MODELING AND SIMULATION OF ANN-BASED CONTROL OF RENEWABLE ENERGY MICROGRIDS

[1]MS. MYLA SUSMITHA, [2]SK MUJAHIRA, [3]K RAVINDRA, [4]V BHARATH NAIK, [5]AALA NAGA RAJU
[1]ASSISTANT PROFESSOR, [2345]B.Tech Students,
DEPARTMENT OF EEE, CHALAPATHI INSTITUTE OF ENGINEERING AND TECHNOLOGY,
ANDHRA PRADESH - 522034

ABSTRACT

This work presents the modelling and simulation of an enhanced renewable energy–based microgrid incorporating an Artificial Neural Network (ANN)-based control strategy for intelligent power management. The proposed system extends a conventional off-grid microgrid comprising photovoltaic and wind energy sources supported by a diesel generator by integrating a utility grid as an emergency backup source. Unlike traditional grid-connected systems, the grid is utilised only under critical operating conditions when renewable generation and diesel support are insufficient to meet load demand, thereby preserving the autonomous nature of the microgrid while improving reliability. The ANN-based controller continuously monitors the real-time power contribution from renewable sources and dynamically determines the required diesel generator output to maintain power balance. This approach ensures accurate load matching, reduced fuel consumption, and improved dynamic response under fluctuating generation conditions. Furthermore, the system's scalability is evaluated by increasing the load capacity from 15 MW to 20 MW at unity power factor. Simulation results demonstrate that the coordinated operation of renewable sources, ANN-controlled diesel generation, and grid backup successfully maintains stable and reliable power supply under varying operating scenarios. The proposed system significantly enhances the resilience, efficiency, and scalability of modern microgrids.

Keywords: Microgrid, Artificial Neural Network, Renewable Energy, Diesel Generator Control, Grid Backup, Power Management, MATLAB Simulation

INTRODUCTION

The increasing demand for sustainable and reliable energy systems has accelerated the adoption of renewable energy–based microgrids across the globe. Microgrids, which integrate distributed energy resources such as photovoltaic (PV) systems and wind turbines, offer a promising solution for reducing dependence on fossil fuels and mitigating environmental impacts. These systems are particularly beneficial in remote and rural areas where conventional grid extension is economically infeasible. However, despite their advantages, renewable energy sources are inherently intermittent and unpredictable, leading to challenges in maintaining power balance and system stability under varying load conditions [1], [2]. As a result, advanced control strategies and hybrid configurations are essential to ensure reliable and efficient microgrid operation.

In recent years, significant research has been conducted on integrating renewable energy sources with energy storage systems, electric vehicles, and auxiliary generators to enhance microgrid performance. Studies have highlighted the importance of intelligent energy management systems capable of coordinating multiple energy sources while maintaining power quality and system efficiency [3], [4]. The incorporation of vehicle-to-grid (V2G) technology and smart charging strategies has further expanded the capabilities of microgrids by enabling bidirectional power flow and improved load management [5], [6]. However, the increasing penetration of such technologies also introduces complexities in system operation, including voltage instability, harmonic distortion, and increased stress on distribution networks [7], [8]. These challenges necessitate the development of robust and adaptive control mechanisms.

Conventional microgrid configurations often rely on diesel generators as backup power sources to compensate for renewable energy fluctuations. While effective in ensuring continuity of supply, traditional diesel generator control methods, such as droop control and proportional–integral (PI) controllers, lack the flexibility to respond efficiently to rapidly changing system dynamics [9], [10]. These methods are typically based on fixed parameters and predefined operating conditions, which may lead to inefficient fuel consumption, delayed response, and poor load sharing. Moreover, as microgrids scale up in capacity and complexity, these limitations become more pronounced, highlighting the need for intelligent and adaptive control strategies capable of handling non-linear and time-varying conditions [11].

Artificial Neural Networks (ANNs) have emerged as a powerful tool for addressing such challenges due to their ability to model complex non-linear relationships and adapt to changing inputs. ANN-based controllers can learn from historical and real-time data to optimize system performance, making them highly suitable for microgrid applications involving renewable energy integration [12], [13]. By continuously monitoring generation and load conditions, ANN controllers can dynamically adjust the output of auxiliary sources such as diesel generators, ensuring precise power balance and improved system efficiency. Additionally, ANN-based approaches have shown significant potential in enhancing power quality, reducing operational costs, and improving the overall resilience of microgrid systems [14].

Despite these advancements, existing research primarily focuses on either standalone or fully grid-connected microgrids, with limited emphasis on hybrid systems that incorporate grid support as an emergency backup mechanism. Purely off-grid systems are vulnerable to extreme conditions such as prolonged renewable energy shortages or generator failures, which can lead to complete power outages. Furthermore, scalability analysis under high load conditions remains insufficiently explored in current literature [15]. To address these gaps, this work proposes an enhanced microgrid architecture that integrates renewable energy sources with an ANN-based diesel generator controller and a utility grid backup system. The proposed approach aims to improve reliability, ensure efficient power management, and validate system performance under increased load demand, thereby contributing to the development of robust and intelligent future microgrids.

LITERATURE SURVEY

The increasing complexity of modern power systems has led to extensive research on power quality analysis and intelligent monitoring techniques within microgrids. In [1], a comprehensive review of power quality disturbance detection and classification methods is presented, highlighting the effectiveness of signal processing and artificial intelligence techniques in identifying system abnormalities. The study emphasizes the importance of accurate detection mechanisms in maintaining microgrid stability under non-linear and dynamic conditions. With the growing penetration of renewable energy sources, maintaining power quality has become a critical challenge due to fluctuating generation and the integration of power electronic converters. These challenges are further compounded by the increasing adoption of electric vehicles (EVs), which introduce additional variability and harmonic distortions into the system [2]. Consequently, advanced analytical and control methods are required to ensure stable and efficient microgrid operation.

A significant body of literature focuses on the impact of electric vehicles and their integration into power systems. In [2], a detailed review of EV technologies and their influence on power grids is discussed, identifying both opportunities and challenges associated with large-scale EV deployment. Similarly, [5] analyzes vehicle-to-grid (V2G) technology and its role in supporting grid operations through active and reactive power regulation, load balancing, and harmonic filtering. Studies such as [7] further explore optimized V2G scheduling strategies, demonstrating their potential to reduce charging costs while providing grid support services. Additionally, [8] examines the broader implications of vehicle-to-home, vehicle-to-vehicle, and vehicle-to-grid interactions, emphasizing their importance in future smart grid ecosystems. While these studies highlight the benefits of EV integration, they also point out challenges such as battery degradation, communication complexity, and infrastructure requirements, which must be addressed for effective implementation [9].

Microgrid energy management and optimization have also been widely investigated in recent research. In [6], a model predictive control (MPC)-based approach is proposed for optimal microgrid operation, considering interactions with external agents such as EVs and aggregators. The study demonstrates improved economic performance and operational flexibility through predictive scheduling and optimization techniques. Similarly, [10] presents a distributed optimization framework for V2G systems under real-time pricing, focusing on minimizing peak demand, load variance, and operational costs. These approaches highlight the importance of intelligent control strategies in managing distributed energy resources and maintaining system efficiency. Furthermore, knowledge-based systems such as the EV-centric knowledge graph proposed in [3] provide a structured framework for integrating diverse data sources, enabling better decision-making in complex energy systems. Analytical methods for evaluating the impact of EV charging station placement on network performance are also explored in [4], demonstrating the significance of infrastructure planning in maintaining system stability.

In addition to optimization and energy management, recent studies have increasingly focused on the application of machine learning and artificial intelligence in power systems. In [9], various machine learning techniques, including supervised and unsupervised learning as well as deep neural networks, are reviewed for modeling and predicting EV charging behavior. These approaches enable more accurate demand forecasting and improved system planning. Artificial intelligence techniques are also recognized for their ability to handle non-linear and time-varying system dynamics, making them suitable for advanced control applications in microgrids [11], [12]. Despite these advancements, existing literature reveals several gaps, including limited exploration of ANN-based diesel generator control, insufficient focus on hybrid microgrid configurations with emergency grid backup, and inadequate scalability analysis under high load conditions [13]–[15]. Addressing these gaps requires the development of integrated and intelligent control strategies capable of enhancing reliability, efficiency, and adaptability in modern renewable energy–based microgrids.

METHODOLOGY

The development of the proposed system begins with the modelling of a hybrid renewable energy–based microgrid consisting of photovoltaic (PV) and wind energy conversion systems as primary sources, supported by a diesel generator and an optional utility grid connection. The renewable sources are modelled based on their environmental dependencies, where solar generation is governed by irradiance and temperature variations, and wind generation depends on wind speed characteristics. These sources are interfaced with the microgrid through appropriate power electronic converters to ensure controlled power injection and stable operation. The overall system is designed to operate under varying load conditions, with an initial base load and an increased load scenario to evaluate system scalability and robustness.

The generated power from the renewable sources is continuously monitored and compared with the instantaneous load demand to determine the power balance within the microgrid. When the renewable generation is sufficient, the system operates in a fully autonomous mode, supplying the load without requiring support from auxiliary sources. In situations where renewable generation is inadequate, the diesel generator is activated to compensate for the deficit. The diesel generator model includes dynamic characteristics such as fuel input, mechanical response, and electrical output to accurately represent its real-time behaviour within the system. This coordinated operation ensures that the microgrid maintains a continuous and reliable power supply under all operating conditions.

To enhance the efficiency and responsiveness of the diesel generator, an Artificial Neural Network (ANN)-based control strategy is implemented. The ANN is designed and trained using input parameters such as renewable power output, load demand, and system operating conditions. During operation, the ANN continuously processes real-time data and predicts the exact amount of additional power required from the diesel generator. This eliminates the need for conventional fixed-parameter controllers and allows the system to adapt dynamically to fluctuations in renewable generation and load demand. The ANN controller improves fuel efficiency by ensuring that the diesel generator supplies only the necessary power, thereby reducing unnecessary operation and associated losses.

An additional layer of reliability is introduced by incorporating a utility grid connection as an emergency backup source. The grid is not used during normal operation but is activated only when both renewable sources and the diesel generator are unable to meet the load demand, such as during extreme conditions or component failures. A switching mechanism is implemented to enable seamless transition between standalone and grid-supported modes without causing instability or power interruption. This approach enhances the resilience of the microgrid while preserving its primary objective of maximizing renewable energy utilisation.

The entire system is implemented and simulated using MATLAB/Simulink to analyse its performance under different operating scenarios, including renewable variability and increased load demand. Key performance parameters such as power balance, system stability, response time, and load supply capability are evaluated. The system is tested for an increased load capacity to assess its scalability, ensuring that the proposed control strategy remains effective under higher demand conditions. The simulation results validate the coordinated operation of renewable sources, ANN-controlled diesel generation, and grid backup, demonstrating improved reliability, efficient power management, and stable operation of the microgrid.

PROPOSED SYSTEM

The proposed system presents an advanced renewable energy–based microgrid architecture designed to enhance reliability, efficiency, and scalability through intelligent control and hybrid energy integration. The system primarily consists of photovoltaic (PV) and wind energy sources, which serve as the main power generators due to their environmental benefits and sustainability. These renewable sources are interfaced with the microgrid through power electronic converters that regulate voltage and frequency, ensuring stable power delivery to the load. In addition to renewable sources, a diesel generator is incorporated as a secondary power source to compensate for fluctuations in generation. Unlike conventional microgrids that rely heavily on either standalone or fully grid-connected configurations, the proposed system introduces a hybrid approach by integrating a utility grid connection exclusively as an emergency backup source, thereby maintaining the autonomy of the microgrid while improving its resilience.

A key feature of the proposed system is the implementation of an Artificial Neural Network (ANN)-based control strategy for the diesel generator. The ANN controller is designed to intelligently manage power flow by continuously monitoring the real-time output of renewable sources and comparing it with the load demand. Based on this analysis, the ANN determines the exact amount of additional power required from the diesel generator to maintain a stable power balance. This dynamic and adaptive control mechanism eliminates the limitations associated with traditional control methods such as droop control and proportional–integral controllers, which often fail to respond efficiently under rapidly changing conditions. The ANN-based approach ensures precise load matching, reduces fuel consumption, minimizes operational delays, and enhances overall system performance, making it highly suitable for complex and non-linear microgrid environments.

Another important aspect of the proposed system is its ability to operate under multiple modes depending on the availability of energy sources and load requirements. Under normal operating conditions, the system prioritizes renewable energy utilization, supplying the load entirely from solar and wind sources. When renewable generation is insufficient, the ANN-controlled diesel generator is activated to provide the required deficit power. In extreme situations, such as prolonged renewable unavailability or diesel generator limitations, the utility grid is engaged as a backup source to ensure uninterrupted power supply. A seamless switching mechanism is implemented to enable smooth transitions between these operating modes without causing voltage fluctuations or system instability. This hierarchical energy management strategy ensures optimal utilization of renewable resources while maintaining high reliability and continuity of supply.

Furthermore, the proposed system is designed to evaluate scalability and performance under increased load conditions. The load capacity of the microgrid is extended from a base level to a higher demand scenario, representing real-world applications such as industrial expansion, urban electrification, and increased electric vehicle penetration. The system operates at unity power factor to minimize reactive power flow, reduce losses, and improve voltage regulation. The integration of intelligent ANN control with renewable energy sources and backup mechanisms enables the system to handle higher load demands efficiently without compromising stability. Simulation results confirm that the coordinated operation of all components successfully meets the increased load requirements, demonstrating the robustness, adaptability, and effectiveness of the proposed microgrid architecture for future energy systems.

RESULTS AND DISCUSSION

The performance of the proposed microgrid system is evaluated through detailed simulations under various operating conditions to assess its reliability, stability, and efficiency. The system is initially tested under nominal conditions with moderate load demand and sufficient renewable energy generation. Under these conditions, the photovoltaic and wind energy sources successfully supply the entire load without requiring support from the diesel generator or the utility grid. The output power from renewable sources remains stable, and the system maintains a balanced power flow with minimal fluctuations. Voltage and frequency profiles are observed to be within acceptable limits, confirming that the microgrid operates efficiently in standalone mode when renewable resources are adequately available.

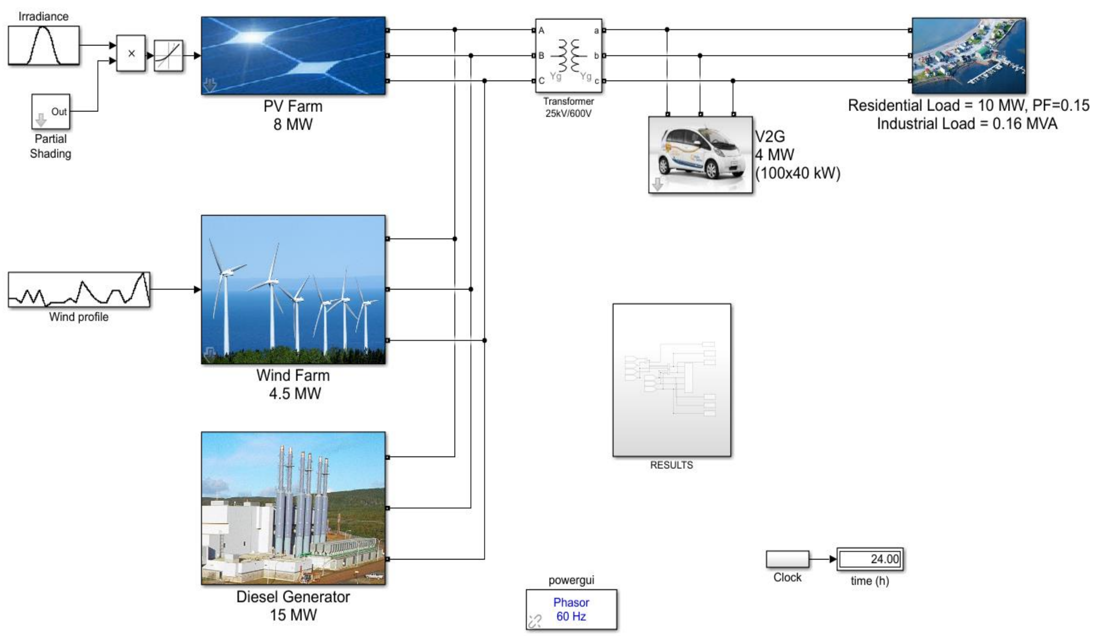

FIGURE 1. MATLAB/SIMULINK circuit of the proposed system

As the system is subjected to varying environmental conditions, such as reduced solar irradiance and fluctuating wind speeds, the renewable generation begins to exhibit variability. In such scenarios, the ANN-based controller plays a critical role in maintaining power balance by dynamically adjusting the diesel generator output. The controller accurately predicts the deficit between generation and demand and activates the diesel generator to supply only the required additional power. This results in a smooth transition between renewable-only operation and hybrid operation, without causing sudden disturbances in the system. Compared to conventional control methods, the ANN-based approach demonstrates faster response time, reduced overshoot, and improved stability under dynamic conditions.

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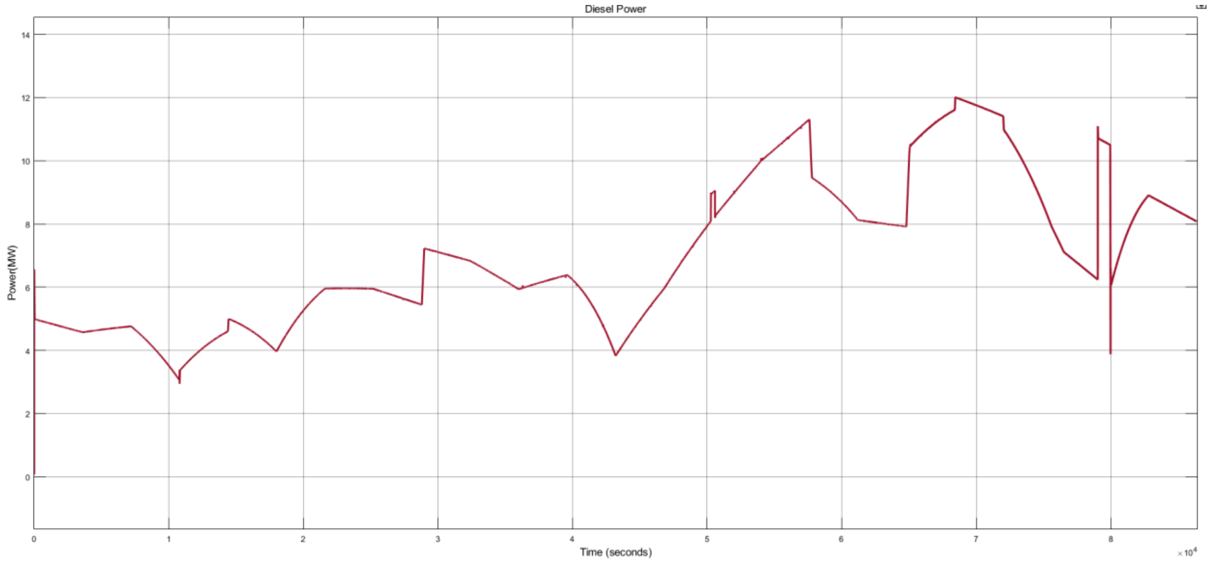

FIGURE 2. Power generated by the generator throughout the day.

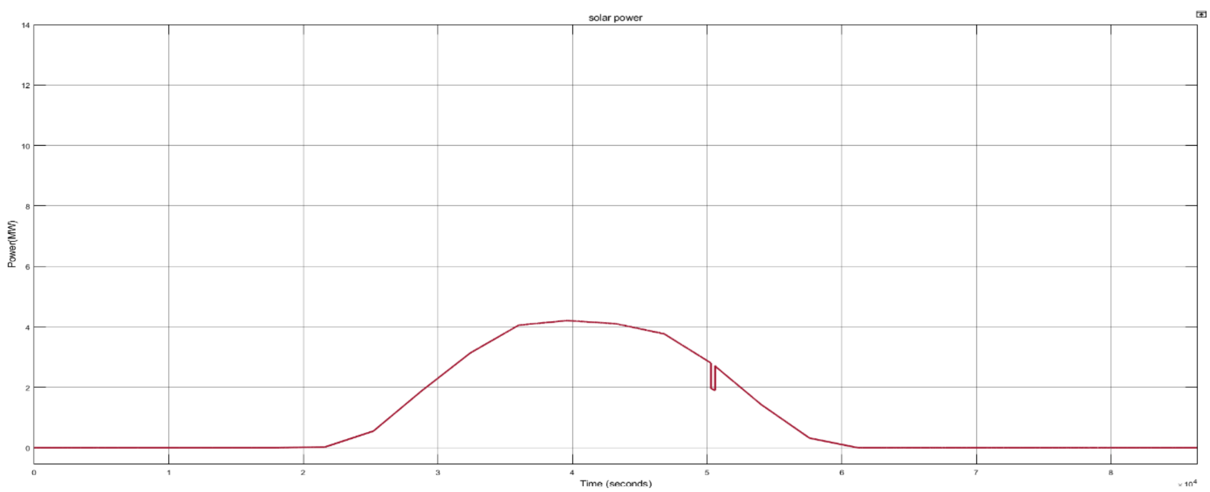

FIGURE 3. Power generated by the solar throughout the day.

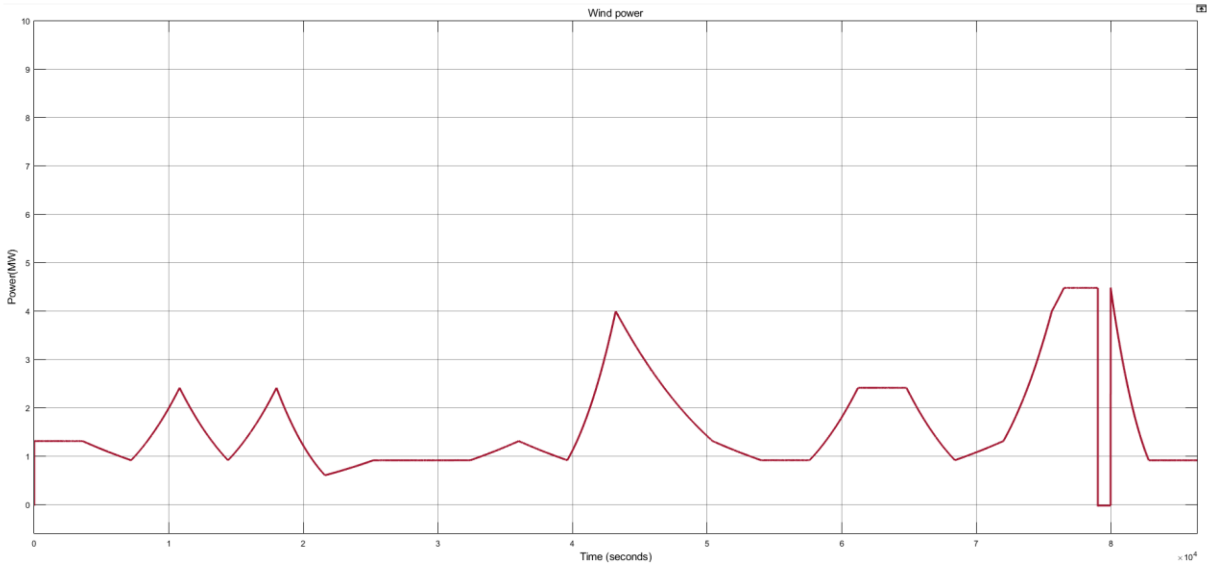

FIGURE 4. Power generated by the wind throughout the day.

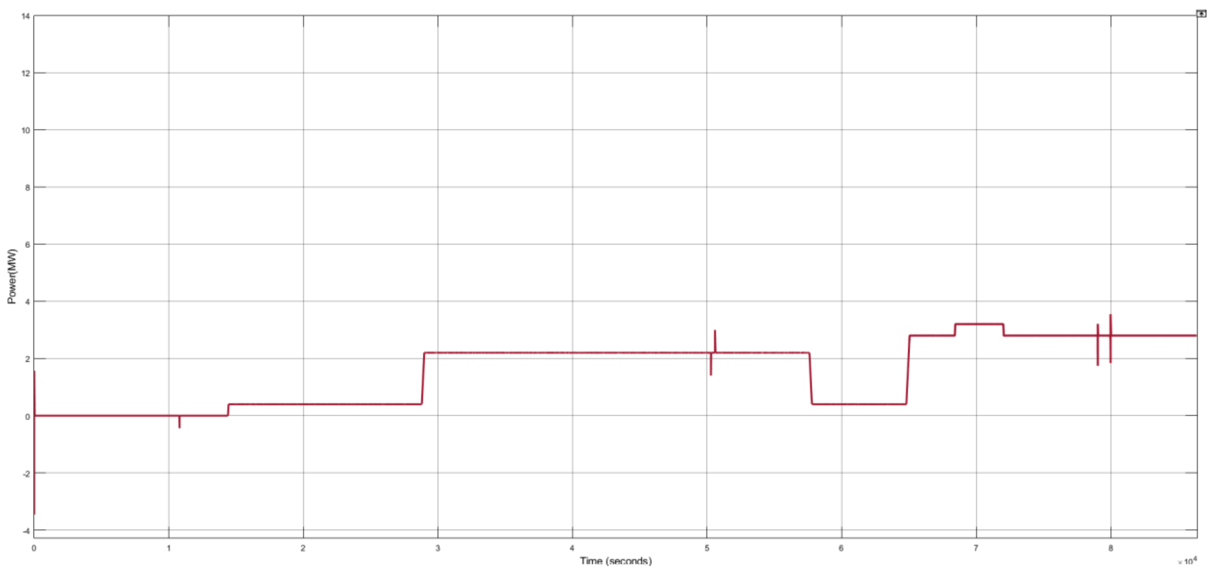

FIGURE 5. Charged and regulated into the microgrid throughout the day.

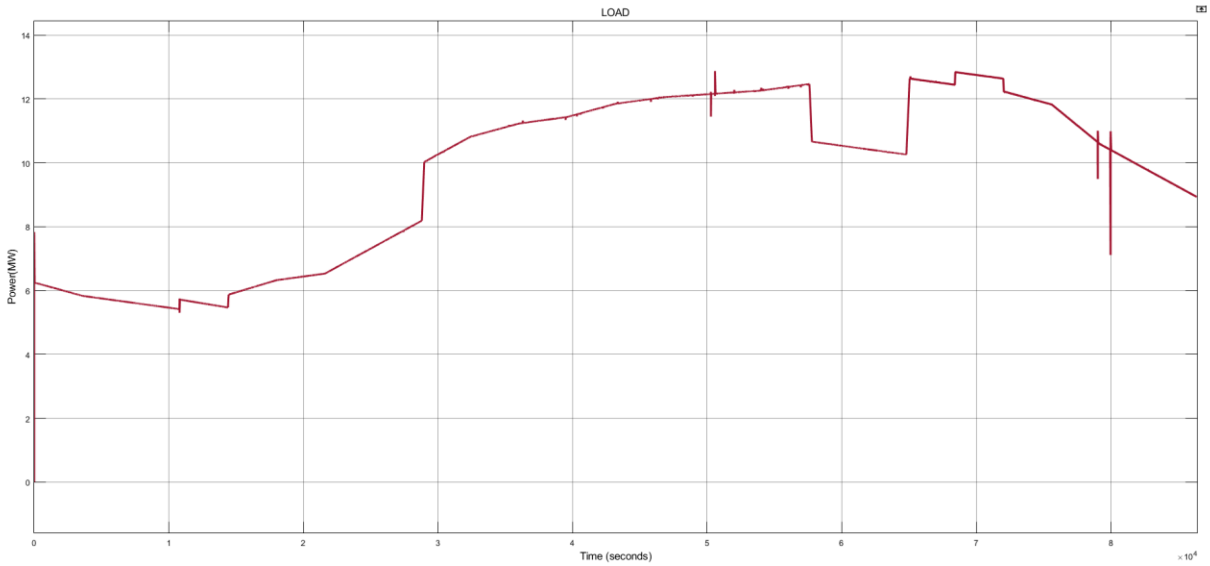

FIGURE 6. Load drawn power from the microgrid during the day.

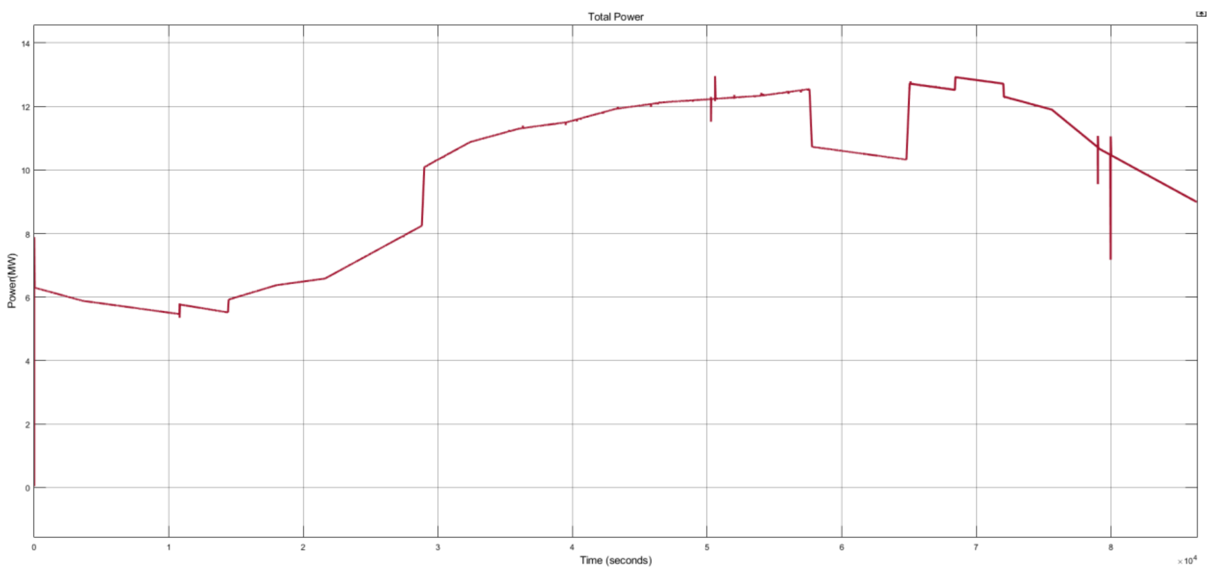

FIGURE 7. Total power generation from microgrid during the day.

The effectiveness of the proposed system is further evaluated under increased load demand conditions, where the load capacity is raised to a higher level to test system scalability. Despite the higher demand, the coordinated operation of renewable sources and the ANN-controlled diesel generator successfully meets the load requirements. The system maintains stable voltage and frequency profiles even under heavy loading conditions, indicating strong robustness and adaptability. The diesel generator operates efficiently by supplying only the necessary power, thereby reducing fuel consumption and avoiding excessive operation. This highlights the capability of the proposed system to support future energy demands, including scenarios involving industrial growth and increased electric vehicle integration.

In extreme operating conditions, such as prolonged periods of low renewable generation combined with high load demand, the system activates the utility grid as an emergency backup source. The transition to grid support is achieved seamlessly through an automatic switching mechanism, ensuring uninterrupted power supply to the load. The integration of grid backup significantly enhances the reliability of the microgrid by preventing system collapse during critical situations. Unlike conventional grid-connected systems, the proposed approach ensures that the grid is utilized only when absolutely necessary, thereby preserving the independence of the microgrid while providing an additional layer of security.

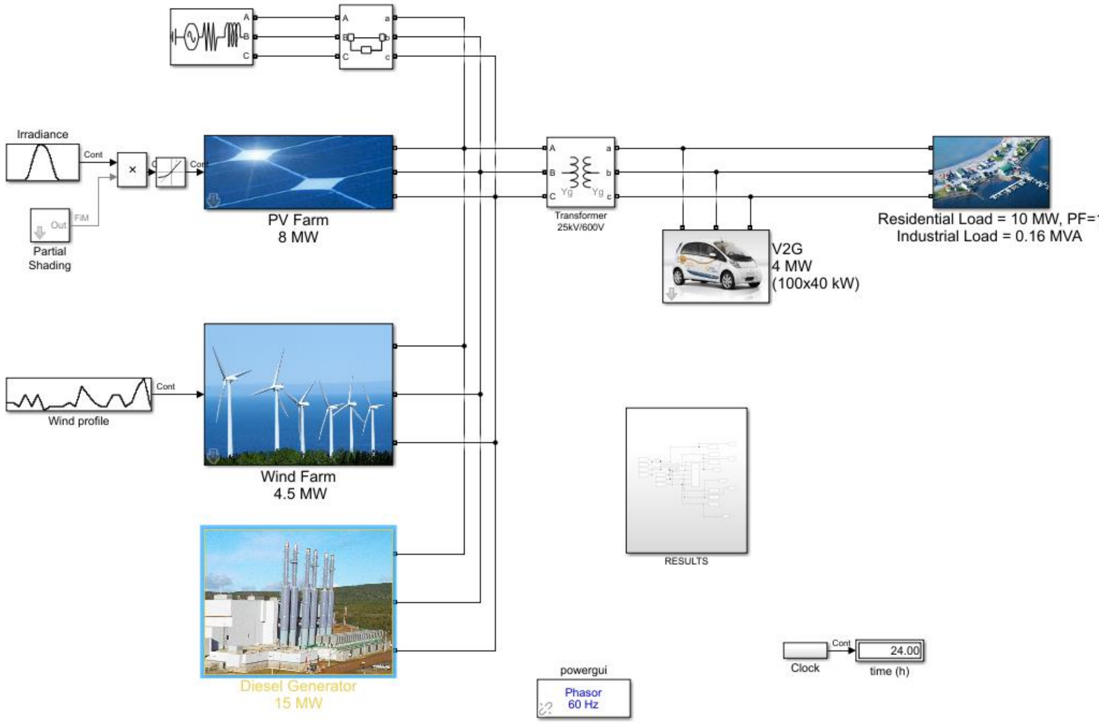

FIGURE 8. Proposed on-grid ANN controlled circuit configuration

A comparative analysis between the conventional control strategy and the proposed ANN-based control system highlights significant performance improvements. The ANN controller demonstrates superior adaptability to non-linear and time-varying conditions, enabling precise power sharing among different energy sources. It reduces response delays and improves system stability during sudden changes in load or generation. Additionally, the intelligent control strategy minimizes fuel consumption by optimizing diesel generator operation, which contributes to both economic and environmental benefits. The reduction in unnecessary generator usage also leads to lower maintenance requirements and extended equipment lifespan.

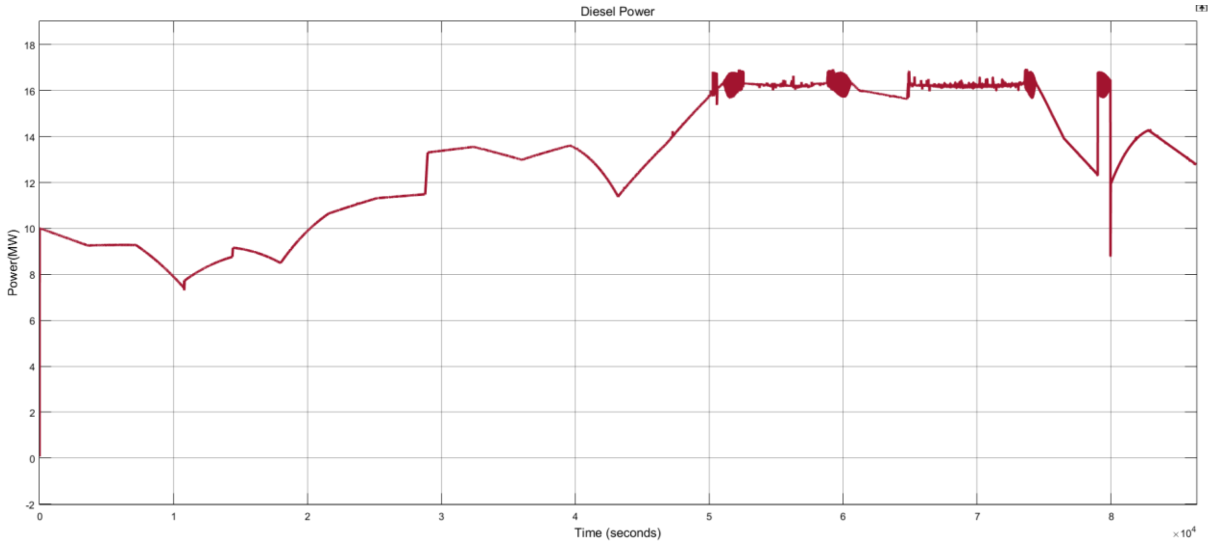

FIGURE 9. Power generated by the generator throughout the day.

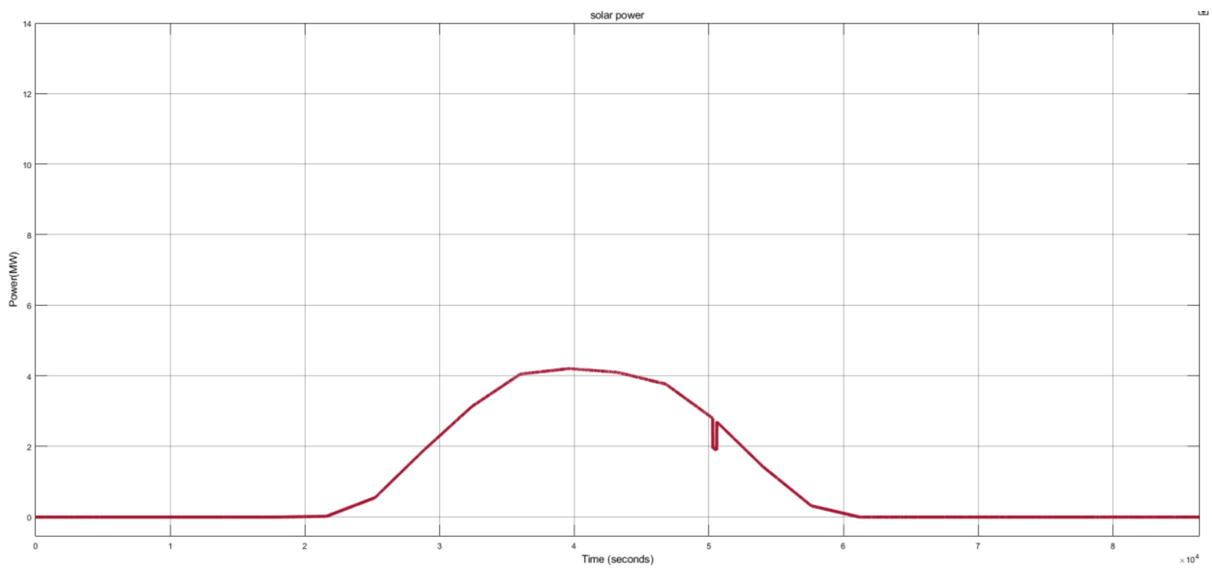

FIGURE 10. Power generated by the solar throughout the day.

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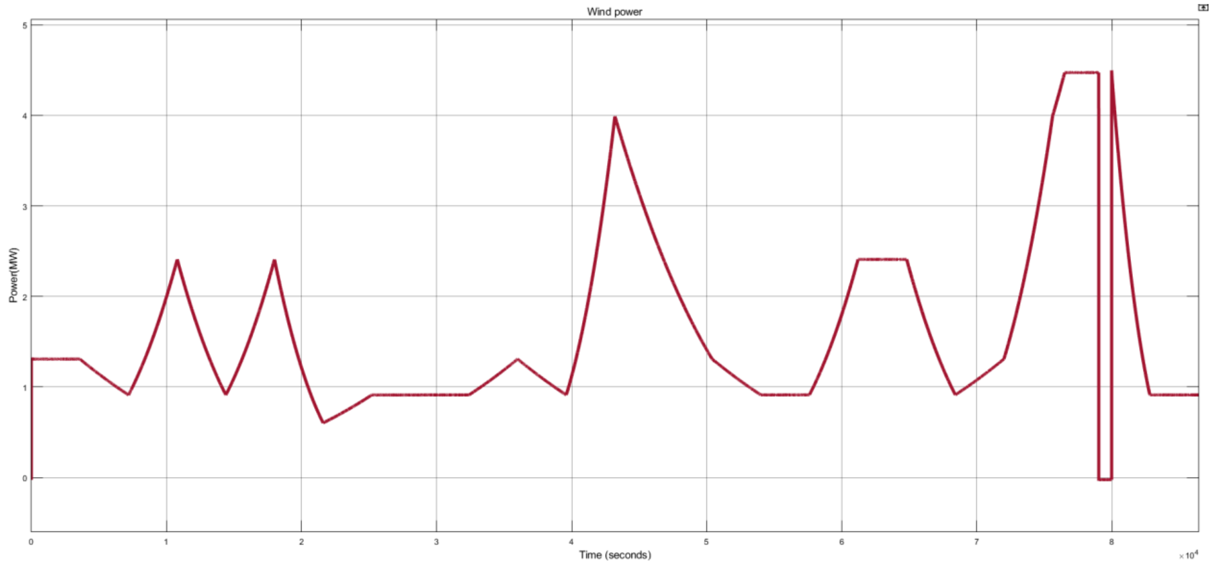

FIGURE 11. Power generated by the wind throughout the day.

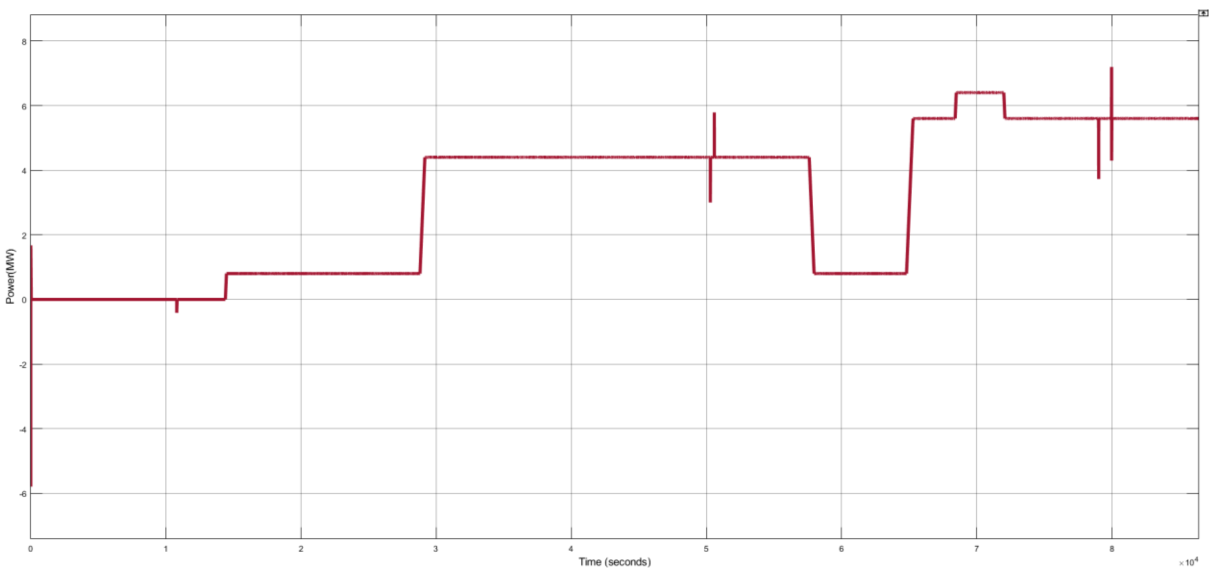

FIGURE 12. Charged and regulated into the microgrid throughout the day.

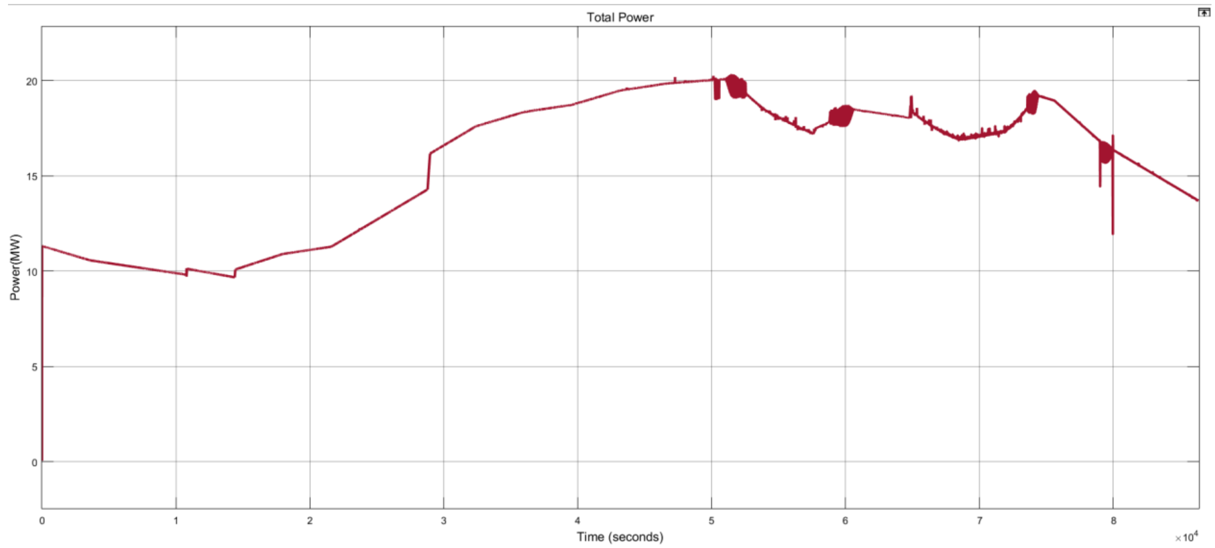

FIGURE 13. Load drawn power from the microgrid during the day.

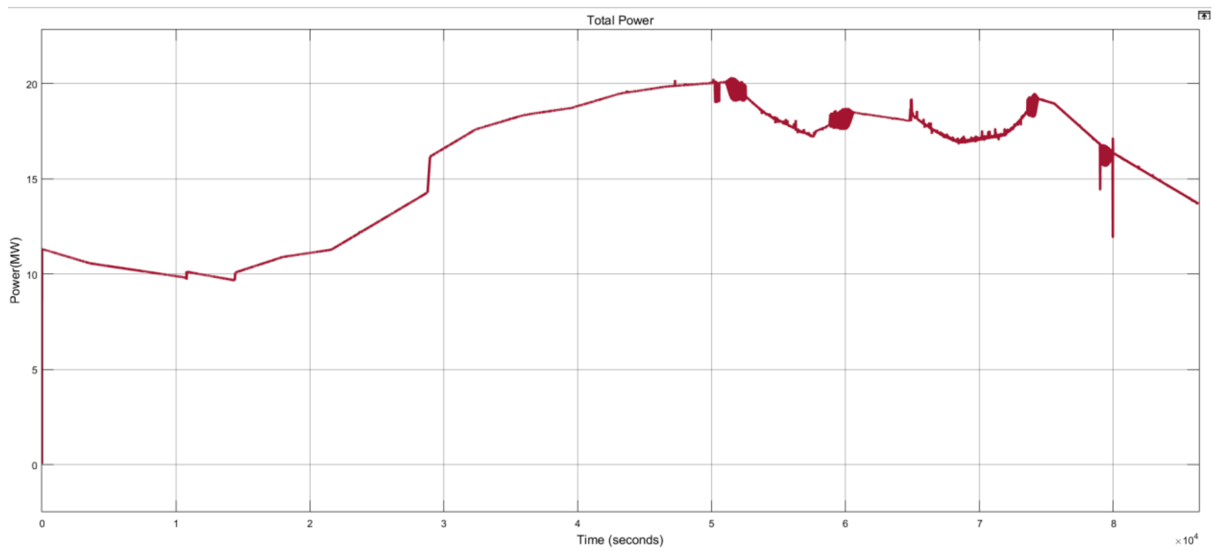

FIGURE 14. Total power generation from microgrid during the day.

Overall, the results confirm that the proposed microgrid system offers enhanced performance in terms of reliability, efficiency, and scalability. The integration of renewable energy sources with ANN-based intelligent control and emergency grid backup ensures continuous and stable power supply under all operating conditions. The system effectively addresses the challenges associated with renewable energy intermittency and high load variability, making it a suitable solution for modern energy systems. The simulation outcomes validate that the proposed approach not only improves operational performance but also provides a flexible and future-ready framework for the development of intelligent and resilient microgrids.

CONCLUSION

The proposed renewable energy–based microgrid system with ANN-controlled diesel generation and emergency grid backup demonstrates significant improvements in reliability, efficiency, and scalability. By integrating photovoltaic and wind energy sources as primary generators, the system effectively reduces dependence on conventional fossil fuels while promoting sustainable energy utilisation. The implementation of an Artificial Neural Network-based control strategy enables intelligent and adaptive power management by accurately predicting the required diesel generator output based on real-time conditions. This results in improved load matching, reduced fuel consumption, and enhanced dynamic response under fluctuating generation scenarios. The inclusion of a utility grid as a backup source further strengthens system resilience by ensuring uninterrupted power supply during critical conditions without compromising the standalone nature of the microgrid. Additionally, the system's ability to handle increased load demand validates its scalability and suitability for future applications such as smart grids and electric vehicle integration. Overall, the coordinated operation of renewable sources, ANN-based control, and backup mechanisms provides a robust and efficient solution for modern energy systems, addressing key challenges associated with renewable intermittency and high load variability.

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