



Enhanced Frequency and Voltage Control of Interconnected Power Systems Using ANN-Based LFC–AVR Strategy

Dr. J. Srinu Naick | C. Purushotham | S. Imam Vali | O. Vijay Kumar | P. Mastan

Department of Electrical and Electronics Engineering, Chadalawada Ramanamma Engineering College, Tirupati, Andhra Pradesh, India.

To Cite this Article

Dr. J. Srinu Naick, C. Purushotham, S. Imam Vali, O. Vijay Kumar & P. Mastan (2026). Enhanced Frequency and Voltage Control of Interconnected Power Systems Using ANN-Based LFC–AVR Strategy, International Journal for Modern Trends in Science and Technology, 12(05), 444-451. <https://doi.org/10.5281/zenodo.20567990>

Article Info

Received: 07 May 2026; Revised: 26 May 2026; Accepted: 30 May 2026.

Copyright © The Authors ; This is an open access article distributed under the [Creative Commons Attribution License](#), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

KEYWORDS

Load Frequency Control (LFC), Automatic Voltage Regulation (AVR), Artificial Neural Network (ANN), Adaptive Control, Frequency Deviation, Nonlinear Systems, Intelligent Control, Power System Stability, Optimization Techniques, Hybrid Power Systems

ABSTRACT

Load Frequency Control (LFC) and Automatic Voltage Regulation (AVR) are critical for maintaining stability and reliable operation in interconnected power systems. Conventional control methods, such as classical PID controllers, are widely used due to their simple structure and ease of implementation; however, their performance degrades under varying load conditions and system uncertainties. To improve system response, fuzzy PID controllers have been introduced, where membership functions are used to map input variables such as frequency deviation and its rate of change into fuzzy sets, enabling rule-based linguistic control. Although fuzzy controllers enhance transient performance, their effectiveness depends heavily on the proper design of membership functions and rule base. Further improvements have been achieved using optimization-based techniques such as NLTA, Modified Particle Swarm Optimization (MPSO), and Arithmetic Optimization Algorithm (AOA), which help in reducing overshoot and settling time. However, these methods lack real-time adaptability and struggle to handle highly nonlinear and dynamic operating conditions. To overcome these limitations, this paper proposes an Artificial Neural Network (ANN)-based controller for the LFC loop to provide adaptive and intelligent frequency regulation. The ANN effectively captures nonlinear relationships between system inputs and outputs, using frequency deviation and rate of change of frequency as inputs to generate an adaptive control signal. The AVR loop operates in coordination with the ANN-based LFC to ensure simultaneous voltage regulation. Simulation results demonstrate that the proposed ANN controller significantly improves system performance by enhancing dynamic response, reducing settling time, and maintaining stability under varying operating conditions and uncertainties. The proposed approach provides a robust and adaptive solution for modern LFC–AVR control.

1. Introduction

The secure and reliable operation of modern interconnected power systems requires continuous regulation of system frequency and terminal voltage under varying load conditions and network disturbances [1]. Frequency and voltage are the primary indicators of power system stability, and any significant deviation from their nominal values can adversely affect system performance, power quality, and equipment lifespan [2]. With the increasing complexity of power networks due to growing electricity demand, renewable energy integration, distributed generation, and deregulated market environments, maintaining stable frequency and voltage has become a major challenge for power system operators [3]. Load Frequency Control (LFC) plays a crucial role in maintaining the balance between power generation and load demand by regulating the active power output of generating units [4]. Whenever a sudden load change occurs, an imbalance between generated and consumed power leads to frequency deviations. If these deviations are not corrected promptly, they may propagate throughout the interconnected network and threaten overall system stability [5]. Therefore, the primary objective of LFC is to restore system frequency to its nominal value while minimizing tie-line power deviations between interconnected areas [6]. Similarly, Automatic Voltage Regulation (AVR) is responsible for maintaining generator terminal voltage within acceptable limits by controlling the excitation system [7]. The AVR system regulates reactive power flow and improves voltage stability during disturbances and load variations. Since voltage and frequency dynamics are inherently coupled in practical power systems, coordinated operation of LFC and AVR is essential for achieving satisfactory dynamic performance and overall system reliability [8]. Conventionally, proportional-integral-derivative (PID) controllers have been widely used in LFC and AVR applications because of their simple structure, ease of implementation, and low computational requirements [9]. Although PID controllers provide acceptable performance under nominal operating conditions, their effectiveness deteriorates when system parameters vary or nonlinear disturbances are introduced [10]. Large overshoots, oscillations, and prolonged settling times are commonly observed under heavy load changes and uncertain operating conditions, limiting the applicability

of classical controllers in modern power systems [11]. To overcome the limitations of conventional PID controllers, researchers have proposed various intelligent control techniques. Among them, Fuzzy Logic Controllers (FLCs) have attracted significant attention because they can incorporate human expertise and linguistic rules into the control process [12]. Fuzzy PID controllers utilize membership functions to map system variables such as frequency deviation and change in frequency deviation into fuzzy sets, allowing rule-based control actions to be generated without requiring an accurate mathematical model [13]. These controllers have demonstrated improved transient performance and robustness compared with classical PID approaches [14]. Despite their advantages, the effectiveness of fuzzy controllers largely depends on the appropriate design of membership functions and rule bases [15]. Improper selection of fuzzy parameters may lead to degraded performance and increased computational complexity. Furthermore, determining optimal membership functions for large-scale interconnected systems often requires extensive trial-and-error procedures and expert knowledge [16]. To further enhance controller performance, numerous optimization techniques have been employed for tuning controller parameters. Metaheuristic algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), Artificial Bee Colony (ABC), and Ant Colony Optimization (ACO) have shown promising results in minimizing performance indices and improving system response [17]. Recently, advanced optimization approaches including Nonlinear Threshold Accepting (NLTA), Modified Particle Swarm Optimization (MPSO), and Arithmetic Optimization Algorithm (AOA) have been successfully applied to LFC and AVR problems [18]–[20]. These techniques effectively reduce overshoot, undershoot, and settling time while improving damping characteristics. Although optimization-based controllers achieve better dynamic performance, they are generally designed offline and tuned for specific operating conditions [21]. As power systems become increasingly nonlinear and uncertain due to renewable energy penetration, fluctuating loads, and changing operating scenarios, fixed-parameter optimization techniques may fail to provide satisfactory performance under all conditions [22]. Consequently, there is a growing need for adaptive and intelligent

control strategies capable of learning system behavior and adjusting control actions in real time. Artificial Neural Networks (ANNs) have emerged as powerful tools for modeling and controlling nonlinear dynamic systems [23]. Inspired by the biological nervous system, ANNs possess learning, adaptation, and generalization capabilities that enable them to capture complex relationships between system inputs and outputs. Unlike conventional controllers, ANN-based controllers do not require precise mathematical models and can adapt their control actions according to changing operating conditions [24]. In power system applications, ANN controllers have demonstrated excellent performance in frequency regulation, voltage control, load forecasting, fault diagnosis, and energy management. By utilizing frequency deviation and rate of change of frequency as input signals, ANN-based LFC schemes can generate adaptive control actions that effectively suppress oscillations and improve dynamic response. When coordinated with the AVR system, ANN controllers provide simultaneous frequency and voltage regulation, thereby enhancing overall system stability and robustness against disturbances and uncertainties [25]. Motivated by these advantages, this paper proposes an

ANN-based controller for coordinated LFC–AVR operation in an interconnected power system. The ANN controller utilizes frequency deviation and its derivative as input variables to generate adaptive control signals for frequency regulation, while the AVR loop maintains the generator terminal voltage within desired limits. The proposed approach aims to overcome the limitations of conventional PID, fuzzy PID, NLTA, MPSO, and AOA-based controllers by providing real-time adaptability, improved disturbance rejection capability, and enhanced robustness under varying operating conditions. Simulation studies demonstrate that the proposed ANN-based LFC–AVR strategy significantly improves transient response, reduces settling time, minimizes oscillations, and ensures stable operation of the interconnected power system.

2. Mathematical Representation of AVR System

The AVR system is responsible for maintaining the generator terminal voltage within acceptable limits. It consists of four main components: amplifier, exciter, generator, and sensor, each represented by a first-order transfer function as shown in Fig.1.

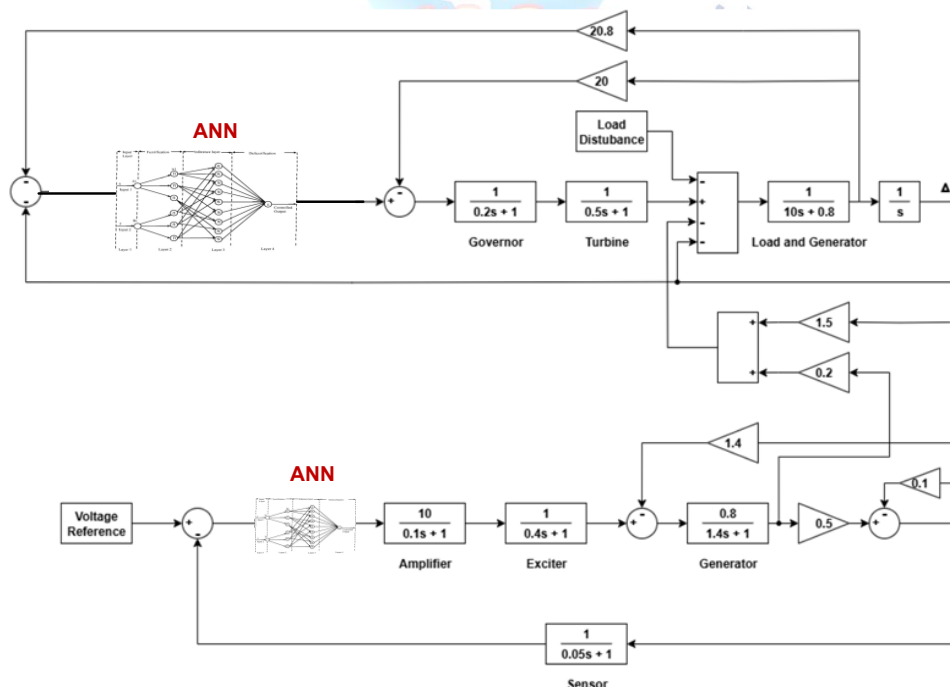


Fig.1 Proposed Single-area LFC-AVR combined model.

The overall transfer function of the AVR system is given by:

$$TF_{AVR}(s) = \frac{V(s)}{\Delta V(s)} = \frac{M(\sigma_4 s + 1)}{M + (\sigma_1 s + 1)(\sigma_2 s + 1)(\sigma_3 s + 1)(\sigma_4 s + 1)} \quad (1)$$

Where: $1^L H$

- M: Amplifier gain
- σ_1 : Amplifier time constant
- σ_2 : Exciter time constant

- σ_3 : Generator time constant
- σ_4 : Sensor time constant

The time-domain representation of the AVR system can be expressed as:

$$\left(\prod_{(i=1)}^4 \sigma_i D^4 + \sum_{(i<j<k)} \sigma_i \sigma_j \sigma_k D^3 + \sum_{(i<j)} \sigma_i \sigma_j D^2 + \sum_{(i=1)}^4 \sigma_i D + (1 + M) \right) v(t) = M(\sigma_4 D + 1) \Delta v(t) \quad (2)$$

Where:

- $v(t)$: Output voltage
- $\Delta v(t)$: Error in reference voltage
- D : Differential operator

The characteristic equation of the AVR system is:

$$\left(\prod_{(i=1)}^4 \sigma_i S^4 + \sum_{(i<j<k)} \sigma_i \sigma_j \sigma_k S^3 + \sum_{(i<j)} \sigma_i \sigma_j S^2 + \sum_{(i=1)}^4 \sigma_i S + (1 + M) \right) = 0 \quad (30)$$

This equation is used to analyze the stability of the AVR system.

3. Mathematical Representation of LFC System

The LFC system regulates system frequency by maintaining the balance between generation and load demand. The mathematical model is developed for both single-area and two-area interconnected systems.

Two-Area LFC System Equations

The frequency dynamics of Area 1 and Area 2 are given by:

$$\frac{d}{dt} (\Delta f_1(t)) = \frac{K_{gen}}{T_{gen}} \left[\Delta P_{mech1}(t) + \Delta P_{gen1}(t) - \Delta P_{tie}(t) - \Delta P_{Load1}(t) - \frac{1}{K_{gen}} \Delta f_1(t) \right] \quad (4)$$

$$\frac{d}{dt} (\Delta f_2(t)) = \frac{K_{gen}}{T_{gen}} \left[\Delta P_{mech2}(t) + \Delta P_{gen2}(t) - \Delta P_{tie}(t) - \Delta P_{Load2}(t) - \frac{1}{K_{gen}} \Delta f_2(t) \right] \quad (5)$$

Governor Dynamics

$$\frac{d}{dt} (\Delta P_{gov1}(t)) = \frac{1}{T_{gov1}} \left[\Delta P_{ref1}(t) - \frac{1}{R} \Delta f_1(t) - \Delta P_{gov1}(t) \right] \quad (6)$$

$$\frac{d}{dt} (\Delta P_{gov2}(t)) = \frac{1}{T_{gov2}} \left[\Delta P_{ref2}(t) - \frac{1}{R} \Delta f_2(t) - \Delta P_{gov2}(t) \right] \quad (7)$$

Tie-line Power Exchange

$$\frac{d}{dt} (\Delta P_{tie}(t)) = T [\Delta f_1(t) - \Delta f_2(t)] \quad (8)$$

Area Control Error (ACE)

$$ACE_1(t) = -\Delta P_{tie}(t) - B \Delta f_1(t) \quad (9)$$

$$ACE_2(t) = \Delta P_{tie}(t) - B \Delta f_2(t) \quad (10)$$

Parameters Description

- $\Delta f_1, \Delta f_2$: Frequency deviations
- ΔP_{tie} : Tie-line power deviation
- ΔP_{mech} : Mechanical power change

- ΔP_{gen} : Generator power change
- ΔP_{gov} : Governor output
- ΔP_{Load} : Load change
- R : Speed regulation (droop)
- B : Frequency bias factor
- T : Synchronizing coefficient

4. Combined LFC–AVR System

The overall system considered in this work is a combined LFC–AVR system, which integrates both frequency and voltage control loops.

LFC System Parameters

- Governor time constant: 0.2 s
- Turbine time constant: 0.5 s
- Load inertia time constant: 10 s
- Speed regulation (R): 2.4 Hz/pu MW
- Bias factor (B): 0.425 pu MW/Hz

AVR System Parameters

- Amplifier time constant: 0.1 s
- Exciter time constant: 0.4 s
- Generator time constant: 1.4 s
- Gains: 10 (amplifier), 1 (exciter), 0.8 (generator)

In the conventional approach:

- The LFC loop is controlled using a fuzzy PID controller
- The AVR loop is controlled using a trial-and-error tuned PID controller

In the proposed work, these control strategies can be enhanced using advanced techniques such as ANN to improve system performance.

The combined LFC–AVR model enables simultaneous regulation of frequency and voltage, providing a more realistic representation of practical power systems.

5. Proposed ANN controller for Double-area LFC-AVR combined model.

An Artificial Neural Network (ANN) controller is developed for the Load Frequency Control (LFC) loop to enhance frequency stability in interconnected power systems as shown in Fig.2. The ANN controller replaces the conventional PID/PI controller to provide faster dynamic response, improved adaptability to nonlinear system behavior, and better handling of uncertainties such as load variations and renewable energy fluctuations.

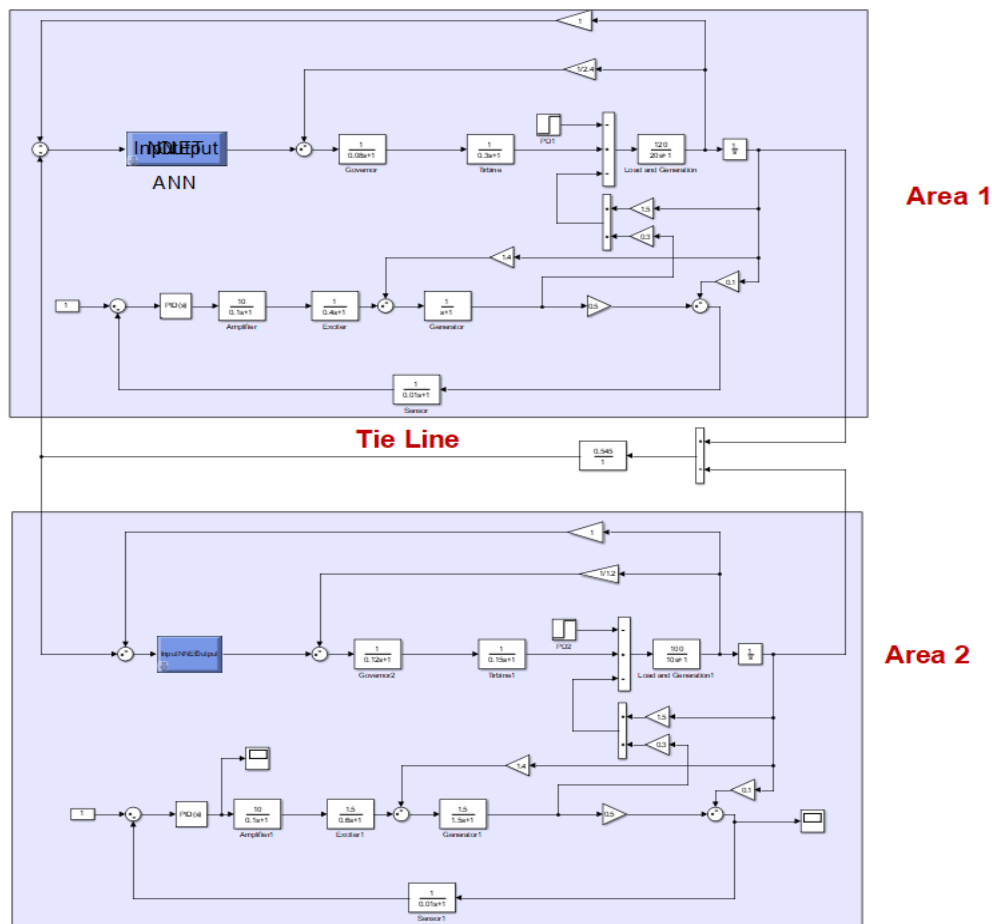


Fig.2 Proposed Two-area LFC-AVR combined model.

The designed ANN is a multi-layer feed forward neural network, consisting of:

- Input layer: 3 neurons
- Hidden layer: 5 neurons
- Output layer: 1 neuron

Thus, the ANN architecture is represented as [3, 5, 1]. The network is trained using the Levenberg–Marquardt (LM) algorithm, which ensures fast convergence and minimal error.

A. Input and Output Selection

The ANN controller receives three normalized input parameters:

$$I = (e(t), \dot{e}(t), e_{int}(t)) \quad (11)$$

Where:

$$e(t) = \Delta f_{ref} - \Delta f(t) \quad (12)$$

is the frequency error,

$$\dot{e}(t) = \frac{de(t)}{dt} \quad (13)$$

is the rate of change of frequency error, and

$$e_{int}(t) = \int e(t) dt \quad (14)$$

is the accumulated error.

ANN Output

The ANN produces a control signal $u(t)$, which is used to regulate the governor system:

$$u(t) = f_{ANN}(I) \quad (15)$$

This control signal is used to:

- Adjust the governor reference input
- Regulate turbine mechanical power
- Maintain system frequency within permissible limits

B. Network Structure and Transfer Function

The ANN output is mathematically expressed as:

$$u(t) = f_o \left(\sum_{j=1}^5 w_{oj} \cdot f_h \left(\sum_{i=1}^3 w_{ji} I_i + b_j \right) + b_o \right) \quad (16)$$

Where:

- w_{ji}, w_{oj} : Connection weights
- b_j, b_o : Bias terms
- $f_h(x) = \tanh(x)$: Hidden layer activation function
- $f_o(x) = x$: Output layer (linear function)

Input Normalization

To improve training efficiency, inputs are normalized as:

$$I_{norm} = \frac{I - I_{min}}{I_{max} - I_{min}} \quad (17)$$

C. Training Process

The ANN is trained using input–output datasets obtained from system simulations under various operating conditions such as:

- Load disturbances
- Generation variations
- Tie-line power fluctuations

The objective is to minimize the Mean Squared Error (MSE):

$$E = \frac{1}{N} \sum_{k=1}^N (T_k - \hat{T}_k)^2 \quad (18)$$

Where:

- T_k : Target output
- \hat{T}_k : ANN predicted output

Weight Update (LM Algorithm)

$$\omega_{k+1} = \omega_k - [J^T J + \mu I]^{-1} J^T e \quad (19)$$

Where:

- J : Jacobian matrix
- μ : Damping factor
- e : Error vector

Training Parameters

- Epochs: 1000
- Performance goal: 1×10^{-12} \times times 10^{-12}
- Training algorithm: LM (trainlm)
- Activation functions:
 - Hidden layer: tansig / logsig
 - Output layer: purelin

D. Integration with LFC System

Once trained, the ANN controller replaces the conventional PID controller in the LFC loop.

LFC Control Action

The ANN output is used to regulate the governor input:

$$\Delta P_{ref}(t) = f_{ANN}(e(t), \dot{e}(t), e_{int}(t)) \quad (20)$$

This control signal:

- Adjusts turbine mechanical power
- Minimizes frequency deviations
- Improves system stability

Multi-Area System Application

In multi-area systems, the ANN controller also helps regulate:

- Tie-line power deviation
- Area Control Error (ACE)

$$ACE = \Delta P_{tie} + B \cdot \Delta f \quad (21)$$

The ANN dynamically adjusts control signals to maintain:

- Scheduled power exchange
- Frequency balance across areas

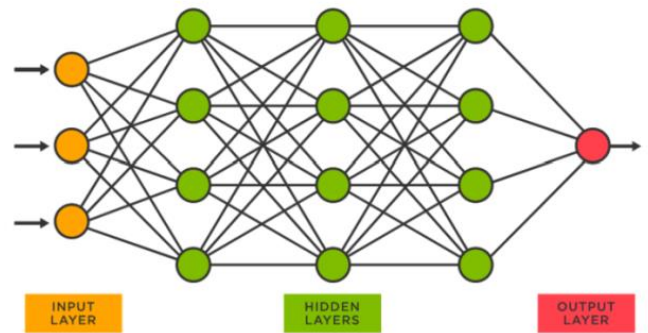


Fig.3 Design of a backpropagation network to provide a standard reference signal.

6. Simulation Results and Discussion

The performance of the proposed ANN-based LFC–AVR controller is evaluated and compared with the conventional Fuzzy PID controller under load disturbance conditions. The comparison is carried out in terms of frequency deviations in Area 1 and Area 2, as well as tie-line power response. The obtained simulation results demonstrate the effectiveness of the ANN controller in enhancing the dynamic performance and stability of the interconnected power system.

A. Frequency Response of Area 1

Fig. 4 shows the frequency response of Area 1 for both the Fuzzy PID and ANN controllers. Following the disturbance, the Fuzzy PID controller exhibits noticeable oscillations and a longer settling period before reaching the nominal frequency of 50 Hz. In contrast, the ANN controller rapidly restores the frequency with negligible overshoot and significantly reduced oscillations. The frequency reaches its steady-state value much faster, indicating superior disturbance rejection capability and improved dynamic performance.

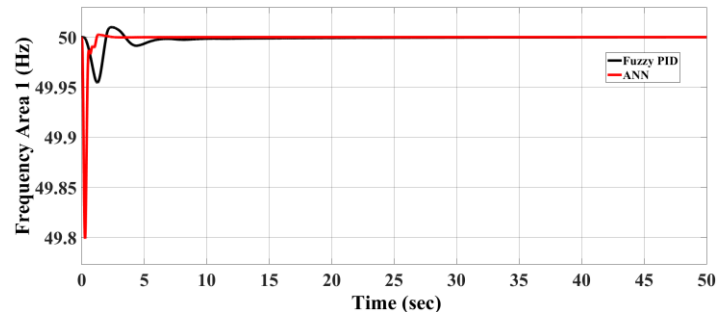


Fig.4 Area-1 Frequency Deviation Response (Δf_1)

B. Frequency Response of Area 2

The frequency deviation in Area 2 is illustrated in Fig. Fig.5. it can be observed that the Fuzzy PID controller experiences larger undershoot and oscillatory behavior

following the disturbance. The ANN controller effectively suppresses these oscillations and quickly returns the frequency deviation to zero. The reduced settling time and improved damping characteristics confirm the robustness of the proposed ANN-based control strategy under varying operating conditions.

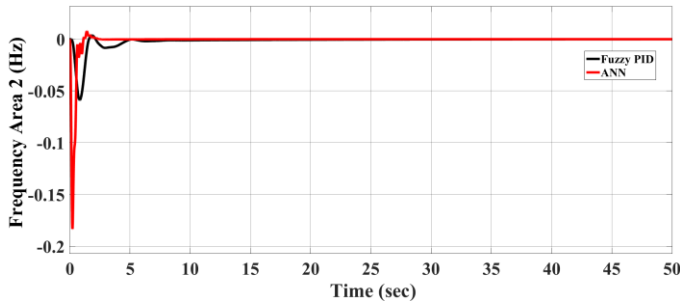


Fig.5 Area-2 Frequency Deviation Response (Δf_2)

C. Tie-Line Power Response

Fig. Fig.6 presents the tie-line power deviation between the interconnected areas. The Fuzzy PID controller produces considerable oscillations and a slow decay rate, resulting in prolonged power exchange fluctuations between the two areas. Conversely, the ANN controller maintains the tie-line power deviation very close to zero throughout the simulation period. The rapid damping of oscillations demonstrates the ability of the ANN controller to effectively coordinate power sharing and maintain system stability.

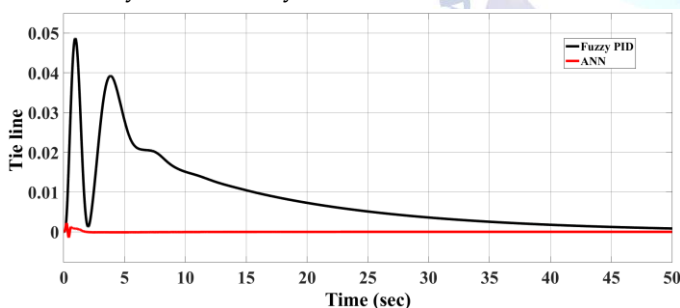


Fig.6 Inter-Area Tie-Line Power Deviation (ΔP_{tie})

The simulation results clearly indicate that the proposed ANN-based LFC–AVR controller outperforms the conventional Fuzzy PID controller. The ANN controller provides faster frequency restoration, lower overshoot, reduced oscillations, and shorter settling times in both control areas. Furthermore, tie-line power deviations are significantly minimized, leading to improved coordination between interconnected areas. These improvements are achieved due to the adaptive learning capability of the ANN, which effectively captures the nonlinear dynamics of the power system and generates appropriate control actions under varying operating conditions. Therefore, the proposed ANN-based

LFC–AVR strategy offers a robust and efficient solution for maintaining frequency and voltage stability in modern interconnected power systems.

6. Conclusion

This paper presented an enhanced ANN-based Load Frequency Control (LFC) and Automatic Voltage Regulation (AVR) strategy for interconnected power systems. The proposed controller utilizes the adaptive learning capability of Artificial Neural Networks to effectively regulate system frequency while operating in coordination with the AVR loop to maintain voltage stability under varying operating conditions and load disturbances. Simulation results demonstrated that the ANN-based controller provides superior dynamic performance compared with the conventional Fuzzy PID controller. The proposed approach significantly reduced frequency deviations in both control areas, minimized tie-line power oscillations, and achieved faster settling times with improved damping characteristics. Furthermore, the ANN controller exhibited excellent robustness against system nonlinearities and uncertainties, ensuring stable operation of the interconnected power system. The results confirm that the proposed ANN-based LFC–AVR strategy enhances overall system stability, improves disturbance rejection capability, and maintains reliable frequency and voltage regulation. Therefore, the proposed method offers an effective and intelligent control solution for modern interconnected power systems characterized by dynamic operating conditions and increasing complexity.

Conflict of interest statement

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

REFERENCES

- [1] R. Irfan, M.M. Gulzar, S. Habib, A. Shakoore, H. Ahmad, A.F. Murtaza, Multistage control for frequency and voltage stability in a multi-area power network with nonlinear dynamics, Results. Eng. 26 (2025) 104724.
- [2] .D. Chetty, R. Gandhi, G. Sharma, E. Çelik, R. Kumar, Enhanced automatic voltage regulation using an extended PIDA controller optimised by the snake algorithm, Results. Eng. 26 (2025) 105181.
- [3] Gupta D. Kumar, G. Dei, A. Kumar Soni, A.V. Jha, B. Appasani, N. Bizon, A. Srinivasulu, P. Nsengiyumva, Fractional order PID controller for load frequency control in a deregulated hybrid

- power system using Aquila Optimization, Results. Eng. 23 (2024) 102442.
- [4] T. Ali, S.A. Malik, I.A. Hameed, A. Daraz, H. Mujlid, A.T. Azar, Load frequency control and automatic voltage regulation in a Multi-area interconnected power system using nature-inspired computation-based control methodology, Sustainability 14 (2022) 12162.
- [5] N. Nahas, M. Abouheaf, M. Noomane Darghouth, A. Sharaf, A multi-objective AVR- LFC optimization scheme for multi-area power systems, Electr. Power Syst. Res. 200 (2021) 107467.
- [6] E. Rakhshani, K. Rouzbehi, S. Sadeh, A new combined model for simulation of mutual effects between lfc and avr loops, in: 2009 Asia-Pacific Power and Energy Engineering Conference, 2009, pp. 1–5.
- [7] J. Morsali, Z. Esmaeili, Proposing a new hybrid model for LFC and AVR loops to improve effectively frequency stability using coordinative CPSS, in: Proceeding of 28th Iranian Conference on Electrical Engineering (ICEE) Tabriz, Iran, Aug. 2020, pp. 1–7.
- [8] S. Oladipo, Y. Sun, Z. Wang, An effective hFPAPFA for a PIDA-based hybrid loop of load frequency and terminal voltage regulation system, in: Proceeding IEEE PES/ IAS PowerAfrica, Nairobi, Kenya, Aug. 2021, pp. 1–5.
- [9] A. Ghosh, A.K. Ray, M. Nurujjaman; Jamshidi, Voltage and frequency control in conventional and PV integrated power systems by a particle swarm optimized Ziegler–Nichols based PID controller, SN. Appl. Sci. 3 (2021) 1–13.
- [10] A. Soundarrajan, S. Sumathi, C. Sundar, Particle swarm optimization based LFC and AVR of autonomous power generating system, IAENG. Int. J. Comput. Sci. 37 (37) (2010) 1.
- [11] A. Gupta, A. Chauhan, R. Khanna, Design of AVR and ALFC for single area power system including damping control, Recent. Adv. Comput. Sci. RAECS IEEE (2014).
- [12] G. Salman, A.S. Jafar, A.I. Ismael, Application of artificial intelligence techniques for LFC and AVR systems using PID controller, Int. J. Power Electron. Drive Syst. 10 (2019) 1694–1704.
- [13] A.M. Hamza, M.S. Saad, H.M. Rashad, A. Bahgat, Design of LFC and AVR for single area power system with PID controller tuning by BFO and ziegler methods, Int. J. Comput. Sci. Telecommun. 4 (5) (May 2013) 12–17.
- [14] Imdadullah B. Alamri, M.A. Hossain, M.S.J Asghar, Electric Power network interconnection: a review on current status, Future Prospects. Res. Dir. Electron. 10 (2021) 2179.
- [15] T.D. Raj, C. Kumar, P. Kotsampopoulos, H.H. Fayek, Load frequency control in two- area multi-source power system using bald Eagle-Sparrow search optimization tuned PID controller, Energies 16 (2014), 2023.
- [16] K.V. Chandrakala, S. Balamurugan, Simulated annealing based optimal frequency and terminal voltage control of multi-source multi area system, Int. J. Electr. Power Energy Syst. 78 (2016) 823–829.
- [17] R. Rajbongshi, L.C. Saikia, Combined control of voltage and frequency of multi- area multisource system incorporating solar thermal power plant using LSA optimised classical controllers, IET Gener. Transm. Distrib. 11 (2017) 2489–2498.
- [18] D.K. Lal, A.K. Barisal, Combined load frequency and terminal voltage control of power systems using moth flame optimization algorithm, J. Electr. Syst. Inf. Technol. (2019) 6.
- [19] B. Dekaraja, L.C. Saikia, S.K. Ramoji, M.K. Behera, S.K. Bhagat, Impact of RFB and HVDC link on combined ALFC-AVR studies of a GTPP integrated hydro-thermal systems using a Cascade fuzzy PD-TID controller, in: Proceedings of the 4th International Conference on Energy, Power and Environment (ICEPE), Shillong, India, 2022, pp. 3–8, 29 April–1 May.
- [20] R. Irfan, M.M. Gulzar, A.S. b, S.H. d, H. Ahmad, S.A.H. G, H. Tehreem, Robust operating strategy for voltage and frequency control in a non-linear hybrid renewable energy-based power system using communication time delay, Comput. Electr. Eng. 123 (2025) 110119.
- [21] S. Pahadasingh and C. Jena, “Design of CC-3DOF-PD controller for load frequency control of multi area multi source system using TLBO algorithm,” vol. 11, no. 4, pp. 292–8, 2020.
- [22] D. Kumar, G. Lloyds Raja, M. Alkhatib, U.R. Muduli, Enhancing lfc with relocated fractional imc for power systems under communication latency, in: 2024 IEEE 4th International Conference on Sustainable Energy and Future Electric Transportation (SEFET), IEEE, 2024, pp. 01–06.
- [23] N. Kumari, P. Aryan, G. Lloyds Raja, U.R. Muduli, Robust stability and sensitivity analysis of optimized fuzzy integral-derivative controllers in multi-area hybrid power systems, in: 2024 IEEE 4th International Conference on Sustainable Energy and Future Electric Transportation (SEFET), 2024, pp. 1–5. IEEE.
- [24] D. Kumar, G. Lloyds Raja, O.A. Zaabi, M. Alkhatib, U.R. Muduli, Resilient PID controller for communication latency in interconnected power systems, in: 2024 IEEE Energy Conversion Congress and Exposition (ECCE), 2024, pp. 1653–1658. IEEE.
- [25] P. Aryan, N. Kumar, G.L. Raja, M. Meneses, R. Vilanova, Resilient frequency-shifted IMC-PID scheme for mitigating scaling and random attacks in thermal plants amid delay, IFAC Pap. 58 (7) (2024) 293–298, no.