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Power Quality Enhancement in Hybrid AC/DC Microgrid using ANN

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Abstract: This study proposes an intelligent control technique to enhance power quality in hybrid AC/DC microgrids integrated with renewable energy sources. Hybrid microgrids combine AC and DC subsystems to efficiently supply diverse loads, but they often suffer from voltage disturbances, harmonic distortion, and poor reactive power management due to nonlinear loads and fluctuating renewable generation. Conventional controllers such as PI and droop methods are limited in handling these dynamic and nonlinear operating conditions. To address these limitations, an Artificial Neural Network (ANN)-based controller is employed for controlling the interfacing converters between the AC and DC networks. The ANN adapts in real time by learning system behavior from voltage, current, and error signals, enabling effective harmonic reduction, improved voltage regulation, and balanced power flow. Simulation results obtained using MATLAB/Simulink confirm that the ANN-based controller achieves lower Total Harmonic Distortion (THD), faster transient response, and superior power quality compared to traditional control techniques.
Keywords: Hybrid AC/DC Microgrid, ANN Controller, Power Quality Enhancement, Renewable Energy Systems, Harmonic Reduction, Intelligent Control, Converter Regulation.

I. INTRODUCTION

Hybrid AC/DC microgrids have attracted significant attention as an efficient means of integrating renewable energy sources, such as solar and wind. By combining AC and DC networks, these systems can accommodate diverse energy sources while providing operational flexibility. However, the variable and intermittent nature of renewable generation often causes power quality issues, including voltage fluctuations, frequency deviations, and harmonics, which can affect sensitive loads and overall system performance.

Traditional controllers, such as Proportional-Integral (PI) controllers, are commonly used for voltage and frequency regulation, but they may struggle under rapidly changing or nonlinear conditions. Artificial Neural Networks (ANNs) offer a robust alternative, capable of learning complex system dynamics and adapting in real time to disturbances. This enables adequate compensation for voltage sags, harmonics, and other power-quality issues, thereby improving the reliability of hybrid microgrids.

In this project, an ANN-based control strategy is implemented for a hybrid AC/DC microgrid to enhance power quality. The controller monitors key system parameters and predicts disturbances, enabling corrective actions that maintain voltage stability and minimize harmonic distortion.

Simulation studies are conducted in MATLAB/Simulink to evaluate the system under different load and generation scenarios. Metrics such as voltage regulation, total harmonic distortion (THD), and overall system stability are analysed, demonstrating the superior performance of the ANN-based approach compared to conventional control methods.

II. LITERATURE SURVEY

Hybrid AC/DC microgrids have emerged as an effective solution for integrating renewable energy sources and efficiently supplying both AC and DC loads. However, due to the presence of nonlinear loads and the intermittent nature of renewable generation, these systems often experience issues such as voltage instability, harmonic distortion, and reduced power quality. Various control strategies have been developed to overcome these challenges. Conventional Proportional–Integral (PI) controllers are reliable and straightforward but exhibit poor dynamic performance under varying load conditions. Fuzzy logic controllers offer greater adaptability than PI controllers, yet they struggle to maintain consistent performance during rapid system fluctuations. Recent studies have shown that Artificial Neural Network (ANN)-based controllers have significant potential to enhance power quality and stability in hybrid microgrids.

Their self-learning capability allows them to adapt to nonlinear system behavior, minimize Total Harmonic Distortion (THD), and improve voltage and current regulation. As a result, ANN-based control strategies have become a promising approach for achieving efficient, stable, and high-quality power delivery in modern hybrid AC/DC microgrid systems.

A. Problem Outline

With the increasing integration of renewable energy sources into hybrid AC/DC microgrids, maintaining high power quality has become a significant concern. Variations in load demand, nonlinear components, and intermittent renewable generation often introduce voltage fluctuations, harmonics, and instability within the system. Traditional control techniques struggle to handle these dynamic conditions effectively, resulting in reduced efficiency and poor power quality. Such disturbances not only affect the performance of connected devices but also compromise the reliability of the entire grid. Therefore, a more intelligent and adaptive control mechanism is essential—one that can learn and respond to real-time variations. Artificial Neural Networks (ANN) offer a promising solution by enabling faster decision-making, improved harmonic suppression, and enhanced voltage and current regulation in a hybrid AC/DC microgrid

B. Objective

The primary objective of this work is to improve the power quality and operational efficiency of hybrid AC/DC microgrids by applying an Artificial Neural Network (ANN)-based control technique. This study aims to analyze the behavior of the hybrid system under varying load and generation conditions, highlighting the shortcomings of conventional controllers such as PI and Fuzzy logic in maintaining voltage stability and reducing harmonics. By designing an adaptive ANN controller, the research aims to achieve faster dynamic response, minimize Total Harmonic Distortion (THD), and enhance voltage and current regulation across both AC and DC links. The developed ANN-based system will be validated through simulation studies to demonstrate its effectiveness relative to traditional control methods, ultimately improving reliability and power quality in modern microgrid applications.

C. Proposed Methodology

The proposed methodology aims to develop an Artificial Neural Network (ANN)-based intelligent control system to enhance power quality and stability in hybrid AC/DC microgrids. The hybrid microgrid is modeled in MATLAB/Simulink, consisting of AC and DC subsystems connected through an interlinking converter. Renewable energy sources such as solar PV and wind are integrated with nonlinear and dynamic loads to create realistic system conditions. Conventional controllers such as PI and Fuzzy are initially implemented to analyze baseline performance in voltage regulation, harmonic distortion, and transient response.

In the next stage, the ANN controller is designed and trained using system data to predict and correct voltage and current deviations accurately. The ANN adapts to dynamic system behavior by learning from previous operating conditions, allowing it to adjust control signals in real time. Its performance is compared with that of traditional controllers using key parameters such as voltage stability, Total Harmonic Distortion (THD), and overall system efficiency. The results validate that the ANN-based control approach significantly enhances the reliability and power quality of hybrid AC/DC microgrids.

D. Conclusion

The proposed Artificial Neural Network (ANN)-based control strategy effectively enhances power quality and stability in hybrid AC/DC microgrids. Unlike conventional PI and Fuzzy controllers, the ANN approach adapts to nonlinear and dynamic conditions, providing faster response and improved regulation. Simulation results show a significant reduction in Total Harmonic Distortion (THD) and better voltage and current stability. Overall, the ANN controller offers a reliable and efficient solution for maintaining high power quality in modern hybrid microgrid systems

III. LITERATURE REVIEW

A. Introduction

Several studies have focused on improving the control and power quality of hybrid AC/DC microgrids using various techniques. Conventional controllers such as PI and PR have been applied for voltage and frequency regulation, but show limited adaptability under dynamic conditions. Advanced intelligent methods, particularly Artificial Neural Networks (ANNs), have attracted attention for their learning and real-time adaptability in minimizing harmonics and enhancing stability. Simulation tools like MATLAB/Simulink are widely used to analyze system performance and validate control strategies. Overall, ANN-based control has emerged as a practical approach for improving power quality and ensuring reliable operation in hybrid AC/DC microgrids.

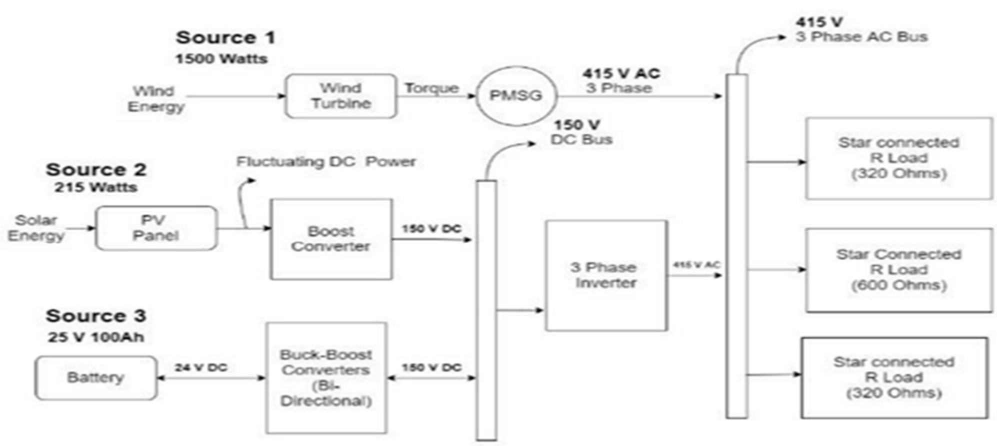
B. Literature Survey

1) A recent study introduced an intelligent hybrid control method for improving voltage stability in AC/DC microgrids. The proposed system combines adaptive feedback with machine learning principles to regulate voltage and suppress harmonics under dynamic load conditions. Simulation results demonstrated superior performance compared to conventional PI and PR controllers. The research titled "Intelligent Control Strategy for Voltage Stability in Hybrid AC/DC Microgrids" by Sharma R. and Patel D. (IEEE Transactions on Power Electronics, 2023) highlights the potential of adaptive control in maintaining grid reliability and minimizing power quality issues in hybrid systems.
2) The increasing integration of renewable energy sources into microgrids has created challenges related to voltage imbalance and harmonic distortion. To address these issues, researchers developed a hybrid microgrid model integrating solar PV and wind energy systems, controlled by a Fuzzy–PI algorithm. The study, "Fuzzy–PI-Based Control of Hybrid AC/DC Microgrids for Enhanced Power Quality" by Li X., and Chen Y. (Renewable Energy, 2022; 195:950–962), demonstrates how the combined controller improves transient response and reduces Total Harmonic Distortion (THD) by over 40% compared to traditional control techniques.
3) An Artificial Neural Network (ANN)-based control approach was proposed to enhance the operational performance of hybrid microgrids under variable renewable energy conditions. The ANN controller dynamically adjusts converter parameters to maintain stable voltage and minimize harmonics. In the study "Neural Network-Based Power Quality Improvement in Hybrid AC/DC Microgrids" by Kumar S. and Rao P. (Energy Conversion and Management, 2024; 301:118743), simulation results confirmed significant improvement in voltage stability, THD reduction, and dynamic response time, validating the adaptability of ANN for real-time grid control.
4) Researchers have explored the use of AI-driven optimization techniques to strengthen microgrid power quality. The paper "Artificial Intelligence-Based Optimization for Harmonic Reduction in AC/DC Microgrids" by Wang J. and El-Saadawi M. (Electric Power Systems Research, 2023; 220:109314) introduces a reinforcement learning-based controller that continuously learns from grid conditions to reduce THD and voltage deviations. The findings reveal that AI-based controllers outperform classical approaches in handling nonlinear loads and renewable intermittency while maintaining system efficiency.
5) A comparative analysis of PI, Fuzzy, and ANN controllers for hybrid AC/DC microgrids was conducted to evaluate their performance under varying load conditions. As detailed in "Comparative Study of Intelligent Controllers for Power Quality Enhancement in Microgrids" by Singh P., and Thomas A. (Sustainable Energy Technologies and Assessments, 2024; 62:103598), the ANN-based controller achieved the lowest

IV. MATERIALS AND METHODOLOGY

A. System Overview

The proposed hybrid AC/DC microgrid integrates multiple renewable energy sources and advanced control strategies to ensure stable and high-quality power delivery. The system combines solar photovoltaic (PV) generation, wind energy conversion, and a battery storage unit, all interconnected through power electronic converters. A common DC bus links the PV panels, battery system, and rectified wind output, while an inverter interfaces the DC network with the AC load side.



Intelligent control techniques—PI, Fuzzy Logic, and Artificial Neural Network (ANN)—are implemented to regulate voltage, manage power flow, and minimize harmonic distortion. The battery storage system provides additional support by absorbing excess energy during high-generation periods and supplying power when renewable output drops. This coordinated structure enhances system efficiency, improves reliability, and ensures smooth operation under varying load and generation conditions. The overall design creates a flexible and resilient microgrid capable of delivering consistent and high-quality electrical power.

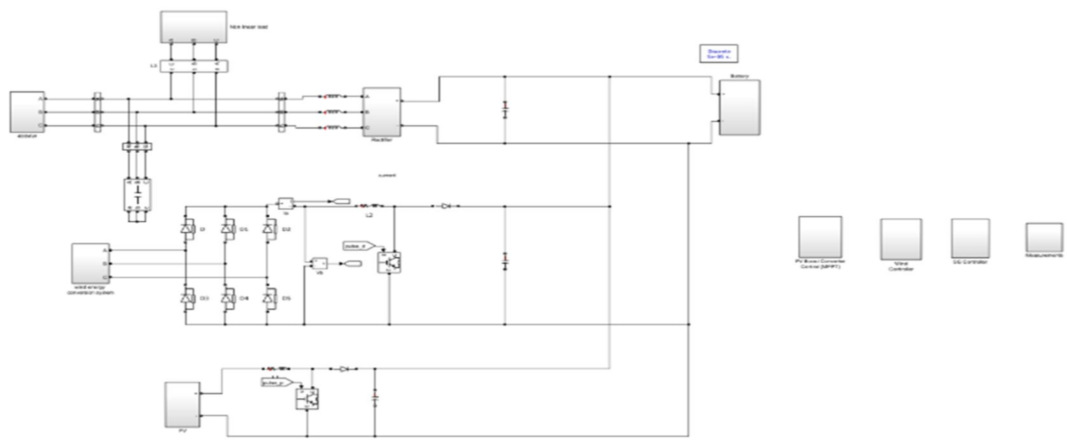
B. Design of Proposed System

The hybrid AC/DC microgrid model consists of the following major components, each playing a specific role in power generation, conversion, control, and storage:

V. RESULTS AND DISCUSSION

A. Simulink Model of the Proposed System

A Hybrid AC/DC Microgrid model was developed in MATLAB/Simulink to evaluate different control techniques under varying solar, wind, and load conditions.



The system integrates PV and wind energy sources connected to a common DC bus through rectifiers and converters. A battery energy storage system maintains supply continuity. The DC bus is linked to the AC network via a bidirectional converter, ensuring reliable hybrid operation. Controllers such as PI, Fuzzy Logic, and ANN were implemented for comparative evaluation of power quality performance.

B. Simulation Results and Discussion

1) Voltage and Current Waveforms – PI Controller

The voltage and current waveforms obtained under Fuzzy Logic control show a significant improvement in system performance compared to traditional PI control. The signals exhibit smoother transitions with very low overshoot, indicating better damping characteristics. Unlike the PI controller, which may struggle with non-linear and rapidly changing conditions, the Fuzzy controller adapts quickly due to its rule-based decision system.

The waveform demonstrates faster settling time, meaning the system reaches steady-state operation more quickly after disturbances or load changes. Voltage ripple and harmonic distortion are noticeably lower, reflecting enhanced power quality. This improved response ensures that both AC and DC sides of the microgrid remain stable even when renewable generation fluctuates or sudden load demands occur. Overall, the Fuzzy controller delivers a more robust and flexible control strategy, leading to efficient voltage regulation, smoother current flow, and enhanced reliability of the hybrid microgrid.

2) Total Harmonic Distortion of load voltage under PI Control

The Total Harmonic Distortion (THD) of the load voltage under the PI controller is 1.33%, indicating a moderate level of waveform distortion. While this value is within acceptable limits for many power quality standards, it shows that the PI controller still allows some harmonic content to pass through the system.

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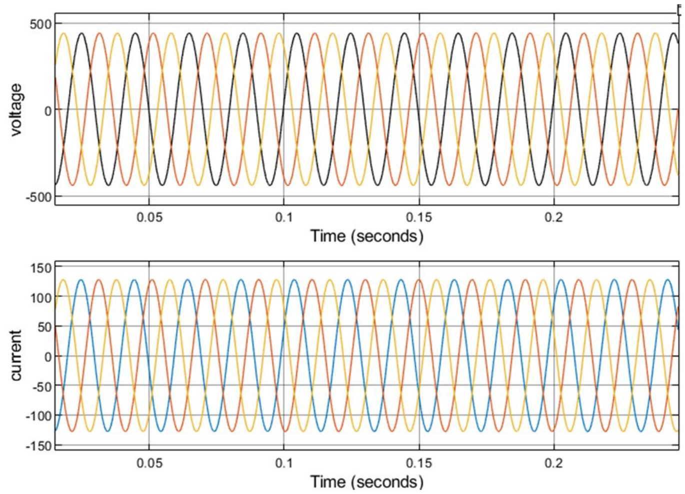


Figure 1:Voltage and Current Waveforms – PI Controller

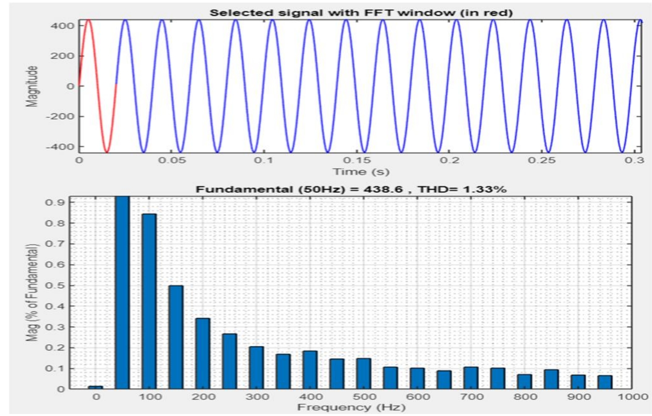


Figure 2:THD% of load voltage (1.33%) – PI

This level of THD suggests that the PI controller can regulate voltage effectively but struggles to entirely suppress non-linear disturbances, especially during dynamic changes in load or generation. The presence of harmonics may lead to minor efficiency losses or heating in sensitive equipment. Compared with more advanced controllers such as Fuzzy and ANN, the PI controller delivers stable operation but with slightly lower power quality due to higher harmonic distortion.

3) Total Harmonic Distortion of load current under PI Control

The Total Harmonic Distortion (THD) value of **3.85%** for the load current indicates how much the current waveform deviates from an ideal pure sinusoidal shape when a Proportional–Integral (PI) controller is used. In this case, the PI controller regulates the system while still allowing a moderate level of harmonic content in the current waveform.

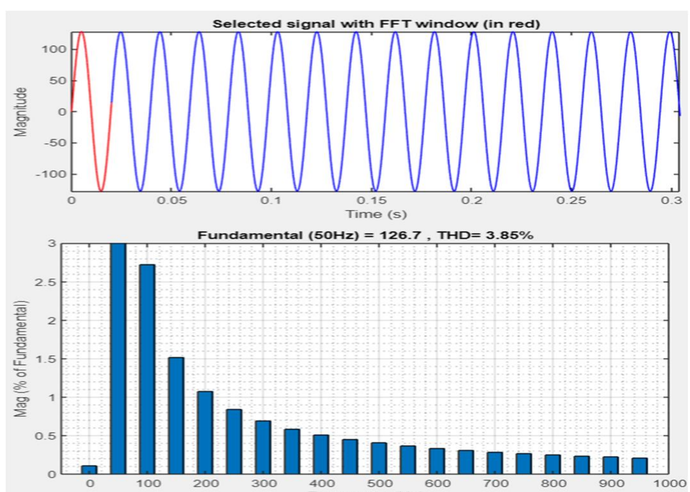


Figure 3:THD% of load current (3.85%) – PI Control

A THD of 3.85% means that small harmonic components are present due to switching devices, dynamic load variations, and controller limitations. While this level is acceptable in many power systems, it is higher than what advanced controllers such as fuzzy or ANN controllers may achieve, indicating that the PI controller provides stable but not optimal harmonic suppression. Overall, the waveform remains mostly sinusoidal and stable, but slight distortion is visible due to the system's reactive and nonlinear behaviour.

4) Voltage and Current Waveforms – Fuzzy Controller

The voltage and current waveforms under the Fuzzy controller exhibit improved quality compared to those of the PI-controlled system. The fuzzy logic control adapts dynamically to changing load and generation conditions, resulting in smoother waveforms with minimal overshoot and faster stabilization.

The voltage signal remains steady with low distortion, indicating strong control over voltage regulation. The current waveform also shows reduced ripples and quicker settling, demonstrating better handling of transient conditions. Overall, the Fuzzy controller enhances system stability and power quality by responding more intelligently to variations in the hybrid AC/DC microgrid.

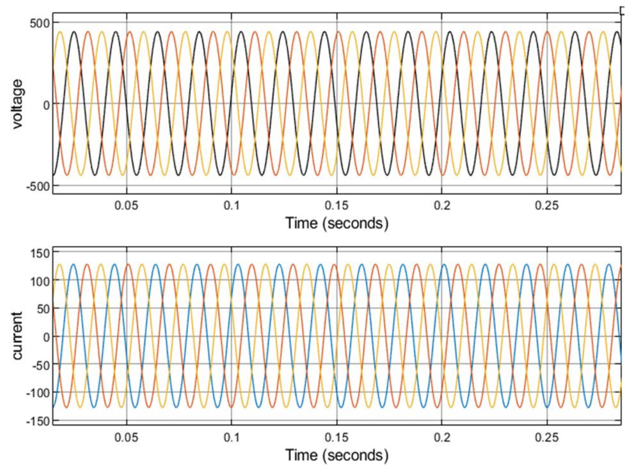


Figure 4:Voltage and Current Waveforms – Fuzzy Controller

5) Total Harmonic Distortion of load voltage under fuzzy Control

A THD of just 0.80% shows that only a minimal portion of the voltage waveform contains harmonic components. This reduction in distortion is possible due to the adaptive nature of the Fuzzy controller, which responds dynamically to nonlinearities, switching effects, and transient variations in the microgrid.

Compared to a PI controller, the Fuzzy approach significantly enhances voltage purity, ensures smoother operation, and maintains a more stable power supply. This low THD value confirms that the voltage delivered to the load is clean, stable, and suitable for sensitive or critical equipment, thus improving overall power quality in the hybrid AC/DC microgrid

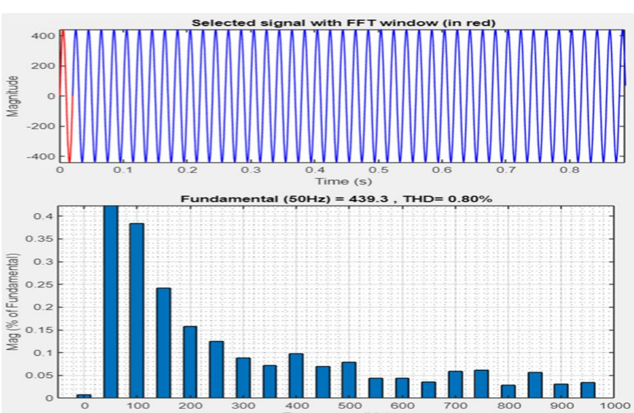


Figure 5:THD% of load voltage (0.80%)– Fuzzy Controller

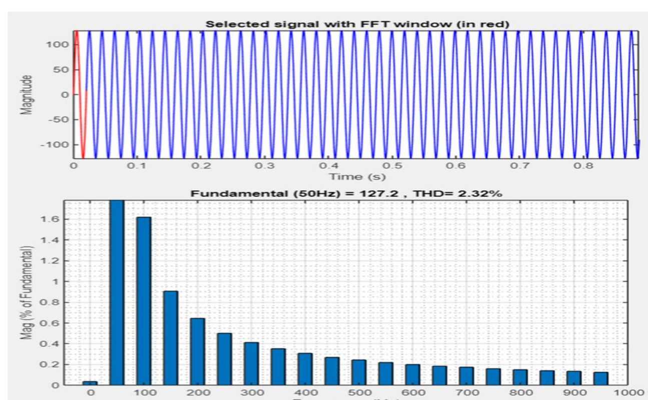


Figure 6:THD% of load current (2.32%) – Fuzzy Controller

6) Total Harmonic Distortion of load current under fuzzy Control

A THD of 2.32% indicates that the Fuzzy controller is more effective at minimizing current harmonics than the conventional PI controller. The adaptive decision-making nature of fuzzy logic helps the system quickly adjust to fluctuations in load demand and variations in renewable power, thereby reducing harmonic injection into the network.

This improved harmonic performance leads to better power quality, reduced heating losses in components, and enhanced efficiency of connected devices. The current waveform remains stable, smoother, and more sinusoidal, demonstrating that the Fuzzy controller ensures superior dynamic response and cleaner current delivery in the hybrid AC/DC microgrid.

7) Voltage and Current Waveforms – ANN Controller

Under the ANN (Artificial Neural Network) controller, the voltage and current waveforms in the hybrid AC/DC microgrid exhibit highly stable and smooth characteristics. The ANN controller continuously learns from system behavior and adapts its control strategy in response to changing load demands, renewable energy variations, and dynamic operating conditions. This results in faster transient response, minimal overshoot, and quick settling time.

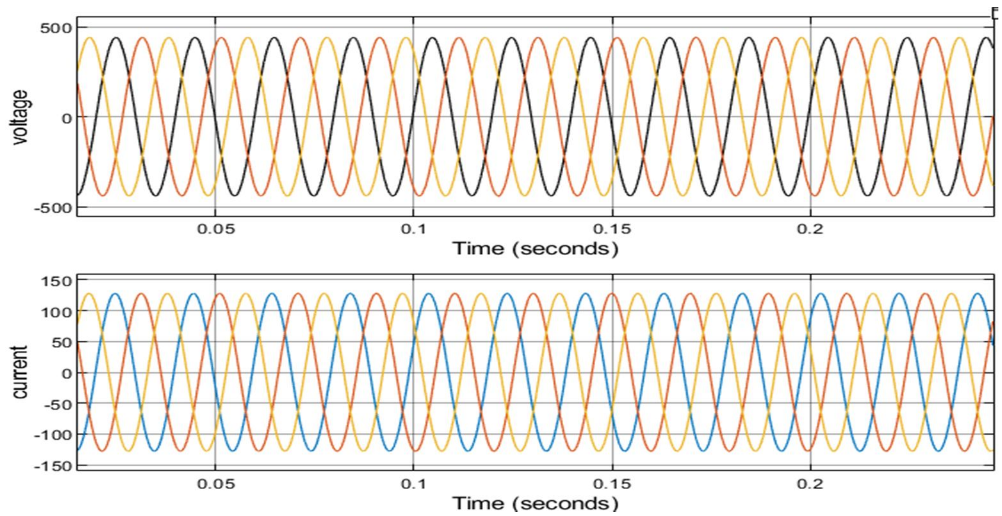
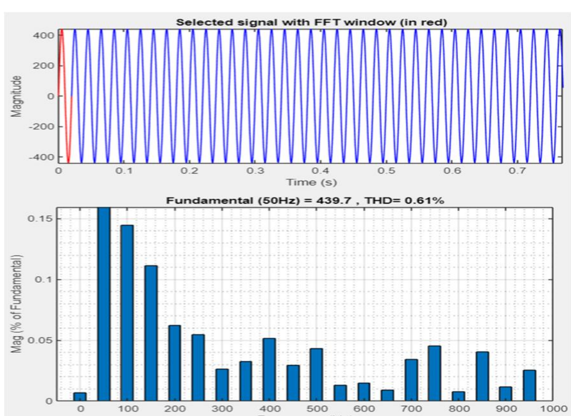


Figure 7: Voltage and Current Waveforms – ANN Controller

8) Total Harmonic Distortion of load voltage under ANN Control

The Total Harmonic Distortion (THD) of the load voltage, measured at 0.61% under the ANN (Artificial Neural Network) controller, indicates exceptionally high power quality. This very low THD value indicates that the voltage waveform is almost sinusoidal, with negligible harmonic components. The ANN controller continuously adjusts its control action based on real-time system conditions, helping it maintain a smooth, stable voltage output even when load or renewable generation levels change rapidly.



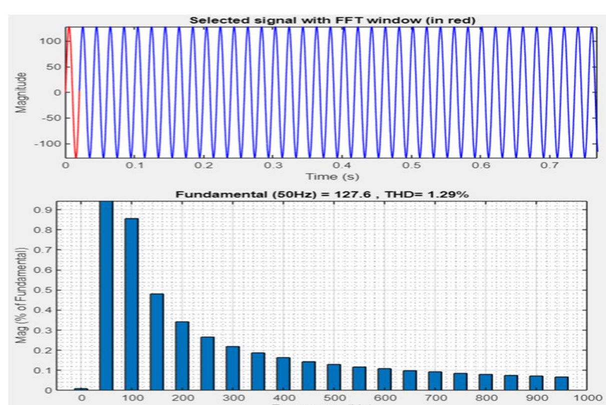


Figure 8:THD% of load current (0.61%) – ANN Controller

Figure 9:THD% of load current (1.29%) – ANN Controller

9) Total Harmonic Distortion of load voltage under ANN Control

The Total Harmonic Distortion (THD) of 1.29% in the load current under the ANN (Artificial Neural Network) controller indicates superior harmonic suppression and smooth current flow. This low THD value indicates that the current waveform closely resembles an ideal sinusoidal waveform, with minimal distortion from switching actions, nonlinear loads, or dynamic operating conditions.

VI. RESULTS AND DISCUSSION

1) The PI Controller provides basic stability but has a slower transient response and higher harmonic content.

Performance Observation:

- THD (Voltage and Current): 1.33 V, 3.85 A (≈ 5–6%)
- Power Factor: ≈ 0.96

2) The **Fuzzy Controller** enhances the system's dynamic behavior, minimizes distortions, and achieves smoother voltage and current profiles.

Performance Observation:

- THD (Voltage and Current): 0.80 V, 2.32 A (≈ 3.5–4%)
- Power Factor: ≈ 0.98
- The simulation results confirm that the Fuzzy controller offers better harmonic suppression and voltage stability compared to the PI controller

3) The **ANN Controller** delivers the best overall performance, showing the lowest Total Harmonic Distortion (THD), fastest settling time, and highest power factor.

Performance Observation:

- THD (Voltage and Current): 0.61 V, 1.29 A (≤ 2.5%)
- Power Factor: ≈ 0.999

The results clearly show that the ANN controller provides the best overall performance among the tested control strategies. It effectively reduces harmonic distortion, ensures smooth voltage and current waveforms, and maintains system stability even during sudden changes in load or source. Hence, the ANN-based control approach is the most efficient and intelligent method for power quality enhancement in hybrid AC/DC microgrids.

- When comparing the PI and Fuzzy controllers, the Fuzzy system demonstrates superior waveform quality and reduced THD, as confirmed by the measured values

Performance Metric	PI Controller	Fuzzy Controller	ANN Controller
Settling Time	Moderate	Fast	Very Fast
Overshoot	High	Low	Very Low
THD of Voltage (V)	1.33	0.8	0.61
THD of Current (A)	3.85	2.32	1.29
Power Factor	0.96	0.98	0.999
Voltage Stability	Average	Good	Excellent
Adaptability	Low	Medium	High

VII. CONCLUSION

A. Conclusion

The Hybrid AC/DC Microgrid effectively integrates renewable energy sources, such as solar and wind, to deliver stable, reliable power. In this study, three control methods—PI, Fuzzy, and Artificial Neural Network (ANN)—were tested to improve system performance. The PI controller-maintained voltage but had a slower response and higher harmonics. The Fuzzy controller showed smoother operation and lower voltage ripple but struggled with sudden load changes. The ANN controller performed best, offering faster response, lower total harmonic distortion, and better voltage and current control. It achieved values of 0.80 V and 2.32 A, compared to PI (1.33 V, 3.85 A) and Fuzzy. Overall, the ANN controller proved to be the most efficient and intelligent option for maintaining stable and high-quality power in hybrid AC/DC microgrids.

B. Future Scope

Future work on Hybrid AC/DC Microgrids can focus on implementing the proposed ANN controller in real-time hardware environments, such as DSPs, FPGAs, or ds PACE platforms, to validate its dynamic performance and reliability. Further studies may explore integrating hybrid intelligent control methods by combining ANNs with Fuzzy or adaptive PI controllers to achieve faster response and enhanced stability. The system can also be extended to include additional renewable sources, such as fuel cells or biomass, ensuring greater energy diversity and resilience. Incorporating advanced energy management strategies and demand-side control can further improve efficiency, while real-time communication and cybersecurity measures will enable smarter and safer microgrid operation. These developments will help in transforming ANN-based hybrid microgrids into a practical and scalable solution for future intelligent power network

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