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Optimization of Automatic Generation Control in Interconnected Power System using PSO - Enhanced PID Controller

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Automatic Generation Control, Two-Area Interconnected Power System, Particle Swarm Optimization, PID Controller with Derivative Filter (PIDm,; Frequency Regulation, Tie-Line Power Control, Area Control Error, Optimization Techniques

ABSTRACT

Automatic Generation Control (AGC) plays a vital role in maintaining system frequency and scheduled tie-line power flow in interconnected power systems under varying load conditions. In this paper, a robust AGC strategy for a two-area interconnected power system is proposed using a Particle Swarm Optimization (PSO)–based controller tuning approach. A proportional–integral–derivative controller with derivative filtering (PIDm) is employed to mitigate the adverse effects of load disturbances and measurement noise. The controller parameters are optimally tuned by minimizing a multi-objective performance index formulated as a weighted combination of the integral of time multiplied absolute error (ITAE) of frequency deviations, tie-line power deviations, and area control errors (ACEs). The PSO algorithm is utilized due to its fast convergence, simplicity, and strong global search capability, enabling effective optimization of the controller gains. The performance of the proposed PSO-tuned PIDm controller is evaluated under various load disturbance scenarios to validate its robustness and dynamic response characteristics. Simulation results demonstrate significant improvements in frequency regulation, tie-line power stabilization, and reduced settling time compared to conventional and existing optimization-based AGC controllers. Statistical analysis further confirms the superiority and reliability of the proposed PSO-based AGC approach, proving its effectiveness for enhancing stability and operational performance in two-area interconnected power systems.

1. INTRODUCTION

The rapid growth of electrical power demand, coupled with the increasing interconnection of large-scale power systems, has made maintaining system stability a major challenge for modern utilities. Among the various stability issues, frequency regulation and tie-line power control are of paramount importance for ensuring secure and reliable power system operation. Any imbalance between power generation and load demand results in frequency deviations, which, if not corrected promptly, may lead to system instability, equipment damage, or even large-scale blackouts [1], [2]. To address these challenges, Automatic Generation Control (AGC) is employed as a secondary control mechanism to restore system frequency and scheduled tie-line power exchanges to their nominal values following load disturbances. In interconnected power systems, AGC operates by continuously monitoring frequency deviations and tie-line power flows and adjusting generator outputs accordingly. The primary objective of AGC is to minimize Area Control Error (ACE), which is a linear combination of frequency deviation and tie-line power deviation for each control area [3], [4]. Traditional AGC schemes were initially implemented using conventional proportional–integral (PI) controllers, owing to their simple structure and ease of implementation [5]. However, conventional PI-based AGC controllers often exhibit poor dynamic performance under nonlinearities, parameter uncertainties, and varying operating conditions [6]. With the increasing penetration of complex loads, nonlinear components, and renewable energy sources, the limitations of conventional control strategies have become more evident. Power systems are inherently nonlinear and time-varying, and fixed-gain controllers fail to provide satisfactory performance under wide-ranging disturbances [7], [8]. To overcome these drawbacks, advanced control strategies such as PID controllers, fractional-order controllers, robust control, and intelligent control techniques have been proposed for AGC applications [9]–[11]. Among these, PID controllers remain widely used in practical power systems due to their flexibility and effectiveness in improving transient response [12]. Despite their advantages, PID controllers are sensitive to noise, particularly in the derivative term. To mitigate this issue, PID controllers with derivative filtering (PIDm) have been introduced, where a low-pass filter is added to the derivative action to suppress high-frequency noise while retaining the benefits of derivative control [13], [14]. Proper tuning of PIDm controller parameters is crucial for achieving optimal AGC performance. However, analytical tuning methods often fail to deliver optimal results due to the nonlinear and multi-objective nature of the AGC problem [15]. In recent years, optimization-based tuning techniques have gained significant attention in AGC research. Metaheuristic algorithms such as Genetic algorithm [16] bacteria foraging optimization [17], gravitational search algorithm [18], grey wolf optimizer (GWO) [19], whale optimization [20], bat algorithm [21], firefly algorithm [22]. These methods provide better global search capability and can handle complex, nonlinear objective functions. However, many of these algorithms suffer from drawbacks such as high computational complexity, slow convergence, and dependence on algorithm-specific parameters [23]. Among various metaheuristic optimization techniques, Particle Swarm Optimization (PSO) has emerged as a powerful and efficient algorithm inspired by the social behavior of birds and fish schools [24]. PSO offers several advantages, including simple implementation, fast convergence, fewer tuning parameters, and strong global optimization capability. Due to these features, PSO has been successfully applied to numerous power system optimization problems, such as economic load dispatch, unit commitment, and controller tuning [25], [26]. Nevertheless, its potential for optimizing PIDm controllers in AGC applications continues to be an active research area. In AGC design, the choice of the objective function plays a critical role in determining controller performance. Performance indices such as Integral of Absolute Error (IAE), Integral of Squared Error (ISE), Integral of Time multiplied Squared Error (ITSE), and Integral of Time multiplied Absolute Error (ITAE) are commonly employed [27]. Among these, ITAE is widely preferred in AGC studies because it penalizes prolonged oscillations and ensures faster settling with minimal overshoot. Therefore, a multi-objective ITAE-based performance function incorporating frequency deviations, tie-line power deviations, and ACEs provides a comprehensive assessment of AGC performance. Motivated by the above discussions, this paper proposes a PSO-based PIDm controller for AGC of a two-area interconnected power system. The PSO algorithm is employed to optimally tune the controller parameters by minimizing a composite ITAE-based objective function. The proposed approach aims to enhance frequency regulation, reduce tie-line power oscillations, and improve overall system stability under various load disturbance scenarios. The effectiveness of the proposed method is validated through extensive simulation studies and comparative analysis with existing optimization-based AGC techniques.

2.POWER SYSTEM

An electric power system consists of various electrical components used for the generation, transmission, and distribution of electrical energy. Electric power is generated by interconnected generating units to meet the continuously varying load demand and is transmitted through transmission lines to consumers while maintaining rated voltage and frequency. Power generation sources are broadly classified into conventional and non-conventional resources. Conventional resources include coal, gas, nuclear, and hydroelectric power plants, whereas non-conventional resources such as solar, wind, biomass, tidal, and wave energy are increasingly integrated into modern power systems. In all generating stations, the primary energy source is first converted into mechanical energy, which is then transformed into electrical energy using synchronous generators. The generated power is transmitted over long distances to distribution substations, from where it is supplied to industrial, commercial, and residential consumers. Load demand varies continuously, and any mismatch between generation and demand results in frequency deviations. In a single-area power system, an increase in load demand is met by increasing generator output or by utilizing the stored kinetic energy of rotating machines. In contrast, a multi-area interconnected power system utilizes tie-lines to exchange power between neighboring areas, thereby reducing the stress on individual generating units and improving system reliability and stability.

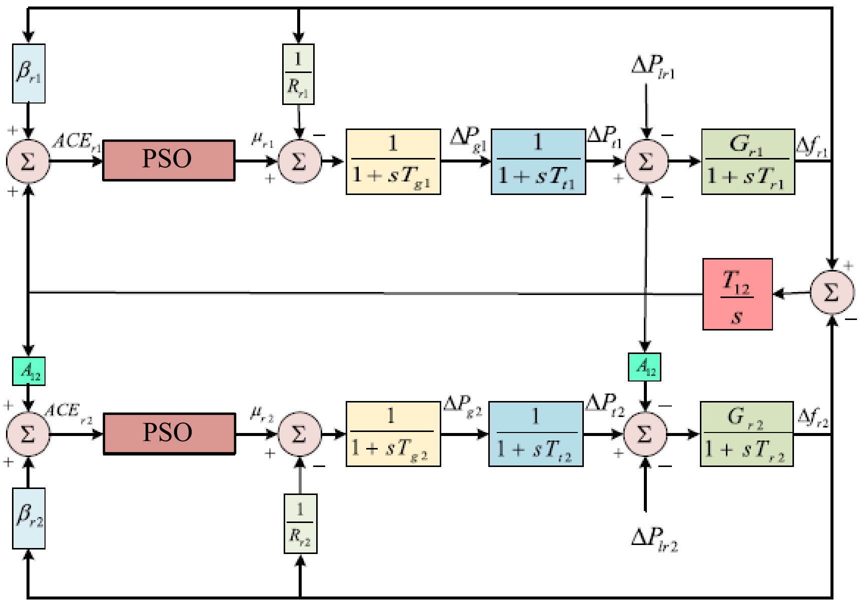


Fig 1. Interconnected PSO controlled power system of two-area.

A. Power System Model under Investigation

In this work, a two-area interconnected thermal power system is considered for automatic generation control analysis. The system configuration and parameters are adopted from a standard benchmark model reported in the literature. Each control area consists of a thermal power plant with a generation capacity of 2000 MW and a nominal load of 1000 MW, forming a realistically interconnected system. The frequency deviations in areas 1 and 2 are denoted by Δfr1 and Δfr2, respectively. The area control errors are represented by ACEr1 and ACEr2, while βr1 and βr2 denote the frequency bias factors. The governor control inputs are μr1 and μr2. The governor speed regulation constants are Rr1 and Rr2.

The governor and turbine dynamics are characterized by the time constants Tg1 and Tg2 for the governors and Tt1 and Tt2 for the turbines. The gains of the power system models are represented by Gr1 and Gr2, and the power system time constants are Tr1 and Tr2. The governor power deviations are represented by ΔPg1 and ΔPg2, while the turbine power deviations are denoted by ΔPt1 and ΔPt2. The load disturbances in areas 1 and 2 are represented by ΔPLr1 and ΔPLr2, respectively. The deviation in tie-line power flow between the two interconnected areas is denoted by ΔPtl.

B. PIDm Controller's Configuration

The proportional–integral–derivative controller is widely preferred in industrial control applications due to its simple structure, ease of tuning, and straightforward implementation. In this work, the standard PID controller structure adopted from the literature is used, as shown in Fig. 2. The PID control scheme consists of three control actions, namely proportional, integral, and derivative components, which together generate the manipulated variable. These control gains are denoted by φp, φi, and φd, respectively.

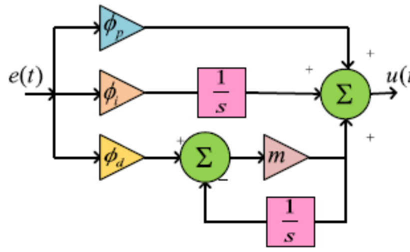


Fig 2. Configuration of controller.

The output of the PID controller is expressed as

$$u(t) = \phi_p e(t) + \phi_i \int_0^t e(t) \cdot dt + \phi_d \frac{d}{dt} e(t) \qquad (1)$$

where $u(t)$ represents the controller output and $e(t)$ denotes the error signal.

For optimal dynamic performance, appropriate tuning of the controller parameters is essential. However, the derivative term is highly sensitive to measurement noise present in the input signal. To alleviate this issue, a low-pass filter is incorporated with the derivative term, resulting in a *PID* controller with derivative filtering, commonly referred to as a *PIDm* controller. The frequency-domain representation of the PIDm controller is given by

$$TF_{PIDm} = \phi_p + \phi_i \left(\frac{1}{s}\right) + \phi_d \left(\frac{1}{\frac{1}{m}+\frac{1}{s}}\right) \qquad (2)$$

Where m denotes the derivative filter coefficient.

In the automatic generation control scheme, the area control errors of areas 1 and 2, denoted by ACEr1 and ACEr2, respectively, serve as the input signals to the controllers. These area control errors are defined as where βr1 and βr2 are the frequency bias factors of areas 1 and 2, respectively. The synchronizing coefficient A12 is taken as −1. This *PIDm* control structure effectively enhances frequency regulation and suppresses tie-line power oscillations by reducing the influence of noise while maintaining fast and stable system response.

3. PROBLEM FORMULATION

Sudden variations in load demand significantly affect the operating conditions of a power system, particularly the generator voltage and system frequency. With continuous growth in load demand and the large-scale integration of renewable energy sources, the structure of modern power systems has become increasingly complex. This increased complexity makes it challenging to maintain system reliability, continuity of power supply, and stable operation under dynamic conditions. Automatic Generation Control (AGC) plays a crucial role in overcoming these challenges by regulating system frequency and controlling tie-line power exchanges among interconnected areas. The primary objective of AGC is to minimize frequency deviations and area control errors (ACE) while ensuring secure and reliable power flow in a multi-area interconnected power system. For effective AGC operation, the parameters of the *PIDm* controller shown in Fig. 2 must be optimally tuned within permissible ranges. Therefore, the formulation of a suitable objective function is essential to obtain the best possible controller parameters under load disturbances.

A. Formulation of Objective Function

The deviations in system frequency, tie-line power, and area control errors are regulated by the controller based on the corresponding error signals. Several performance indices such as Integral of Squared Error (ISE) [22], Integral of Absolute Error (IAE), and Integral of Time multiplied Squared Error (ITSE), and Integral of Time multiplied Absolute Error (ITAE) can be used for controller performance evaluation. In this work, the ITAE criterion is selected because it provides better damping characteristics by penalizing prolonged oscillations and ensuring faster settling time. The individual objective functions considered for minimization are defined as follows:

Frequency deviation objective:

$$\phi_1 = \int_0^{\tau_\delta} t|\Delta f_{r1}(t)|\, dt + \int_0^{\tau_\delta} t|\Delta f_{r2}(t)|\, dt \quad (3)$$

Tie-line power deviation objective:

$$\phi_2 = \int_0^{\tau_\delta} t|\Delta P_{tl}(t)|dt \quad (4)$$

Area control error objective:

$$\phi_3 = \int_0^{\tau_\delta} t|ACE_{r_1}(t)|\, dt + \int_0^{\tau_\delta} t|ACE_{r_2}(t)|\, dt \quad (5)$$

Where τs represents the total simulation time. The objective functions ϕ1, ϕ2, and ϕ3 correspond to ITAE-based measures of frequency deviations, tie-line power fluctuations, and area control errors, respectively. The overall objective function is formulated as a weighted sum of these individual objectives:

$$\phi(\phi_1, \phi_2, \phi_3) = \delta_1\phi_1 + \delta_2\phi_2 + \delta_3\phi_3 \quad (6)$$

Substituting (5)–(7) into (8), the complete objective function is obtained as

$$\phi = \delta_1\left(\int_0^{\tau_\delta} t|\Delta f_{r1}(t)|\, dt + \int_0^{\tau_\delta} t|\Delta f_{r2}(t)|\, dt\right) + \delta_2 \int_0^{\tau_\delta} t\,|\Delta P_{tl}(t)|dt + \delta_3\left(\int_0^{\tau_\delta} t|ACE_{r1}(t)|\, dt + \int_0^{\tau_\delta} t|ACE_{r2}(t)|\, dt\right) \quad (7)$$

where δ1, δ2, and δ3 are weighting factors that represent the relative importance of frequency deviation, tie-line power deviation, and area control error, respectively.

IV. PARTICLE SWARM OPTIMIZATION (PSO)

Particle Swarm Optimization (PSO) is a population-based stochastic optimization technique inspired by the collective social behavior of bird flocks and fish schools. In PSO, a group of candidate solutions, called particles, explores the search space to find the optimal solution by sharing information among themselves. Each particle adjusts its trajectory based on its own experience and the experience of the entire swarm. Due to its simple structure, fast convergence, and strong global search capability, PSO is widely applied to controller tuning problems in power systems.

A. Particle Representation

In the proposed AGC problem, each particle represents a candidate solution consisting of the *PIDm* controller parameters. The position vector of the *i*-th particle is defined as

$$x_i = [\phi_p \quad \phi_i \quad \phi_d \quad m] \quad (8)$$

where ϕp, ϕi, and ϕd are the proportional, integral, and derivative gains of the PID controller, respectively, and m is the derivative filter coefficient.

B. Initialization

Initially, a swarm of particles is generated randomly within predefined upper and lower bounds of the controller parameters. The initial position and velocity of each particle are given by

$$x_i(0) = x_i^{\min} + r\left(x_i^{\max} - x_i^{\min}\right) \quad (9)$$

$$v_i(0) = v_i^{\min} + r\left(v_i^{\max} - v_i^{\min}\right) \quad (10)$$

Where r∈[0,1] is a uniformly distributed random number.

C. Objective Function

The performance of each particle is evaluated using an objective function based on the Integral of Time multiplied Absolute Error (ITAE) criterion. The ITAE index penalizes sustained oscillations and ensures faster settling with reduced overshoot. The objective function is defined as

$$J = \int_0^T t(|\Delta f_{r1}(t)| + |\Delta f_{r2}(t)| + |\Delta P_{tl}(t)| + |ACE_{r1}(t)| + |ACE_{r2}(t)|)dt \quad (11)$$

The optimization goal is

Min J

D. Personal Best and Global Best

Each particle stores its best position achieved so far, known as the personal best and denoted by pbesti. The personal best is updated as

$$pbest_i = \arg\min\left(J_i^k, J_i^{k-1}\right) \quad (12)$$

The best solution among all particles is called the global best and is defined as

$$gbest = \arg\min_i \, (J_i)$$

$$gbest = \arg\min(J_i) \quad (13)$$

E. Velocity Update Equation

The velocity of each particle is updated by considering its previous velocity, the distance from its personal best, and the distance from the global best. The velocity update equation is expressed as

$$v_i^{k+1} = wv_i^k + c_1r_1\left(pbest_i - x_i^k\right) + c_2r_2\left(gbest - x_i^k\right)$$

(14)

Where

w is the inertia weight controlling exploration and exploitation, c1 and c2 are the cognitive and social acceleration coefficients, r1 and r2∈ [0,1] are random numbers.

F. Position Update Equation

The position of each particle is updated using

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (15)$$

To ensure feasible solutions, boundary constraints are applied as

$$x_i^{k+1} = \begin{cases} x_i^{max}, & x_i^{k+1} > x_i^{max} \\ x_i^{min}, & x_i^{k+1} < x_i^{min} \\ x_i^{k+1}, & otherwise \end{cases} \quad (16)$$

G. Inertia Weight Adaptation

To improve convergence behavior, the inertia weight is linearly decreased during the optimization process according to

$$w(k) = w_{\max} - \left(\frac{w_{\max} - w_{\min}}{k_{\max}}\right) k \quad (17)$$

where $k_{\max}$ is the maximum number of iterations.

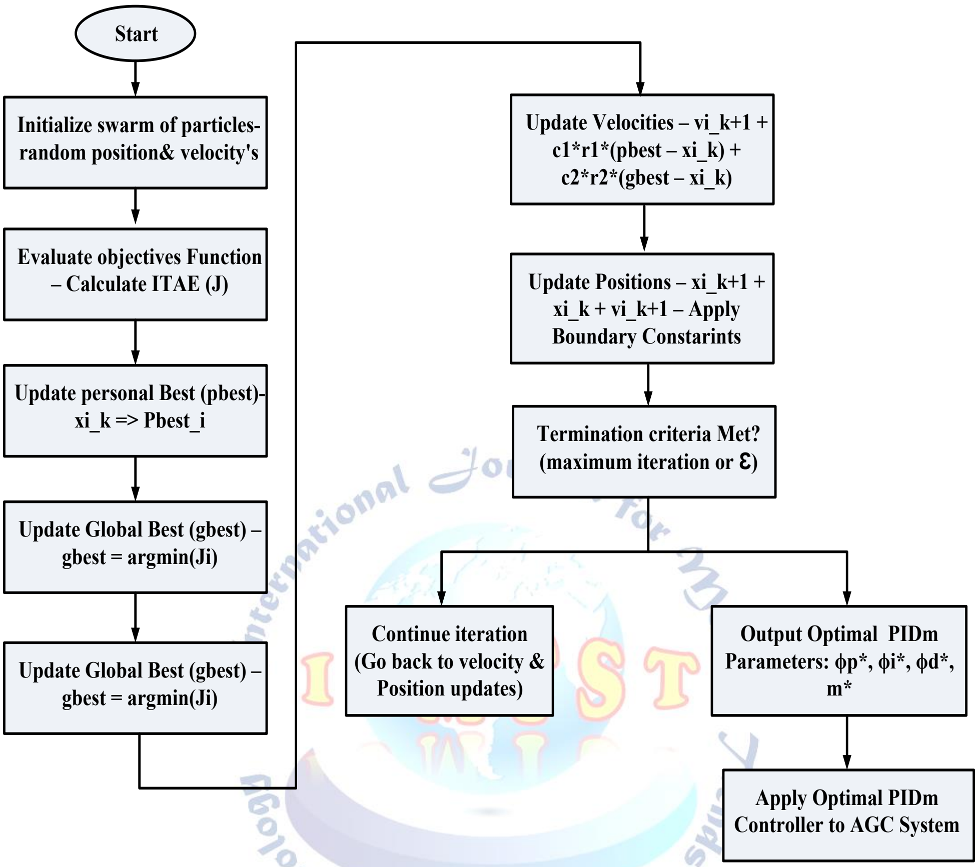


Fig.3 Flow chart for PSO algorithm

H. Termination Criterion

The PSO algorithm is terminated when either the maximum number of iterations is reached or the improvement in the objective function becomes negligible, defined as

$$k = k_{\max} \quad \text{or} \quad |J^{k+1} - J^k| < \varepsilon \quad (18)$$

I. Optimal Controller Parameters

The optimal PIDm controller parameters are obtained from the global best solution as

$$[\phi_p^* \ \phi_i^* \ \phi_d^* \ m^*] = gbest \quad (19)$$

These optimized parameters are then applied to the AGC system to achieve improved frequency regulation and tie-line power control under varying load disturbances.

5. SIMULATION RESULTS AND DISCUSSION

The effectiveness of the proposed PSO-enhanced *PIDm* controller for Automatic Generation Control (AGC) is validated through extensive MATLAB/Simulink simulations on a two-area interconnected power system. To clearly demonstrate the impact of optimization, the system performance is first evaluated using a conventional *PIDm* controller with fixed parameters. Subsequently, the *PIDm* controller is optimally tuned using the Particle Swarm Optimization (PSO) algorithm, and the results are compared.

A. Test System and Simulation Conditions

The simulated system consists of two identical thermal power generation areas interconnected through a tie-line. Each area includes governor, turbine, generator, and load dynamics. The nominal system frequency is maintained at 50 Hz. Area Control Error (ACE) signals are used as control inputs to the AGC controllers. A step load disturbance of 0.01 p.u. is applied in Area-1, while Area-2 remains unchanged, allowing the evaluation of dynamic interactions and tie-line power behavior.

B. Performance of Conventional PIDm Controller

Initially, the AGC system is tested using a conventional *PIDm* controller with manually tuned parameters. The frequency deviation responses of Area-1 (Δf_1) and Area-2 (Δf_2) indicate that although the *PIDm* controller restores system frequency, the response is characterized by significant oscillations and a prolonged settling time. The peak frequency deviation is relatively high, and the system takes a longer duration to reach steady-state conditions. Additionally, the tie-line power deviation (ΔP_{tl}) exhibits noticeable oscillatory behavior before stabilizing as shown in Fig.4. The ACE responses in both areas also show slow convergence to zero, indicating delayed power balance restoration. These results clearly demonstrate that the conventional *PIDm* controller is not sufficient to provide optimal AGC performance under sudden load disturbances.

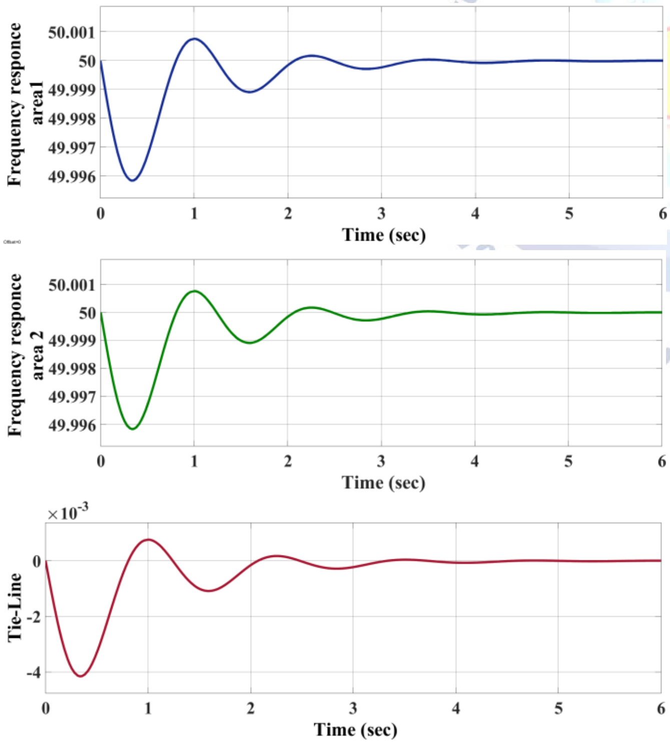


Fig.4 simulation results of *PIDm* controlled power system of two-area

C. Performance of PSO-Tuned PIDm Controller

To overcome the limitations of fixed-parameter control, the *PIDm* controller gains are optimized using the Particle Swarm Optimization algorithm. The PSO minimizes an ITAE-based multi-objective function considering frequency deviations, tie-line power deviations, and ACEs of both areas. The frequency responses obtained with the PSO-tuned *PIDm* controller show a remarkable improvement over the conventional *PIDm* controller. The maximum frequency deviation is significantly reduced, and oscillations are effectively damped as shown in Fig.5. Most importantly, the settling time is considerably shorter, indicating faster dynamic response and improved system stability.

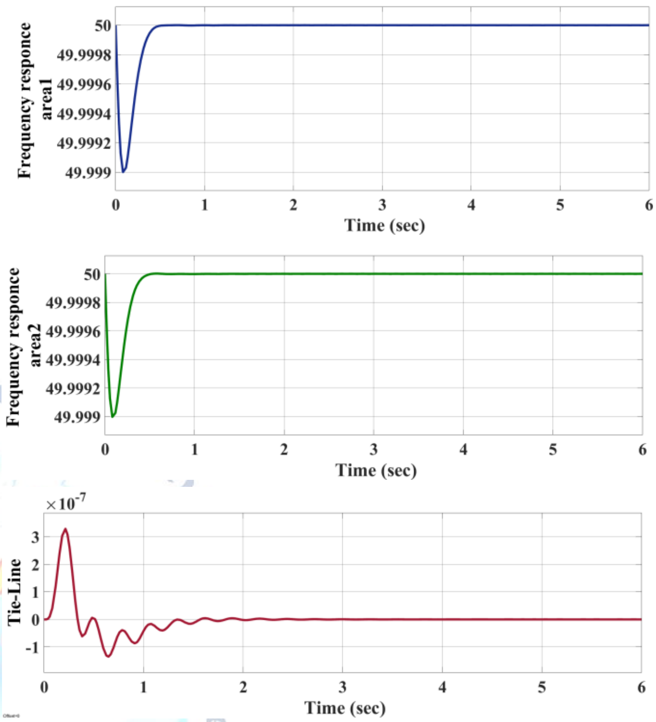
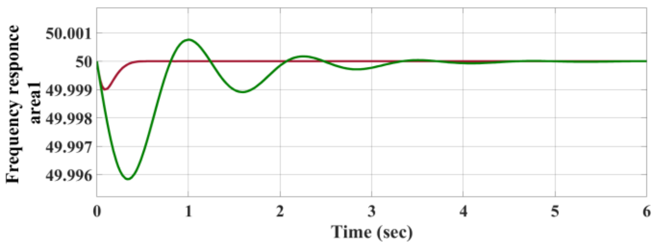


Fig.5 simulation results of PSO controlled power system of two-area

D. Comparative and Statistical Analysis

A quantitative comparison based on performance indices such as ITAE, IAE, peak overshoot, and settling time confirms the superiority of the PSO-based *PIDm* controller. The optimized controller yields significantly lower ITAE values and reduced settling times than the conventional *PIDm* controller. Repeated simulation runs further validate the consistency and robustness of the PSO-tuned controller under varying operating conditions.



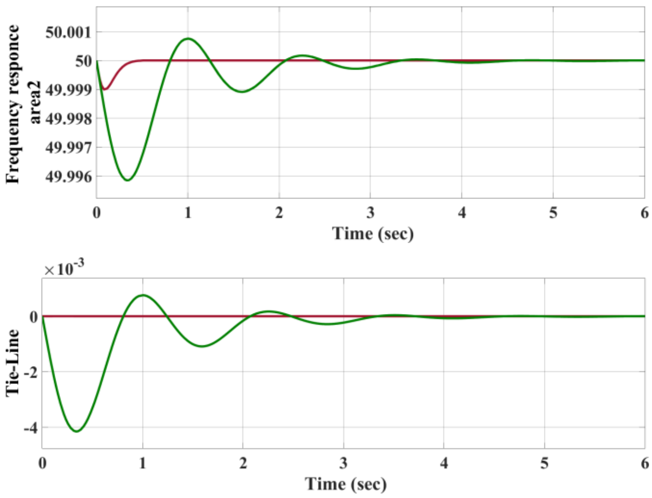


Fig.6 Comparison simulation results of PI & ANN controlled power system of two-area

From the simulation results, it is evident that the conventional *PIDm* controller fails to provide optimal AGC performance due to fixed gain settings, resulting in higher oscillations and delayed settling of frequency and tie-line power responses. In contrast, the PSO-enhanced *PIDm* controller effectively adapts the controller parameters, leading to superior damping characteristics, faster frequency recovery, and improved tie-line power regulation as shown in Fig.6. The results clearly demonstrate that PSO-based optimization significantly enhances AGC performance and provides a robust and reliable solution for interconnected power systems subjected to load disturbances.

6. CONCLUSION

This work presented an optimized Automatic Generation Control (AGC) scheme for a two-area interconnected power system using a Particle Swarm Optimization (PSO)–tuned PID controller with derivative filtering (*PIDm*). The main objective was to improve frequency regulation and tie-line power control under load disturbances while achieving faster dynamic response and enhanced system stability. Simulation studies were initially carried out using a conventional *PIDm* controller with fixed parameters. The results showed that although the *PIDm* controller was able to regulate system frequency, it suffered from larger oscillations and longer settling time in both frequency and tie-line power responses. These limitations highlight the drawbacks of manual tuning and fixed-gain control in interconnected power systems operating under varying load conditions. To overcome these issues, the PIDm controller parameters were optimally tuned using the PSO algorithm based on an ITAE performance criterion. The PSO-tuned PIDm controller demonstrated significant improvements by effectively reducing frequency deviations, suppressing oscillations, and achieving faster settling of system responses. The tie-line power deviations and Area Control Errors (ACEs) were also restored to their scheduled values more quickly and smoothly. Overall, the simulation results confirm that the PSO-based *PIDm* controller provides superior AGC performance compared to the conventional *PIDm* approach. The proposed method offers a robust and efficient solution for interconnected power systems and can be effectively applied to enhance system stability and operational performance under varying load disturbances.

Conflict of interest statement

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

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