tie-line power deviation between the interconnected areas. A transient deviation occurs immediately after the disturbance due to the power imbalance between the areas. However, the PSO-optimized PID controller rapidly damps the oscillations and drives the tie-line power deviation to zero. The quick restoration of scheduled power exchange demonstrates efficient coordination between the interconnected areas and improved system stability.

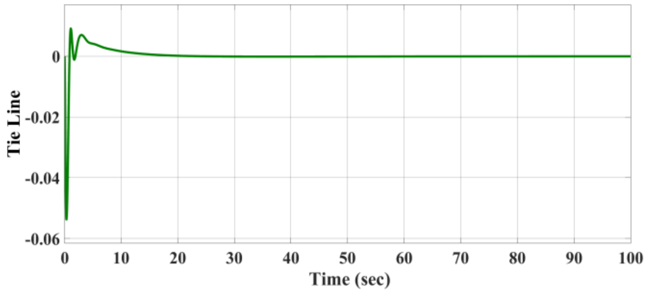


Fig.6 Tie-Line Power Deviation (ΔPtie)

To validate the effectiveness of the proposed PSO-optimized PID controller, its performance is compared with the existing (1+PDn)-FOPI controller under identical operating conditions. The comparison is carried out in terms of Area 1 frequency response, Area 2 frequency response, and tie-line power deviation. The obtained results are presented in Fig. X (a)–Fig. X(c).

B. Comparative results of the existing (1+PDn)-FOPI controller and the proposed PSO-optimized PID controller

a. Area 1 Frequency Response Comparison

Fig. 7 shows the frequency response of Area 1 for both controllers. It can be observed that the conventional (1+PDn)-FOPI controller exhibits a larger overshoot and noticeable oscillations before reaching the nominal frequency. In contrast, the proposed PSO-optimized PID controller significantly reduces the overshoot and suppresses oscillations, enabling the system frequency to settle more rapidly at 50 Hz. The improved damping characteristics demonstrate the effectiveness of PSO in determining optimal controller parameters.

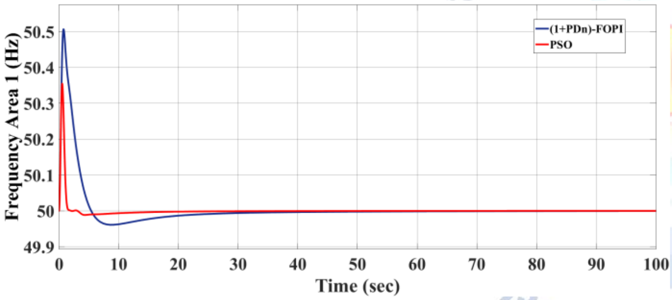


Fig.7. Comparative Area 1 Frequency Response of (1+PDn)-FOPI and PSO-Optimized PID Controllers.

b. Area 2 Frequency Response Comparison

The frequency response of Area 2 is illustrated in Fig. 8. Similar to Area 1, the (1+PDn)-FOPI controller experiences larger transient deviations and a longer settling period. The PSO-based PID controller provides a smoother response with reduced undershoot and faster restoration of the nominal frequency. The results indicate enhanced robustness and improved frequency regulation capability under renewable generation fluctuations and load disturbances.

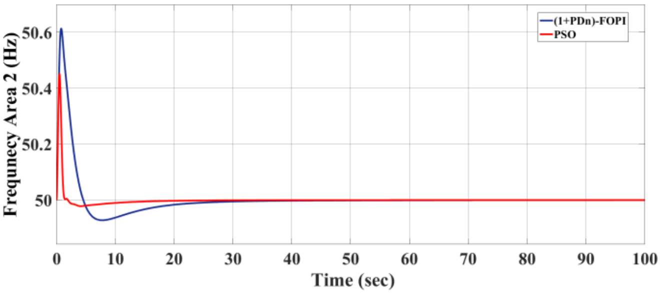


Fig. 8. Comparative Area 2 Frequency Response of (1+PDn)-FOPI and PSO-Optimized PID Controllers.

c. Tie-Line Power Deviation Comparison

Fig. 9 presents the tie-line power deviation response between the interconnected areas. The (1+PDn)-FOPI controller produces larger oscillations and requires a longer time to restore the scheduled tie-line power exchange. Conversely, the proposed PSO-optimized PID controller effectively minimizes the magnitude of tie-line power fluctuations and rapidly damps the oscillations. This behavior ensures improved coordination between control areas and enhances the overall stability of the interconnected system. The comparative results clearly demonstrate the superiority of the proposed PSO-optimized PID controller over the existing (1+PDn)-FOPI controller. The PSO-based controller achieves lower frequency deviations, reduced overshoot and undershoots, faster settling times, and improved damping characteristics in both control areas. Furthermore, tie-line power oscillations are significantly minimized, ensuring stable power exchange between interconnected regions. These improvements are achieved through the efficient optimization capability of the Particle Swarm Optimization algorithm, which identifies optimal PID gains for varying operating conditions. Therefore, the proposed PSO-optimized PID controller provides an effective and computationally efficient solution for load frequency control in renewable-integrated interconnected power systems.

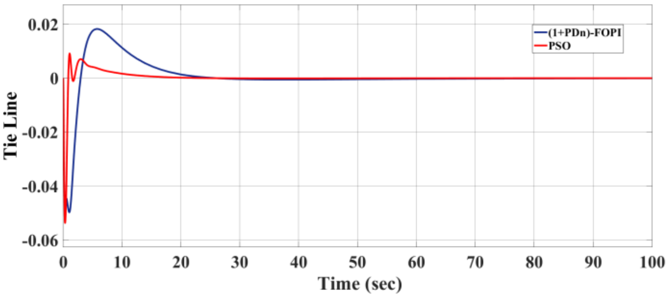


Fig. 9 Comparative Tie-Line Power Deviation Response of (1+PDn)-FOPI and PSO-Optimized PID Controllers.

7. Conclusion

This paper presented a Particle Swarm Optimization (PSO)-based PID controller for enhanced Load Frequency Control (LFC) of renewable-integrated interconnected power systems. The proposed approach was developed to address the challenges associated with frequency regulation in modern power systems characterized by renewable energy penetration, load uncertainties, and dynamic operating conditions. By employing PSO for optimal tuning of PID controller parameters, the proposed method effectively improved system dynamic performance while maintaining computational simplicity. The controller was evaluated on renewable-integrated multi-area power systems under various disturbance scenarios. Simulation results demonstrated that the proposed PSO-optimized PID controller successfully minimized frequency deviations in both control areas and significantly reduced tie-line power oscillations. The system exhibited improved damping characteristics, lower overshoot and undershoot, and faster settling times compared with the existing (1+PDn)-FOPI controller. Furthermore, the optimized controller maintained stable operation despite renewable energy fluctuations and load variations, highlighting its robustness and reliability. Comparative analysis confirmed that the PSO-based controller provides superior frequency regulation performance while requiring lower computational effort than more complex optimization techniques. The fast convergence capability of PSO enables efficient determination of optimal controller gains, leading to enhanced overall system stability and improved power system reliability. Therefore, the proposed PSO-optimized PID controller offers a simple, robust, and computationally efficient solution for load frequency control in renewable-integrated interconnected power systems and represents a promising approach for future smart grid and renewable energy applications.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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