iJRASET
International Journal For Research in
Applied Science and Engineering Technology

# INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

**Volume:** 13 **Issue:** VI **Month of publication:** June 2025

**DOI:** https://doi.org/10.22214/ijraset.2025.70407

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

# Secondary Control Techniques for Frequency Restoration in Microgrids Considering Communication Delays

S Shiva Raj[1], K V Sharma[2], M T Naik[3]
[1]*Master Student,* [2, 3]*Professor, Centre for Energy Studies, JNTUH Collage of Engineering, Kukatpally, Hyderabad, Telangana.*

***Abstract: Microgrids (MGs) offer a sustainable solution for integrating distributed energy resources and allow for independent operation during grid disruptions. Although droop control is widely used for managing power distribution among generation units, it can result in system frequency and voltage deviations. Communication delays within the secondary control system can negatively impact system stability.This study evaluates and compares three secondary control techniques, Proportional-Integral (PI), Fractional-Order Proportional-Integral (FOPI), and Artificial Neural Network (ANN) based controllers, in mitigating frequency deviations in MGs with communication delays. A MATLAB/Simulink-based microgrid model incorporating three voltage source converters (VSCs) is developed to analyze the performance of these controllers under varying conditions. Results demonstrate that ANN-based control significantly outperforms PI and FOPI controllers regarding stability, response time, and robustness to communication delays as ANN controller exhibits lower peak overshoot, faster settling time, and superior adaptability, showing promise for MG secondary control.***

***This research underscores the importance of intelligent control methods in addressing communication-induced disturbances and paving the way for future advancements in decentralized energy management.***

***Keywords: Microgrid, Secondary Control, Frequency Stability, Communication Delay, PI Controller, FOPI Controller, Artificial Neural Networks (ANN).***

## I. INTRODUCTION

Integrating renewable energy sources (RES) into power systems has developed microgrids (MGs). MGs enhance energy resilience and efficiency and can operate autonomously or synchronously with the primary grid, which requires robust control mechanisms to maintain system stability. One of the fundamental challenges in MGs is power sharing among distributed generation (DG) units while maintaining frequency and voltage stability.

Droop control is a widely used technique for power sharing in MGs, but it introduces frequency deviations from nominal values, necessitating a secondary control system (SCS) to correct these deviations. Additionally, communication delays in SCSs can impact MG stability, making control system optimization crucial.

This research investigates three secondary control strategies: Proportional-Integral (PI), Fractional-Order PI (FOPI), and Artificial Neural Network (ANN)- based controllers to mitigate the impact of communication delays on frequency restoration. A MATLAB/Simulink-based microgrid model is developed to evaluate the effectiveness of these control methods. The study aims to improve frequency stability by leveraging advanced control techniques, with ANN-based controllers showing superior performance in reduced overshoot, faster settling time, and robustness against communication delays.

## II. LITERATURE REVIEW

Rapid advancements in power systems have made integrating distributed energy resources possible. The development of microgrids (MGs) enhances energy resilience and efficiency. They can operate autonomously or in coordination with the primary grid, requiring robust control mechanisms to maintain system stability. However, integration is associated with challenges such as frequency instability, voltage fluctuations, and communication delays, necessitating the implementation of advanced secondary control strategies. Studies have been undertaken on various control techniques to enhance microgrid performance, including hierarchical control, fractional-order control, and intelligent learning-based control methods. One of the fundamental challenges in MGs is power sharing among distributed generation units while maintaining frequency and voltage stability.

Droop control is a widely used technique for power sharing in MGs, but it introduces frequency deviations from nominal values, necessitating a secondary control system (SCS) to correct these deviations. Communication delays in SCSs can impact MG stability, making control system optimization crucial.

### A. Hierarchical Control in Microgrids

Microgrid control is structured into primary, secondary, and tertiary levels. Guerrero et al. (2011) presented a hierarchical control approach for both AC and DC microgrids, outlining the droop-based primary control for real-time power sharing and secondary control for frequency restoration. Bidram and Davoudi (2012) extended this Approach by emphasizing the importance of tertiary control in optimizing power flow and economic dispatch. These studies highlighted that droop control is effective but requires a robust secondary control system (SCS) to mitigate deviations and ensure stable operation.

### B. Traditional PI and FOPI-Based Secondary Control

Proportional-integral (PI) controllers have been extensively used for secondary frequency restoration due to their simplicity. However, studies such as those by Madureira et al. (2005) demonstrated that PI-based controllers struggle with communication delays and varying load conditions, leading to performance degradation. To overcome these issues, fractional-order proportional-integral (FOPI) controllers were introduced. Zaheeruddin and Singh (2019) explored FOPI controllers for smart microgrids and demonstrated their improved adaptability over PI controllers. However, FOPI controllers remain susceptible to instability under prolonged communication delays despite better dynamic performance.

### C. Intelligent Control Techniques: ANN-Based Secondary Control

Artificial Neural Networks (ANNs) have gained significant attention due to their ability to learn system behaviours and adapt control responses accordingly. Ahumada et al. (2016) analyzed ANN-based secondary control strategies in islanded microgrids considering communication delays. They concluded that ANN controllers outperformed conventional controllers in terms of overshoot reduction and settling time. Similarly, Dashtdar et al. (2022) demonstrated that ANN-based controllers achieved superior robustness when trained with diverse operating conditions compared to PI and FOPI controllers. These studies emphasize ANN's ability to auto-tune parameters dynamically, thereby eliminating manual tuning requirements associated with conventional controllers.

### D. Impact of Communication Delays on Microgrid Stability

One of the significant concerns in microgrid secondary control is communication delay, which can significantly impact frequency restoration and system response. Kim et al. (2011) investigated the effect of communication delays in coordinated microgrid control strategies and found that increasing delays led to oscillatory behaviour and reduced stability margins. Olivares et al. (2014) analyzed different microgrid control trends and proposed decentralized control as a potential solution to mitigate delay-related instability. Han et al. (2015) also developed robust control mechanisms to counteract frequency deviations induced by delays.

### E. Secondary Control Strategies for Renewable

Energy-Based Microgrids

With the increasing penetration of renewable energy sources (RESs), several studies have investigated adaptive control mechanisms for frequency stabilization. Planas et al. (2012) explored stability analysis in renewable energy-dominated microgrids, emphasizing the importance of secondary controllers in balancing power fluctuations. Similarly, Micallef et al. (2014) proposed voltage harmonic distortion compensation techniques for droop-controlled microgrids. These works highlight the growing necessity for intelligent and adaptive control solutions in future MG operations. This study builds upon these previous works by evaluating ANN-based secondary control in the presence of communication delays and comparing its effectiveness with PI and FOPI controllers in microgrid applications.

## III. MATERIALS AND METHODOLOGY

### A. Microgrid Control Techniques

Microgrids integrate multiple DG units with varying power generation capacities and reliability levels. A hierarchical control system is employed to achieve efficient operation. This system balances power generation and demand, optimizes resource utilization, and maintains system stability under

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

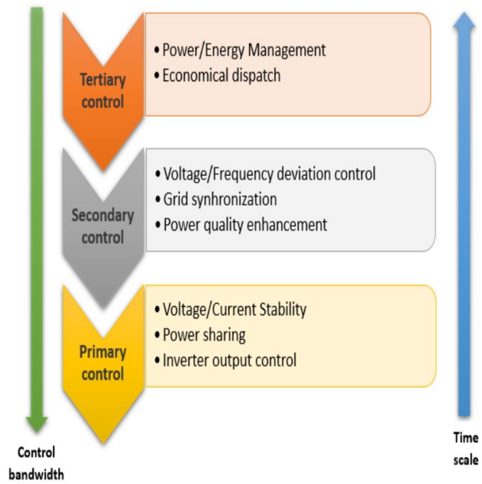


Figure 1: Hierarchical Control Architecture.

Different operational conditions. *Figure 1* illustrates the hierarchical control architecture of a microgrid.

*1) Primary Control*

Primary control operates locally, ensuring real-time voltage and frequency regulation. It primarily relies on:
Droop Control – Adjusts power output based on deviations in voltage and frequency using the equations:

$$F = f_0 - m_p P$$
$$V = V_0 - n_q Q$$

where $m_p$ and $n_q$ are droop coefficients, and P and Q represent active and reactive power, respectively.

Inner Loop Control—This method uses voltage and current control loops to regulate power electronic converters, maintaining stable output from DG units.
While droop control is adequate for power-sharing, it introduces steady-state errors requiring secondary control.
*Figure 2* shows the microgrid's primary control.

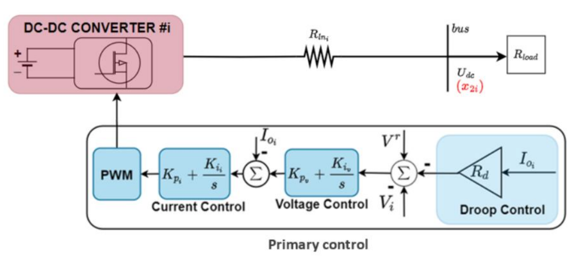


Figure 2: Primary Control of Microgrid.

*2) Secondary Control*

Secondary control compensates for the deviations caused by droop control and restores system parameters to nominal values. Three key approaches to secondary control are:

- Centralized Control: A single controller collects and processes system data, sending corrective signals to DG units.
- Distributed Control: Each DG unit communicates with neighbouring units, achieving self-adjusting frequency and voltage corrections.
- Decentralized Control: Each DG unit operates independently using local measurements without requiring communication links.

These control strategies are shown in *Figure 3*. The secondary control equation for frequency correction is:

$$\Delta f = K_p\, e(t) + K_i \int e(t)dt$$

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

where $K_p$ and $K_i$ are proportional and integral gains, and e(t) is the frequency deviation or error function.

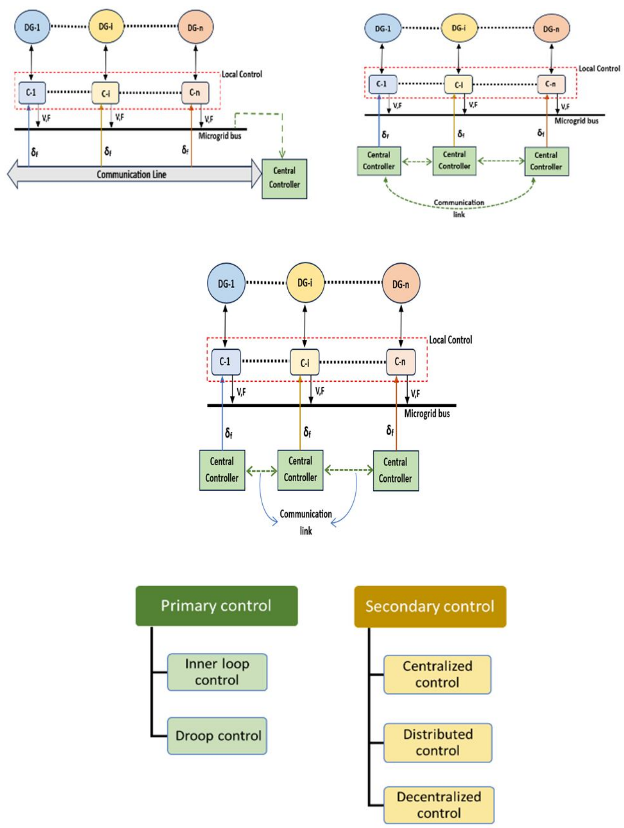



Figure 3: Secondary Control Strategies [Centralized, Distributed & Decentralized].

Tertiary Control

The tertiary control layer optimizes power exchange between the microgrid and the main grid. It operates on a slower timescale (minutes to hours) and focuses on:

- Economic dispatch – Minimizing operational costs while ensuring energy efficiency.
- Grid synchronization – Managing power flow between the microgrid and the primary grid.
- Load forecasting – Anticipating demand fluctuations and adjusting power generation accordingly.

### *B. Impact of Communication Delays*

Secondary and tertiary controls rely on communication networks, which introduce time delays in data transmission. These delays can result in:

- Frequency instability and voltage oscillations.
- Degraded power-sharing efficiency.
- Reduced system response times.

To model communication delays mathematically:

$$G(s) = \frac{K}{1 + sT} e^{-sT}$$

K is the system gain, T is the time constant, and $e^{-sT}$ represents the delay effect.

To mitigate these challenges, predictive control techniques such as Artificial Neural Networks (ANNs) and Model Predictive Control (MPC) are explored.

Hierarchical control is critical in ensuring microgrids' stable, reliable, and cost-effective operation. Primary control ensures immediate stability, secondary control restores system parameters, and tertiary control optimizes energy flow. Future advancements in AI-driven control methods could enhance microgrids' adaptability and resilience in real-world applications.

### *C. Microgrid Model*

A microgrid model comprising solar photovoltaic (PV), DC-DC converters, and three voltage source converters (VSCs) was developed in MATLAB/Simulink. The microgrid operates in both islanded and grid-connected modes, allowing for an assessment of various secondary control techniques. The proposed system considers the influence of renewable energy integration and communication delays on system performance. *Figure 4* illustrates the implemented microgrid model.

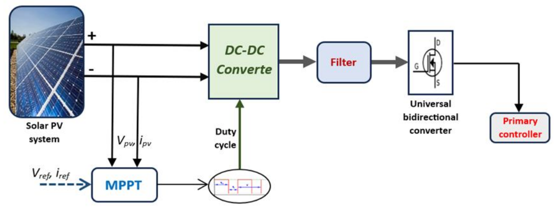



Figure 4: Microgrid System Model

### *D. Control Strategies Implemented*

In this research, three secondary control strategies were examined for frequency and voltage restoration:

*1)* Proportional-Integral (PI) Controller

The conventional PI controller corrects steady-state errors introduced by primary droop control. The control law is defined as:

$$u(t) = K_p\, e(t) + K_i \int e(t)dt$$

where u(t) is the control signal, $K_p$ and $K_i$ are proportional and integral gains, respectively, and e(t) is the frequency deviation error. Although simple to implement, PI controllers exhibit performance limitations under high communication delays.

*2)* Fractional-Order PI (FOPI) Controller

The FOPI controller extends PI control using fractional calculus, enhancing system adaptability. The control law is expressed as:

$$u(t) = K_p\, e(t) + K_i\, D^{\lambda}\, e(t)$$

where $D^{\lambda}$ is the fractional-order integral, $\lambda$ determines the memory effect of past control actions.
This controller improves transient response but presents challenges in parameter tuning.

*3)* Artificial Neural Network (ANN) Controller

The ANN-based controller employs a multi-layer perceptron (MLP) to adjust control parameters based on dynamic system variations. It is trained using backpropagation, minimizing the error function:

$$E = 0.5 * \sum (y_d - y)^2$$

where: "$y_d$" is the desired frequency, and "y" is the actual frequency.
The ANN controller adapts to varying operating conditions, significantly reducing overshoot and settling time. Figure 5 illustrates an ANN controller.

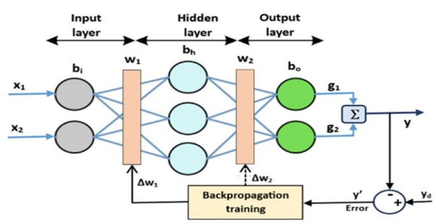



Figure 5: ANN-Based Control Structure

### *E. Simulation Approach*

The microgrid model was simulated under different conditions to evaluate the performance of each control strategy:

- Nominal conditions (without communication delays)
- Communication delay scenarios (0.1s, 0.2s, 0.3s)
- Load variations to assess dynamic adaptability

Performance metrics such as settling time, overshoot, and frequency stability were recorded for comparative analysis.

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

### *F. Performance Evaluation Metrics*

The controllers were assessed based on:

- Settling Time (Ts): This is the time the system frequency takes to stabilize within ±2% of the final value after a disturbance.
- Overshoot (Mp): Maximum deviation from the nominal frequency.
- Robustness: Stability under high communication delays.

## IV. RESULTS AND DISCUSSION

### *A. Simulation Model*

The simulation model consists of a 700V DC source, three VSCs, and AC loads, with secondary controllers implemented in different configurations. *Figure 6* presents the block diagram of the secondary controller-connected microgrid used for analysis. Table 1 summarises the system parameters used in the simulation.

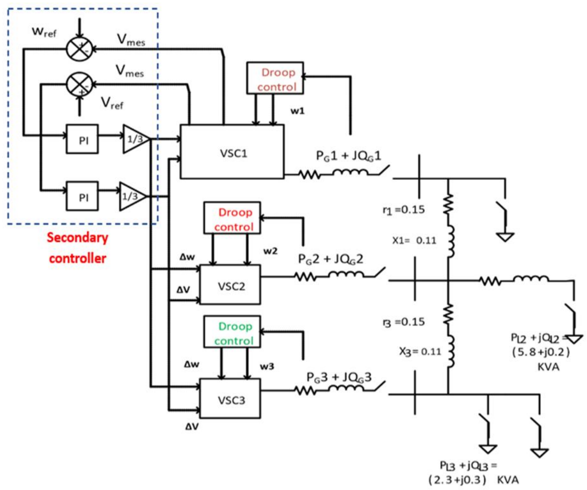



Figure 6: Block Diagram of Secondary Controller Connected Microgrid

Table 1: Microgrid Parameters

| Parameter | Value | Unit |
|---|---|---|
| Source Capacitance (C1) | 40 | μF |
| Filter Inductance (L1) | 6 | mH |
| Line Resistance (R2) | 0.15 | Ω |
| Source Voltage (DC) | 700 | V |
| Inverter Rating | 20 | KVA |

### *B. PI-Based Secondary Control*

The PI controller is tested under different communication delays (0s, 0.1s, 0.2s, and 0.3s). The frequency and active power-sharing responses are evaluated.

- Without communication delay (0s): Frequency stabilizes at 3s with minimal oscillations (*Figure 7*).
- With communication delay (0.2s): Increasing delay leads to more oscillations and longer settling time (*Figure 8*).
  Observation:

1. PI controllers exhibit long settling times and poor performance as communication delay increases.
2. Active power-sharing remains stable but experiences minor oscillations.

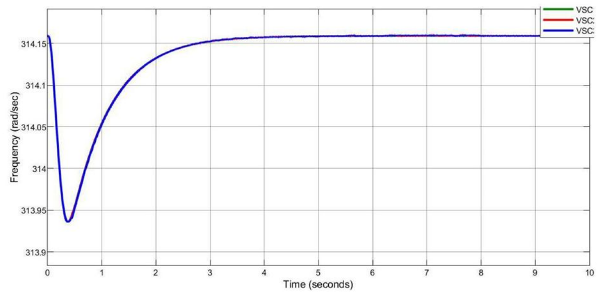



Figure 7: Frequency Response Without Communication Delay

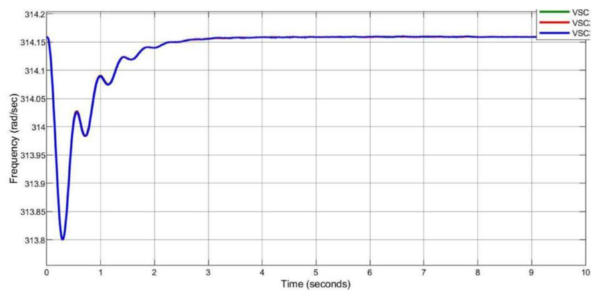



Figure 8: Frequency Response With 0.2s Delay

*C. FOPI-Based Secondary Control*

The FOPI controller improves frequency response with better adaptability than the PI controller.

- Without delay: Faster settling time compared to PI control (*Figure 9*).
- With 0.2s delay, Frequency oscillations increase, with peak overshoot higher than PI control (*Figure 10*).
- With a 0.3s delay, The system becomes unstable due to high oscillations.

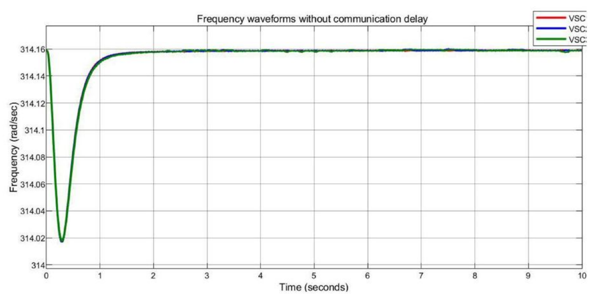



Figure 9: Frequency Response Without Communication Delay (FOPI)

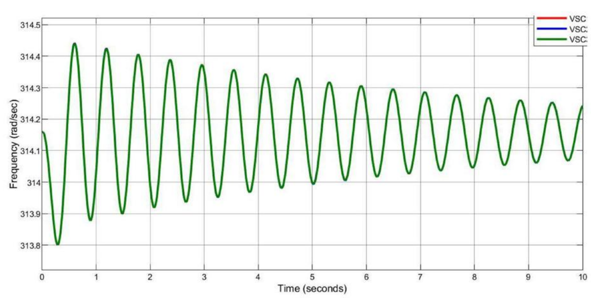



Figure 10: Frequency Response With 0.2s Delay (FOPI)

Observation:

1. Better transient response than PI, but sensitive to communication delay.
2. FOPI provides more tuning flexibility but becomes unstable beyond 0.3s delay.

### *D. ANN-Based Secondary Control*

The ANN-based controller dynamically adjusts control parameters and outperforms PI and FOPI controllers to maintain system stability.

- Without delay: Fastest settling time (1s) and minimal overshoot (*Figure 11*).
- With delay (0.1s - 0.3s): ANN exhibits superior robustness compared to conventional controllers.
- With a 0.3s delay, The ANN maintains stability, whereas FOPI becomes unstable (*Figure 12*).

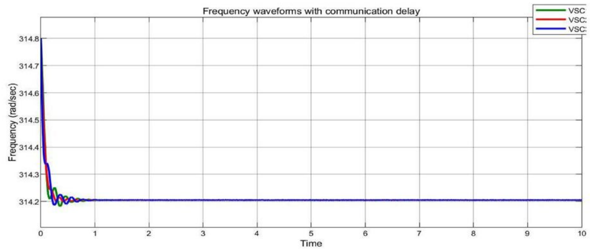



Figure 11: Frequency Response Without Communication Delay (ANN)

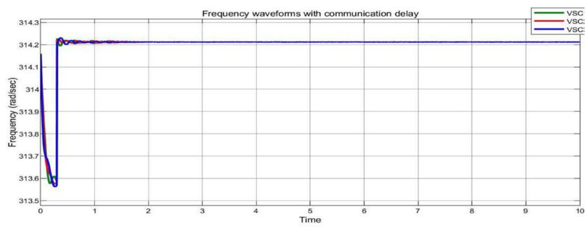



Figure 12: Frequency Response With 0.3s Delay (ANN)

Observation:

1. ANN controller has the shortest settling time and the least oscillations.
2. Best response under communication delays, making it the most effective control strategy.

### *E. Comparative Analysis of Controllers*

A combined frequency deviation analysis for all controllers under different conditions is provided in *Figures (13-15)*.

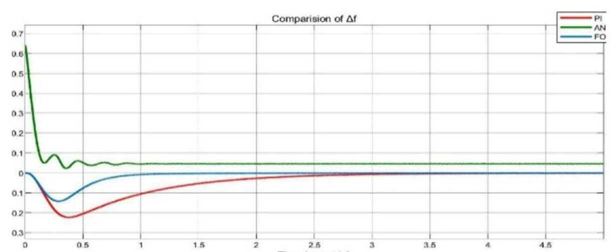



Figure 13: Frequency Deviation Comparison Without Delay

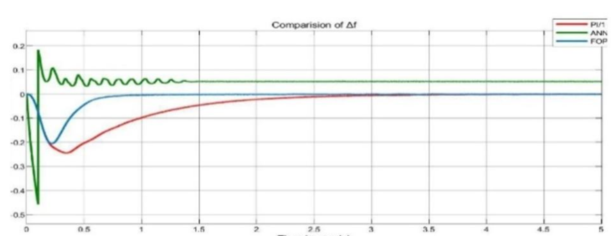



Figure 14: Frequency Deviation Comparison With 0.1s delay

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

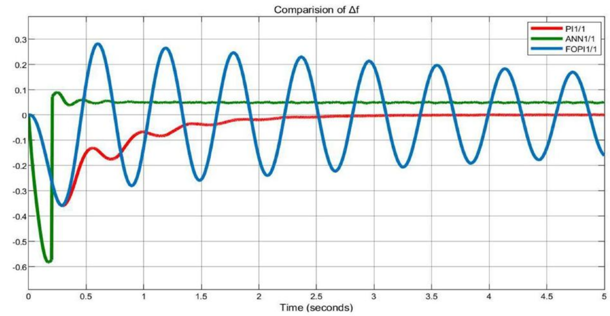


Figure 15: Frequency Deviation Comparison With 0.2s delay

Table 2: Performance Comparison of Controllers

| Controller Type | Settling time (s) | Overshoot (%) | Stability Under Delay |
|---|---|---|---|
| PI Controller | 4.5 | 8.2 | Moderate |
| FOPI Controller | 3.2 | 6.5 | Limited |
| ANN Controller | 1.8 | 3.1 | High |

From the above (*Table 2*), the performance of various controllers can be concluded as follows:

- PI controllers struggle with communication delays, resulting in high settling times and frequency oscillations.
- FOPI controllers perform better in low-delay environments but become unstable beyond 0.3s delay.
- ANN controllers demonstrate the best overall performance with the shortest settling time, minimal overshoot, and robustness against communication delays.

This analysis confirms that ANN-based secondary control optimizes frequency restoration in microgrid systems.

## V. CONCLUSION

Considering communication delays and system uncertainties, this study analyzed the effectiveness of PI, FOPI, and ANN-based secondary control strategies for microgrid frequency stabilization. The simulation results demonstrated that ANN-based control significantly outperforms traditional controllers in terms of response time, stability, and robustness under varying communication conditions.

Key findings include:

1) PI Controller: Exhibited the longest settling time (4.5s) and highest overshoot (8.2%), making it less effective under communication delays.
2) FOPI Controller: Improved dynamic response with a settling time of 3.2s and overshoot of 6.5%, but became unstable beyond 0.3s delay.
3) ANN Controller: Demonstrated the fastest response (settling time: 1.8s, overshoot: 3.1%), proving highly adaptive even under high communication delays.

The ANN-based secondary control method ensures superior frequency restoration, minimized oscillations, and enhanced system stability, making it the most effective strategy for modern microgrids.

## VI. FUTURE SCOPE

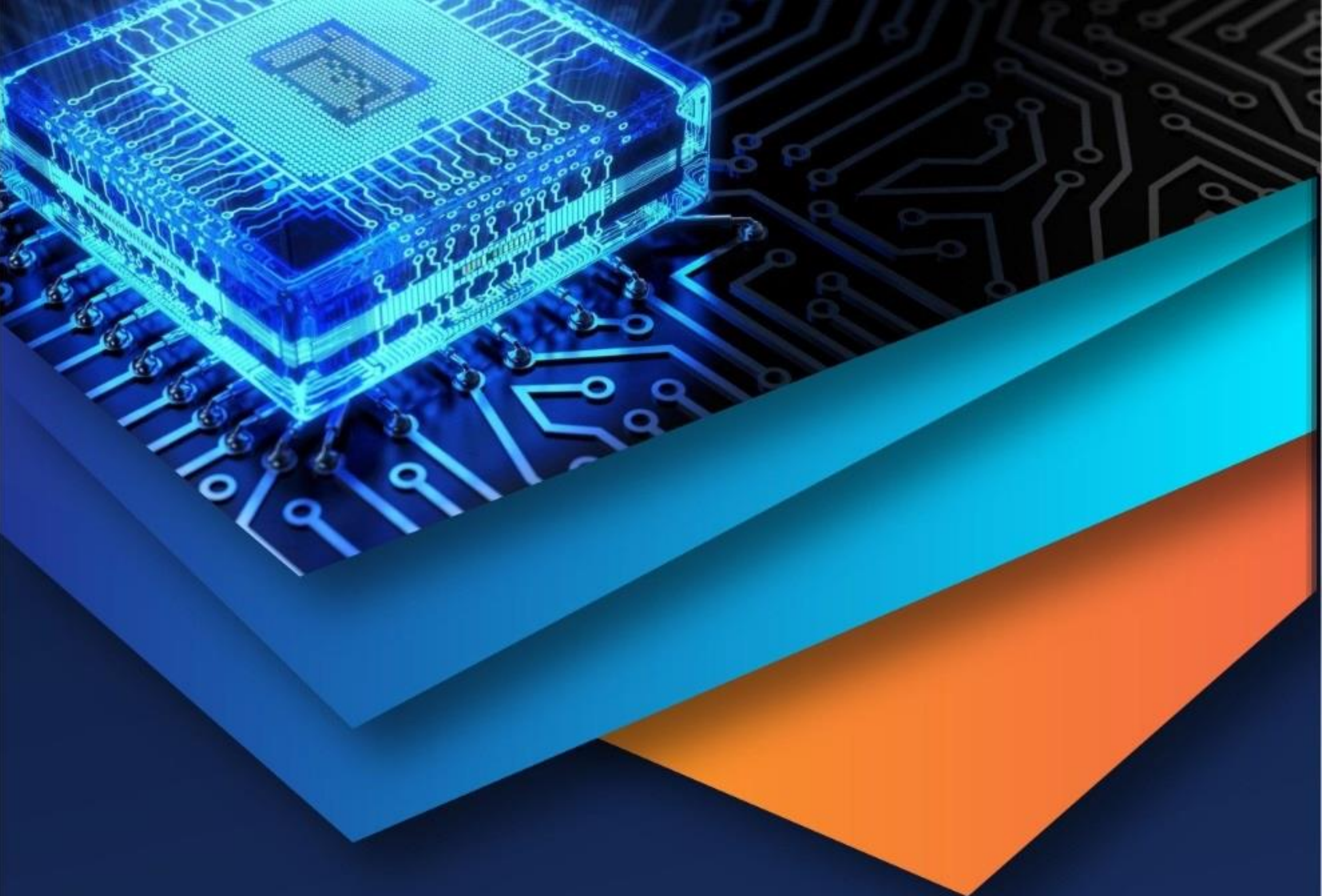
The study on secondary control strategies for microgrid frequency restoration provides significant insights, but further advancements are required to enhance system efficiency and reliability. The following directions are proposed for future research:

- Real-Time Implementation: The proposed ANN-based secondary control strategy should be implemented in real-time hardware using FPGA or DSP platforms to validate its practical feasibility.
- Hybrid Energy Integration: Integrating hybrid energy sources, including wind, fuel cells, and battery storage, will be explored to analyze their impact on microgrid stability.
- Advanced Deep Learning Techniques: To further improve dynamic adaptability, more advanced machine learning models, such as reinforcement learning and deep neural networks (DNNs), can be investigated for predictive secondary control.
- Adaptive Control Optimization: Optimization techniques, such as genetic algorithms (GA) and particle swarm optimization (PSO), can fine-tune controller parameters dynamically.
- Cybersecurity in Microgrids: With increasing reliance on communication networks, the security of microgrid control systems against cyber threats should be studied, focusing on secure communication protocols.

These future developments will contribute to the evolution of intelligent, resilient, and adaptive microgrid control systems capable of maintaining stability under dynamic operational conditions.

## REFERENCES

[1] Guerrero, J. M., Vasquez, J. C., Matas, J., de Vicuna, L. G., & Castilla, M. (2011). Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization. IEEE Transactions on Industrial Electronics, 58(1), 158-172.
[2] Bidram, A., & Davoudi, A. (2012). Hierarchical structure of microgrids control system. IEEE Transactions on Smart Grid, 3(4), 1963-1976.
[3] Olivares, D. E., Mehrizi-Sani, A., Etemadi, A. H., Cañizares, C. A., Iravani, R., Kazerani, M., ... & Jiménez-Estévez, G. A. (2014). Trends in microgrid control. IEEE Transactions on Smart Grid, 5(4), 1905-1919.
[4] Madureira, A. G., & Pecas Lopes, J. A. (2005). Coordinated voltage support in distribution networks with distributed generation and microgrids. IET Generation, Transmission & Distribution, 1(3), 93-100.
[5] Zaheeruddin & Singh, M. (2019). Fractional-order proportional-integral (FOPI) controller for microgrid applications. International Journal of Electrical Power & Energy Systems, 109, 392–401.
[6] Dashtdar, M., Farahmand, H., & Khosravi, A. (2022). Artificial neural network-based secondary control for frequency restoration in microgrids. Energy Reports, 8, 1201-1215.
[7] Kim, J., Lee, H., & Park, J. (2011). The impact of communication delays in distributed secondary frequency control of microgrids. IEEE Transactions on Power Systems, 26(3), 1601-1613.
[8] Planas, E., Andreu, J., Gomis-Bellmunt, O., & Martinez de Alegria, I. (2012). AC and DC technology in microgrids: A review. Renewable and Sustainable Energy Reviews, 19, 407-416.
[9] Micallef, A., Apap, M., Spiteri-Staines, C., & Guerrero, J. M. (2014). Single-phase microgrid voltage control techniques based on droop control. IEEE Transactions on Power Electronics, 31(7), 5083–5098.
[10] Han, Y., Hou, X., Yang, D., Yu, X., Guerrero, J. M., & Vasquez, J. C. (2015). Review of secondary voltage and frequency control techniques in islanded microgrids. IEEE Transactions on Power Electronics, 32(6), 4550-4569.
[11] GAO, F., KANG, R., CAO, J. et al. Primary and secondary control in DC microgrids: a review. J. Mod. Power Syst. Clean Energy 7, 227–242 (2019).
[12] T. L. Vandoorn, J. C. Vasquez, J. De Kooning, J. M. Guerrero, and L. Vandevelde, “Microgrids: Hierarchical control and an overview of the control and reserve management strategies,” IEEE Ind. Electron. Mag., vol. 7, no. 4. pp. 42–55, Dec. 2013.
[13] C. Ahumada, R. Cárdenas, D. Sáez and J. M. Guerrero, "Secondary Control Strategies for Frequency Restoration in Islanded Microgrids with Consideration of Communication Delays," in IEEE Transactions on Smart Grid, vol. 7, no. 3, pp. 1430–1441, May 2016.
[14] C. Wang, X. Yang, Z. Wu et al., "A highly integrated and reconfigurable microgrid testbed with hybrid distributed energy sources," IEEE Transactions on Smart Grid, vol. 7, no. 1, pp. 451–459, Jan. 2016.
[15] F. Blaabjerg, Z. Chen, and S. B. Kjaer, "Power electronics as efficient interface in dispersed power generation systems," IEEE Transactions on Power Electronics, vol. 19, no. 5, pp. 1184–1194, Sept. 2004.
[16] S. Marzal, R. Salas, R. González-Medina et al., "Current challenges and future trends in the field of communication architectures for microgrids," Renewable & Sustainable Energy Reviews, vol. 82, pp. 3610–3622, Feb. 2018.
[17] Y.-S. Kim, E.-S. Kim, and S.-I. Moon, “Frequency and voltage control strategy of standalone microgrids with high penetration of intermittent renewable generation systems,” IEEE Transactions on Power Systems, vol. 31, no. 1, pp. 718-728, Jan. 2016.
[18] J.-Y. Kim, J.-H. Jeon, S.-K. Kim et al., "Cooperative control strategy of energy storage system and microsources for stabilizing the microgrid during islanded operation," IEEE Transactions on Power Electronics, vol. 25, no. 12, pp. 3037–3048, Dec. 2010.
[19] X. Tang and Z. Qi, "Energy storage control in renewable energy based microgrid," in Proceedings of IEEE PES General Meeting, San Diego, USA, Jul. 2012, pp. 1–6.
[20] R. H. Lasseter, "Microgrids," in Proceedings of IEEE PES Winter Meeting, New York, USA, Jan. 2002, pp. 305–308.
[21] S. M. Ashabani and Y. Mohamed, "New family of microgrid control and management strategies in smart distribution grids – analysis, comparison and testing," IEEE Transactions on Power Systems, vol. 29, no. 5, pp. 2257–2269, Sept. 2014.




10.22214/IJRASET

INDEX COPERNICUS
45.98

IMPACT FACTOR:
7.129

TOGETHER WE REACH THE GOAL

IMPACT FACTOR:
7.429


# INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY