International Journal for Modern Trends in Science and Technology
Volume 11, Issue 09, pages 258-266.
ISSN: 2455-3778 online
Available online at: http://www.ijmtst.com/vol11issue09.html
DOI: https://doi.org/10.5281/zenodo.18133881

Artificial Intelligence - Based Optimization for Automatic Generation Control in a Hybrid PV and Reheat Thermal Power System

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To Cite this Article
Dr. J. Srinu Naick, M.Babu, K. Reddy Rani, P.Lavanya & E. Lokesh (2025). Artificial Intelligence - Based Optimization for Automatic Generation Control in a Hybrid PV and Reheat Thermal Power System. International Journal for Modern Trends in Science and Technology, 11(09), 258-266. https://doi.org/10.5281/zenodo.18133881

Article Info
Received: 02 September 2025; Accepted: 28 September 2025.; Published: 30 September 2025.

KEYWORDS

Automatic Generation Control, Artificial Neural Network, Hybrid Power System, Photovoltaic System, Reheat Thermal Power Plant, Frequency Regulation, Tie-Line Power Control, Intelligent Control, Renewable Energy Integration, Power System Stability.

ABSTRACT

This paper presents an artificial intelligence–based control strategy for Automatic Generation Control (AGC) of a two-area hybrid power system comprising a photovoltaic (PV) source and a reheat thermal power plant. The increasing penetration of renewable energy sources and continuous load variations introduce significant uncertainties, making conventional controller-based AGC approaches less effective. To address these challenges, an Artificial Neural Network (ANN) controller is proposed to enhance frequency regulation and tie-line power control under dynamic operating conditions. The ANN controller is trained to capture the nonlinear behavior of the hybrid power system and to generate optimal control actions in response to load disturbances and renewable power fluctuations. The performance of the proposed ANN-based AGC scheme is evaluated under various scenarios, including step load changes in individual areas, simultaneous load disturbances, and parameter uncertainties. Simulation results demonstrate that the ANN controller provides superior dynamic performance compared to conventional PI and optimization-based controllers reported in the literature, achieving reduced frequency deviations, lower overshoot, faster settling time, and improved damping characteristics. The proposed approach confirms the effectiveness of artificial intelligence techniques in improving the reliability and robustness of AGC in complex hybrid PV–thermal power systems.

1. INTRODUCTION

The rapid growth in electrical energy demand, coupled with the large-scale integration of renewable energy sources (RESs), has significantly increased the complexity of modern power systems. Maintaining system stability and reliability under such conditions is a major challenge for power system operators. Among the various stability issues, frequency regulation remains one of the most critical aspects, as even small deviations in system frequency can adversely affect power quality, equipment lifespan, and overall system security. Automatic Generation Control (AGC) plays a vital role in maintaining the balance between generation and load by regulating system frequency and tie-line power exchanges in interconnected power systems [1]–[3]. Traditionally, AGC has been implemented using classical control strategies such as proportional-integral (PI) and proportional-integral-derivative (PID) controllers due to their simplicity and ease of implementation [4], [5]. These controllers are usually designed based on linearized system models and fixed operating conditions. However, modern power systems are increasingly characterized by nonlinear dynamics, parameter uncertainties, load fluctuations, and intermittent renewable generation, which significantly degrade the performance of conventional controllers [6], [7]. As a result, fixed-gain PI/PID controllers often exhibit higher overshoot, longer settling times, and poor damping characteristics when subjected to sudden load disturbances and renewable power variations [8]. The integration of photovoltaic (PV) power systems into conventional thermal power plants has emerged as a promising solution to reduce greenhouse gas emissions and dependence on fossil fuels [9], [10]. However, PV systems introduce additional challenges in AGC operation due to their inherent intermittency, dependency on environmental conditions, and lack of inertia [11]. In hybrid PV–thermal power systems, rapid changes in solar irradiance can cause power imbalances, leading to frequent frequency deviations and tie-line power oscillations [12]. Therefore, advanced AGC strategies are required to ensure stable and reliable operation of such hybrid power systems. To overcome the limitations of classical controllers, several optimization-based techniques have been proposed in the literature for tuning AGC controller parameters. Metaheuristic algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Firefly Algorithm (FA), Salp Swarm Algorithm (SSA), Black Widow Optimization Algorithm (BWOA), and Shuffled Frog Leaping Algorithm (SFLA) have been successfully applied to AGC problems [13]–[18]. These algorithms improve controller performance by minimizing objective functions such as Integral of Squared Error (ISE), Integral of Absolute Error (IAE), and Integral of Time-weighted Absolute Error (ITAE). Recently, novel optimization techniques like the RIME algorithm have also been explored for AGC parameter tuning, demonstrating improved dynamic performance under various operating scenarios [19], [20]. Despite their effectiveness, optimization-based PI/PID controllers still suffer from inherent drawbacks. Their performance heavily depends on accurate system modeling, proper selection of objective functions, and tuning parameters. Moreover, once optimized, the controller gains remain fixed and may not adapt effectively to sudden changes in system dynamics, large disturbances, or uncertainties introduced by renewable energy penetration [21], [22]. This limitation highlights the need for adaptive and intelligent control strategies capable of handling nonlinearities and uncertainties in real time. In recent years, Artificial Intelligence (AI)-based control techniques have gained significant attention in power system applications due to their learning capability, adaptability, and robustness [23]. Among these techniques, Artificial Neural Networks (ANNs) are particularly effective in modeling complex nonlinear systems without requiring precise mathematical models. ANNs can learn from system data and generate appropriate control actions under varying operating conditions, making them suitable for AGC applications in hybrid power systems [24]. Several studies have demonstrated the potential of ANN-based controllers in frequency control and load-frequency control problems [25]. However, the application of ANN controllers in hybrid PV and reheat thermal power systems for AGC is still limited and requires further investigation. Moreover, comparative performance analysis with existing optimization-based controllers under different load disturbances and uncertainty conditions remains an open research area [26]. Motivated by these observations, this paper proposes an Artificial Intelligence–based ANN controller for Automatic Generation Control of a two-area hybrid PV and reheat thermal power system. The proposed ANN-based AGC scheme aims to enhance frequency regulation and tie-line power control by effectively handling nonlinearities, load variations, and renewable power fluctuations. The performance of the proposed controller is evaluated under various operating scenarios and compared with conventional and optimization-based AGC approaches reported in the literature. The results demonstrate the superiority of the ANN-based controller in terms of reduced frequency deviations, faster settling time, improved damping characteristics, and enhanced robustness, thereby validating its effectiveness for modern hybrid power systems.

2. SYSTEM MODELING

The power system considered for the Automatic Generation Control (AGC) investigation in this study is a two-area hybrid power system comprising a photovoltaic (PV) system and a reheat thermal power system. This hybrid configuration is designed to analyze the dynamic interaction between renewable and conventional energy sources under varying load conditions. In the proposed layout, Area-1 integrates the PV generation along with local loads, whereas Area-2 consists of a reheat thermal power plant responsible for supporting system stability and frequency regulation. The two areas are interconnected through a tie-line, enabling power exchange and coordinated control. The schematic representation of the AGC structure for the considered hybrid power system is shown in Fig. 1. The integration of PV systems into power networks introduces significant operational challenges due to the intermittent and uncertain nature of solar energy, which is strongly influenced by environmental conditions such as irradiance and temperature. Relying solely on PV generation can result in frequency oscillations and power imbalance, particularly during sudden load changes or reduced solar availability. Conventional solutions often employ energy storage systems, such as batteries, to mitigate these issues. However, battery-based systems increase overall cost, complexity, and maintenance requirements. In this study, a novel hybrid integration strategy is adopted in which the PV system is directly coordinated with the reheat thermal power system, eliminating the need for battery storage. This coordinated operation enables efficient power sharing between the PV and thermal units, allowing the thermal plant to compensate for PV power fluctuations and maintain frequency stability. Such an approach effectively reduces the adverse effects of PV intermittency while improving the overall efficiency, reliability, and dynamic performance of the hybrid power system. The interdependent operation of both subsystems ensures a rapid and coordinated response to load variations, thereby enhancing AGC performance.

A. Modeling of Reheat Thermal Power System

The reheat thermal power system located in Area-2 consists of four main components: the governor, turbine, reheater, and power system. For AGC analysis, a linearized transfer function–based modeling approach is adopted. Each component is represented by a first-order transfer function, which provides a sufficiently accurate dynamic approximation for load–frequency control studies. Similar modeling approaches have been widely adopted in the AGC literature [1]–[4].

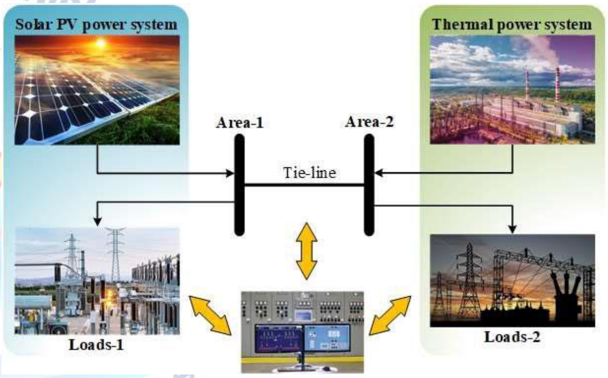

FIGURE 1. Schematic diagram of power system.

The governor transfer function is expressed as:

$$G_g(s) = \frac{K_g}{s\tau_g+1} \qquad (1)$$

where Kg is the governor gain and τg is the governor time constant.

The turbine transfer function is given by:

$$G_t(s) = \frac{K_t}{s\tau_t+1} \qquad (2)$$

where Kt represents the turbine gain and τt denotes the turbine time constant.

The reheater dynamics, which significantly influence the transient response of thermal power plants, are modeled as:

$$G_r(s) = \frac{sK_r\tau_r+1}{s\tau_r+1} \qquad (3)$$

Where Kr is the reheater gain and τr is the reheater time constant.

The power system dynamics in Area-2 are represented by:

$$G_{ps}(s) = \frac{K_{ps}}{s\tau_{ps}+1} \qquad (4)$$

where Kps is the power system gain and τps is the corresponding time constant.

The Area Control Error (ACE), which serves as the primary feedback signal for AGC operation, is computed as:

$$ACE_i = B\Delta f_i + \Delta P_{tie} \quad (5)$$

where B is the frequency bias coefficient, Δfi is the frequency deviation of the ith area, and ΔPtie represents the deviation in tie-line power exchange between the interconnected areas.

B. Modeling of Photovoltaic System

Accurate modeling of the PV system is essential for evaluating its impact on AGC performance. The PV system is initially modeled at the solar cell level, as illustrated in Fig. 2, using an equivalent electrical circuit consisting of a PV current source, a p–n junction diode, and a series resistance. The output current of the PV cell is dependent on solar irradiance and operating temperature, resulting in nonlinear and time-varying behavior. To ensure maximum energy extraction under changing environmental conditions, a Maximum Power Point Tracking (MPPT) mechanism is incorporated into the PV system. The MPPT algorithm continuously adjusts the operating point of the PV panel to extract maximum available power. Since PV systems generate DC power, power electronic converters and inverters are used to convert DC output into AC power suitable for grid integration. Considering the combined dynamics of the PV array, MPPT controller, power electronic converters, and output filters, the overall PV system can be represented by the following transfer function:

$$G_{PV}(s) = \frac{-18s+900}{s^2+100s+50} \quad (6)$$

This transfer function effectively captures the dynamic response of the PV system within the AGC framework.

C. System Parameters

Based on the developed transfer function models, Fig. 3 illustrates the complete dynamic representation of the two-area hybrid PV–reheat thermal power system. The system parameters used in this study are selected from standard AGC literature to ensure realistic and reliable simulation results. The adopted parameter values are as follows:

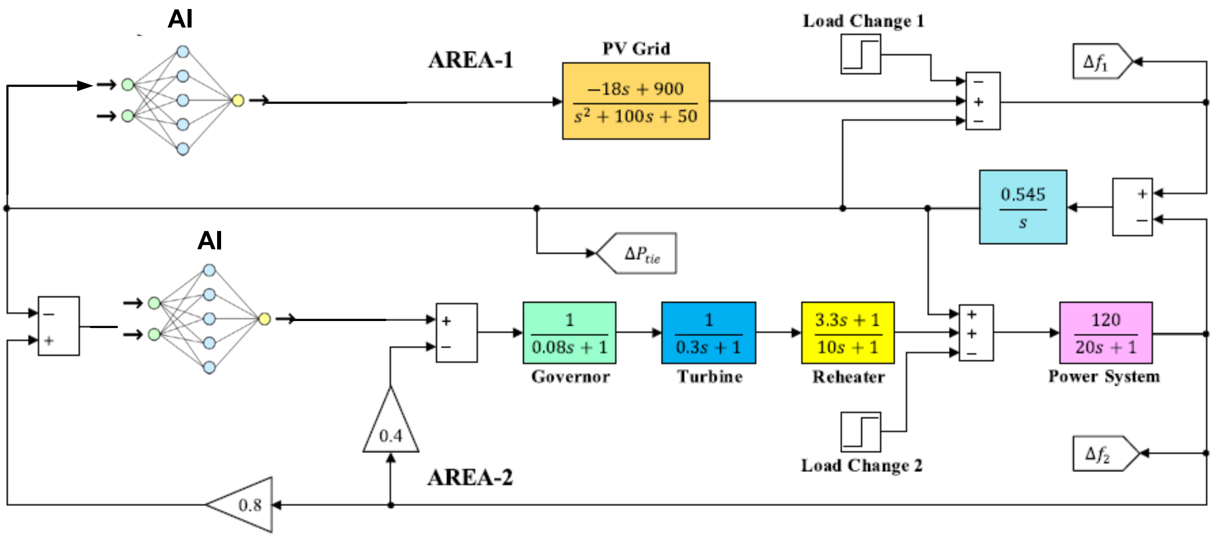

Fig 2. Overall two-area hybrid system

$K_{ps} = 120\,\text{Hz/pu.MW}$

$\tau_{ps} = 20\,\text{s}$

$K_r = 0.33\,\text{Hz/pu.MW}$

$2\pi T_{12} = 0.545\,\text{pu.MW/Hz}$

$\tau_r = 10\,\text{s}$

$\tau_g = 0.08\,\text{s}$

$\tau_t = 0.3\,\text{s}$

$B = 0.8\,\text{pu.MW/Hz}$

$R = 2.5\,\text{Hz/pu.MW}$

These parameters provide a solid foundation for evaluating the performance of the proposed ANN-based AGC controller under various operating conditions.

3. ANN CONTROLLER DESIGN

To address the nonlinear behavior and uncertainties introduced by renewable energy integration and load disturbances in hybrid power systems, an Artificial Neural Network (ANN)-based controller is proposed for the Automatic Generation Control (AGC) of the two-area PV–reheat thermal power system. Unlike conventional fixed-gain controllers, the ANN controller adapts to changing system dynamics by learning the nonlinear mapping between system states and control actions.

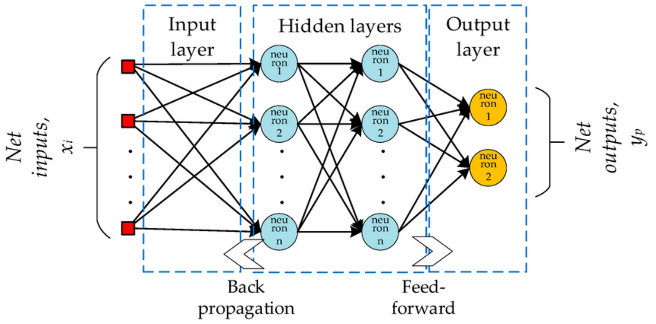

Fig.3 A graphical representation of a three-layer MLP neural network with n neurons.

A. ANN Input–Output Representation

The ANN controller generates the control signal applied to the governor of the thermal power plant. The controller input vector for the ith area is defined as:

$$x_i(t) = \begin{bmatrix} \Delta f_i(t) \\ \frac{d}{dt}\Delta f_i(t) \\ ACE_i(t) \end{bmatrix} \quad (7)$$

Where

$\Delta f_i(t)$ is the frequency deviation of the i^{th} area.

$\frac{d}{dt}\Delta f_i(t)$ is the rate of change of frequency deviation, and

$ACE_i(t)$ is the Area control Error defined in (8).

The ANN output is the control signal:

$$u_i(t) = f_{ANN}\left(x_i(t)\right) \quad (8)$$

Which is applied to the governor to regulate power generation.

B. ANN Architecture and Neuron Model

A feedforward multilayer perceptron (MLP) structure is adopted, consisting of one hidden layer with Nh neurons and one output neuron. The net input to the jth hidden neuron is given by:

$$v_j(t) = \sum_{k=1}^{n} w_{jk}^{(1)}\, x_k(t) + b_j^{(1)} \quad (9)$$

Where

$w_{jk}^{(1)}$ represents the weight between k^{th} input neuro and the j^{th} hidden neuron,

$b_j^{(1)}$ is the bias of the hidden neuron, and

n is the number of the input.

The output of the j^{th} hidden neuron is computed using the tangent sigmoid activation function:

$$h_j(t) = \tanh\left(v_j(t)\right) = \frac{e^{v_j(t)} - e^{-v_j(t)}}{e^{v_j(t)} + e^{-v_j(t)}} \quad (10)$$

The net input to the output neuron is expressed as:

$$v_o(t) = \sum_{j=1}^{N_h} w_j^{(2)}\, h_j(t) + b^{(2)} \quad (11)$$

The ANN output control signal is generated using a linear activation function:

$$u_i(t) = v_o(t) \quad (12)$$

C. Training Objective Function

The ANN is trained using a supervised learning approach to minimize the tracking error between the ANN-generated control signal and an optimal reference signal. The instantaneous error is defined as:

$$e(t) = u_{ref}(t) - u_{ANN}(t) \quad (13)$$

The Mean Squared Error (MSE) objective function is minimized during training:

$$J = \frac{1}{N}\sum_{t=1}^{N} e^2(t) \quad (14)$$

where NNN is the number of training samples.

To enhance AGC performance, the training dataset is generated under various operating scenarios, including step load perturbations and PV power variations.

D. Weight Update Rule

The ANN weights and biases are updated using the Levenberg–Marquardt (LM) backpropagation algorithm, which combines the advantages of gradient descent and the Gauss–Newton method. The weight update rule is given by:

$$w(k+1) = w(k) - [J^{T}J + \mu I]^{-1} J^{T} e \quad (15)$$

Where

J is the Jacobian matrix of partial derivatives of the network errors with respect to the weights,

μ is the damping factor, and

I is the identity matrix.

E. ANN-Based AGC Control Law

The overall AGC control law using the ANN controller can be expressed as:

$$u_i(t) = f_{ANN}\left(\Delta f_i(t), \frac{d}{dt}\Delta f_i(t), B\Delta f_i(t) + \Delta P_{tie}(t)\right) \quad (16)$$

This adaptive control law enables the ANN to continuously adjust the control signal based on real-time system conditions.

F. Stability and Performance Considerations

The ANN controller indirectly ensures system stability by minimizing frequency deviation and tie-line power error. The dynamic performance is evaluated using the Integral of Time-weighted Absolute Error (ITAE) criterion:

$$ITAE = \int_0^T t(|\Delta f_1(t)| + |\Delta f_2(t)| + |\Delta P_{tie}(t)|)dt \quad (17)$$

Minimization of this index leads to faster damping and reduced steady-state error.

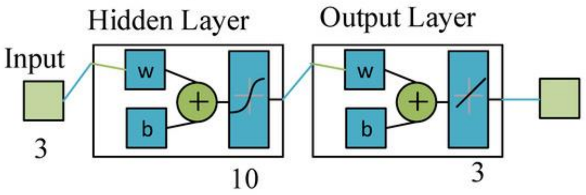

Fig.4 Implementation of ANN controller based two-area hybrid system

4. SIMULATION RESULTS AND DISCUSSION

The effectiveness of the proposed Artificial Neural Network (ANN)-based controller for Automatic Generation Control (AGC) is validated through extensive MATLAB/Simulink simulations on a two-area hybrid PV and reheat thermal power system. To clearly demonstrate the improvement achieved through intelligent control, the system performance is first evaluated using a conventional PI controller with fixed parameters. Subsequently, the PI controller is replaced with the proposed ANN controller, and the dynamic responses are compared under identical operating conditions.

A. Test System and Simulation Conditions

The simulated power system consists of two interconnected areas linked by a tie-line. Area-1 includes a photovoltaic (PV) generation unit along with local loads, while Area-2 consists of a reheat thermal power plant. The nominal system frequency is maintained at 50 Hz. The Area Control Error (ACE) of each area is used as the feedback signal for AGC operation. To evaluate system performance, a step load disturbance of 0.01 p.u. is applied in Area-1, while Area-2 operates under nominal load conditions. This disturbance scenario enables the assessment of frequency deviations in both areas as well as tie-line power exchange dynamics. All simulations are conducted for the same system parameters to ensure a fair comparison between the PI and ANN controllers.

B. Performance of Conventional PI Controller

Initially, the AGC system is tested using a conventional PI controller with manually tuned gain values. The frequency deviation responses of Area-1 (Δf_1) and Area-2 (Δf_2) indicate that the PI controller is capable of restoring the system frequency to its nominal value; however, the dynamic performance is unsatisfactory. Following the load disturbance, the frequency responses exhibit large initial deviations, accompanied by pronounced oscillations and a long settling time as shown in Fig.5. The lack of adaptability in the fixed-gain PI controller results in poor damping of oscillations, particularly due to the intermittent nature of the PV source in Area-1. Moreover, the tie-line power deviation (ΔP_{tie}) shows sustained oscillations before reaching steady state, which may adversely affect inter-area power exchange stability.

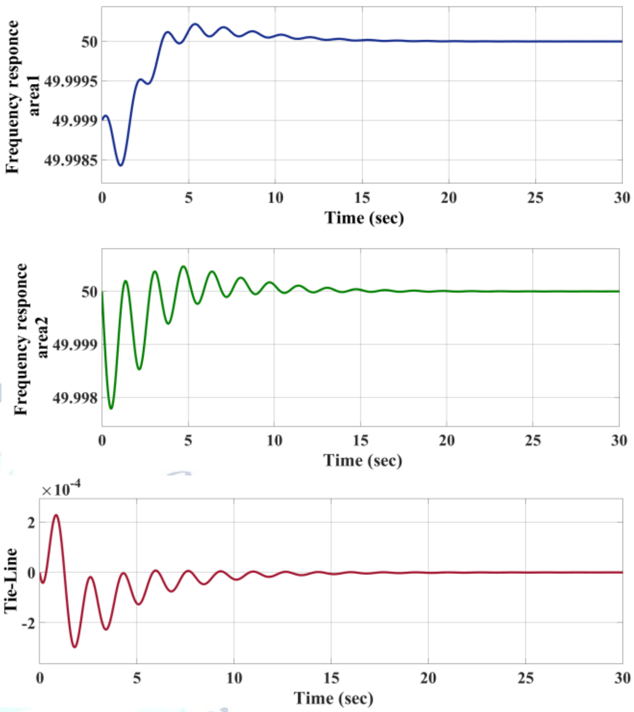

Fig.5 simulation results of PI controlled power system of two-area

The ACE responses in both areas converge slowly to zero, indicating delayed correction of generation–load imbalance. These results clearly demonstrate that the conventional PI controller struggles to handle nonlinear dynamics and renewable energy uncertainties effectively.

C. Performance of Proposed ANN Controller

To overcome the limitations of fixed-parameter control, the conventional PI controller is replaced with the proposed ANN-based AGC controller. The ANN controller dynamically generates the control signal based on real-time measurements of frequency deviation, rate of change of frequency, and ACE. The simulation results show a significant improvement in dynamic performance with the ANN controller as shown in Fig.6. The maximum frequency deviation in both areas is substantially reduced compared to the PI controller. Oscillations are effectively suppressed, and the system reaches steady-state conditions much faster. The ANN controller demonstrates superior learning capability, enabling it to adapt to sudden load changes and PV power fluctuations.

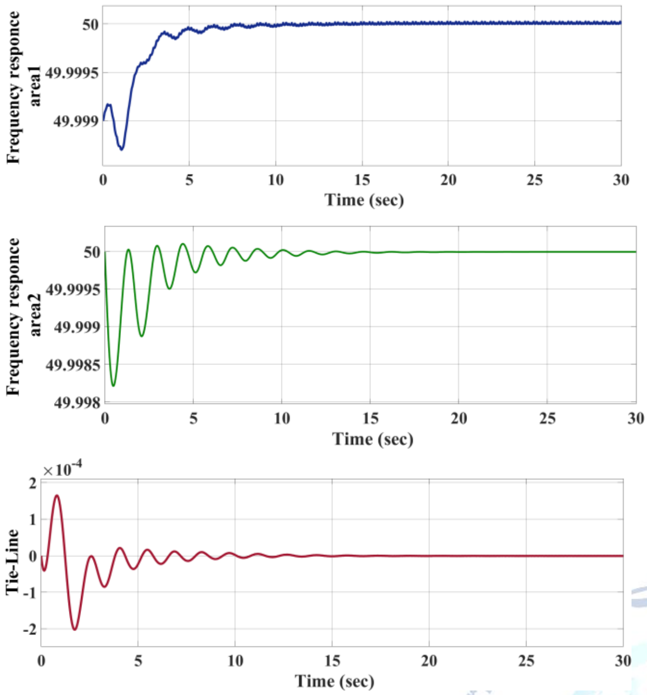

Fig.6 simulation results of ANN controlled power system of two-area

Furthermore, the tie-line power deviation under ANN control settles rapidly with minimal oscillations, indicating improved coordination between the two areas. The ACE signals converge quickly to zero, confirming faster restoration of power balance and enhanced AGC effectiveness.

D. Comparative and Performance Analysis

A quantitative comparison between the PI and ANN controllers is carried out using standard AGC performance indices such as peak overshoot, settling time, and Integral of Time-weighted Absolute Error (ITAE). The ANN controller consistently achieves lower ITAE values, reduced overshoot, and shorter settling times compared to the conventional PI controller as shown in Fig.7. Repeated simulation runs under varying load conditions further validate the robustness and consistency of the ANN-based AGC scheme. Unlike the PI controller, whose performance degrades under changing operating conditions, the ANN controller maintains stable and reliable operation due to its adaptive learning nature.

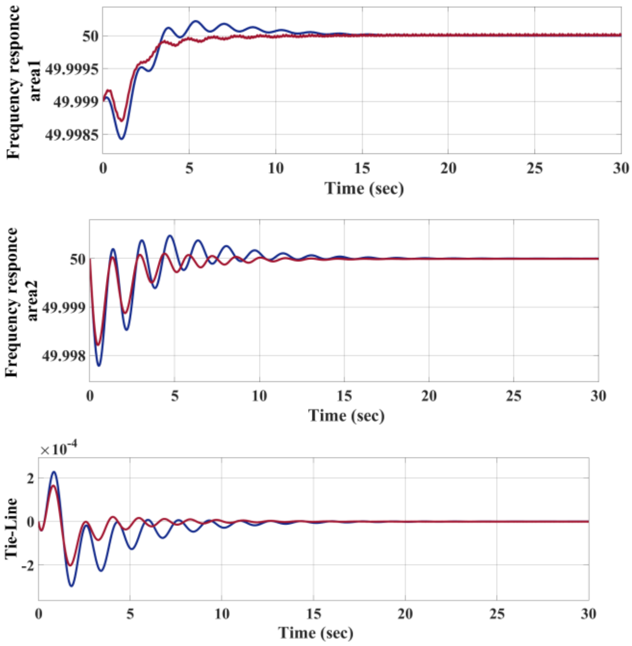

Fig. 7 Comparison of simulation results for PI and ANN controlled two-area hybrid power system

From the simulation results, it is evident that the conventional PI controller fails to deliver optimal AGC performance due to its fixed gain structure, resulting in higher frequency oscillations and delayed settling of both frequency and tie-line power responses. In contrast, the proposed ANN controller significantly enhances AGC performance, offering superior damping characteristics, faster frequency recovery, and improved inter-area power regulation as shown in Fig.7. These results clearly demonstrate that the ANN-based intelligent control strategy provides a robust and efficient solution for AGC in hybrid PV–thermal interconnected power systems subjected to load disturbances and renewable energy uncertainties.

5. CONCLUSION

This paper investigated the Automatic Generation Control (AGC) of a two-area hybrid photovoltaic (PV) and reheat thermal power system using an Artificial Neural Network (ANN)-based controller. The integration of renewable energy sources and varying load demands introduce nonlinearities and uncertainties that limit the effectiveness of conventional fixed-gain controllers. To address these challenges, an intelligent ANN controller was designed to improve frequency regulation and tie-line power control. The performance of the proposed ANN-based AGC scheme was evaluated through MATLAB/Simulink simulations and compared with a conventional PI controller under identical operating conditions. The simulation results demonstrated that the PI controller exhibits larger frequency deviations, higher oscillations, and longer settling times following load disturbances. In contrast, the ANN controller significantly reduced frequency overshoot, improved damping characteristics, and achieved faster restoration of system frequency and tie-line power balance. Overall, the proposed ANN-based controller proved to be a robust and adaptive solution for AGC in hybrid PV–thermal power systems. Its ability to handle nonlinear dynamics and renewable energy uncertainties makes it a promising control strategy for modern interconnected power systems with high renewable penetration.

Conflict of interest statement

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

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