Integration of Renewable Energy and Electric Vehicles in Microgrid Systems: Performance Enhancement with 18MW Capacity and Unity Power Factor

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ABSTRACT

The rapid adoption of Electric Vehicles (EVs) due to increasing environmental concerns and carbon emissions has significantly impacted modern power systems. As EV penetration rises, their integration with microgrids presents challenges related to grid stability, voltage regulation, and energy management. This study investigates the enhanced performance of a renewable energy-integrated microgrid with an upgraded capacity of 18 MW and a unity power factor, ensuring improved efficiency and reduced reactive power losses. The proposed microgrid consists of a diesel generator as the primary power source, supplemented by a Photovoltaic (PV) farm and a wind farm, which contribute to sustainable energy generation. Additionally, a Vehicle-to-Grid (V2G) system is deployed to optimize EV charging and discharging cycles, enhancing flexibility in energy distribution. The study focuses on the dynamic impact of EVs on microgrid performance, considering the nonlinear circuit characteristics of EV systems. Reliable charging infrastructure plays a crucial role in balancing grid loads, particularly in high-demand areas such as hospitals, universities, EV charging stations, and industrial sectors. Advanced control strategies are employed to regulate power flow and maintain voltage stability. The analysis is conducted using MATLAB/Simulink, providing a comprehensive assessment of how the upgraded microgrid, with 18MW capacity and unity power factor, improves operational efficiency, mitigates power fluctuations, and promotes sustainable energy solutions. This research highlights the critical role of renewable energy and EVs in enhancing microgrid performance and ensuring grid reliability.

Keywords: Microgrid Stability, Electric Vehicle Integration, Vehicle-to-Grid (V2G), Renewable Energy Systems, MATLAB/Simulink Modeling, Power Factor Optimization

INTRODUCTION

The global energy sector is witnessing a major transformation driven by the increased adoption of renewable energy sources (RES) and electric vehicles (EVs). With concerns over greenhouse gas emissions and energy security, solar and wind power have become integral to sustainable energy solutions. Simultaneously, EVs are emerging as a cleaner alternative to internal combustion engine vehicles, reducing reliance on fossil fuels. However, integrating these technologies into microgrids presents challenges in terms of grid stability, power quality, and energy management. This study focuses on the modeling and analysis of an 18 MW microgrid system operating at a unity power factor, evaluating its impact on efficiency and stability through MATLAB/Simulink-based simulations.

Renewable energy sources such as solar and wind power are widely recognized for their ability to reduce carbon emissions and reliance on conventional power plants. The declining costs of PV panels and wind turbines have accelerated their adoption, but their intermittent nature poses challenges for microgrid stability. In parallel, the rapid expansion of EVs increases electricity demand and requires robust charging infrastructure. By integrating EVs with vehicle-to-grid (V2G) technology, microgrids can leverage bidirectional energy exchange, enabling better load balancing, peak shaving, and power quality improvements. This study explores the role of power factor correction (PFC) in maintaining a unity power factor, thereby enhancing energy efficiency and minimizing transmission losses.

Despite the benefits of integrating EVs and RES into microgrids, several technical challenges must be addressed. The variability of solar and wind power can cause voltage fluctuations and frequency instability, requiring energy storage systems and advanced forecasting techniques. Similarly, unregulated EV charging can lead to voltage drops, transformer overloads, and harmonic distortions, impacting overall power quality. The nonlinear nature of EV chargers and power converters introduces harmonics into the grid, necessitating filtering solutions and control algorithms to mitigate power quality issues. Effective power management and optimization strategies are crucial for ensuring reliable microgrid operations.

Maintaining grid stability and ensuring a unity power factor in microgrid systems require advanced control mechanisms. The integration of EVs and RES leads to reactive power variations, affecting voltage stability and power factor performance. Advanced solutions such as fuzzy logic controllers, neural network-based optimization, and adaptive power factor correction techniques can help maintain smooth power flow and minimize energy losses. Implementing these strategies ensures optimal microgrid performance, supporting energy reliability and efficiency for diverse applications such as hospitals, universities, and industrial facilities.

MATLAB/Simulink serves as a powerful platform for modeling and simulating microgrid dynamics, offering detailed insights into power electronics, renewable energy integration, and EV charging patterns. In this study, MATLAB/Simulink is employed to evaluate the 18 MW microgrid system, examining V2G interactions, power factor correction, and energy management techniques. By leveraging simulations, this research aims to develop a framework for optimizing microgrid operations, addressing power quality issues, and enhancing energy sustainability. The findings provide valuable recommendations for improving microgrid resilience through intelligent control strategies and AI-based optimizations.

The structure of this paper includes a literature review on renewable energy and EV integration, followed by a detailed microgrid modeling and system configuration. Simulation results are discussed, highlighting power factor correction, V2G capabilities, and overall system efficiency. The study concludes with recommendations for future advancements in microgrid technology, renewable energy integration, and energy storage solutions. The integration of EVs and RES in microgrids is a critical step toward a sustainable energy future, ensuring cleaner, smarter, and more resilient power systems for modern applications.

LITERATURE SURVEY

The integration of renewable energy sources (RES) and electric vehicles (EVs) in microgrid systems has been widely explored in academic research. Several studies emphasize the need for sustainable energy solutions to address the growing global energy demand and environmental concerns. According to [1], renewable energy generation through solar and wind power has gained significant traction due to technological advancements and cost reductions. However, the intermittent nature of RES poses challenges for microgrid stability, requiring robust energy management strategies. Research by [2] highlights the role of smart grids and energy storage systems in optimizing power flow and maintaining grid reliability, especially when integrating EVs with vehicle-to-grid (V2G) capabilities.

EV integration in microgrids introduces both opportunities and challenges. Studies by [3] and [4] suggest that bidirectional power flow from EVs can help in peak load shaving and frequency regulation, thereby enhancing grid stability. However, uncoordinated EV charging may cause voltage drops and increase harmonic distortions, impacting overall power quality. Research by [5] explores various charging strategies, including controlled charging, demand response techniques, and real-time optimization algorithms, to ensure efficient energy utilization. Implementing intelligent control mechanisms such as fuzzy logic and neural networks has been proposed in multiple studies to mitigate power fluctuations and improve power factor performance.

Several studies focus on the importance of power factor correction (PFC) in microgrid systems. According to [6], maintaining a unity power factor improves transmission efficiency and reduces energy losses. The study further elaborates on different PFC techniques, such as active and passive filtering, capacitor banks, and power electronics-based compensation methods. Research by [7] compares conventional PI controllers with advanced fuzzy and AI-based controllers, demonstrating improved power quality and voltage regulation in microgrid environments. The impact of nonlinear EV chargers on harmonic distortions has also been a key area of investigation, with solutions like harmonic filters and advanced control strategies proposed to minimize disturbances in power networks.

The role of MATLAB/Simulink in microgrid modeling and simulation has been extensively examined in academic literature. Studies by [8] and [9] highlight the effectiveness of MATLAB-based simulations in evaluating system dynamics, analyzing power flow, and optimizing energy distribution. Research by [10] explores multi-objective optimization techniques for microgrid energy management, integrating renewable sources, battery storage, and EVs to achieve better operational efficiency. Furthermore, studies have demonstrated the feasibility of implementing AI-based techniques for forecasting energy demand, optimizing V2G interactions, and enhancing load balancing mechanisms.

Advanced control techniques play a crucial role in improving the efficiency of microgrid systems. Research by [11] and [12] investigates the application of model predictive control (MPC), adaptive neuro-fuzzy inference systems (ANFIS), and machine learning algorithms for dynamic energy management. Studies by [13] emphasize the significance of decentralized energy management strategies to enhance resilience against grid disturbances. Moreover, the adoption of blockchain-based energy trading systems has been proposed in recent research to facilitate peer-to-peer energy transactions, ensuring transparency and security in decentralized microgrid networks.

In summary, the literature underscores the potential of renewable energy and EV integration in microgrid systems while highlighting key technical challenges and solutions. Research emphasizes the necessity of smart energy management techniques, power factor correction strategies, and advanced control mechanisms to ensure stable and efficient operations. Future studies should focus on AI-driven predictive models, hybrid energy storage solutions, and decentralized control frameworks to further enhance microgrid reliability and sustainability. This literature survey provides a foundation for the subsequent sections of this study, which explore detailed modeling, analysis, and optimization strategies for an 18 MW microgrid system with unity power factor.

SIMULATION RESULTS

Electrical cars consist of two components. An internal energy source powers the batteries of electric vehicles, while an electric motor facilitates the vehicle's propulsion. Electrical vehicles require external energy sources to charge their batteries. Under these circumstances, it is necessary to charge the cars. EVs utilise several forms of charging. Charging stations can be classify into various categories based on their charging speed and voltage. The challenges facing the development of EVs involve enhancing their range and reducing the time required for charging. Currently, researchers are conducting ongoing, rigorous investigations to address these issues. To expedite the charging process of an electric car, it is advisable to charge the vehicle using DC. We enhance the power output of the charging stations to reduce the duration of charging for EVs. Consequently, the quantity of charging stations with a power exceeding 350 kW is progressively growing. Several charging plugs equip the charging stations, enabling simultaneous charging for multiple automobiles. Simultaneously charging numerous automobiles can lead to significant issues within the microgrid. The escalating load demand on the grid poses a significant issue. The integration of renewable energy sources and EVs into a microgrid is modelled in Fig. 1

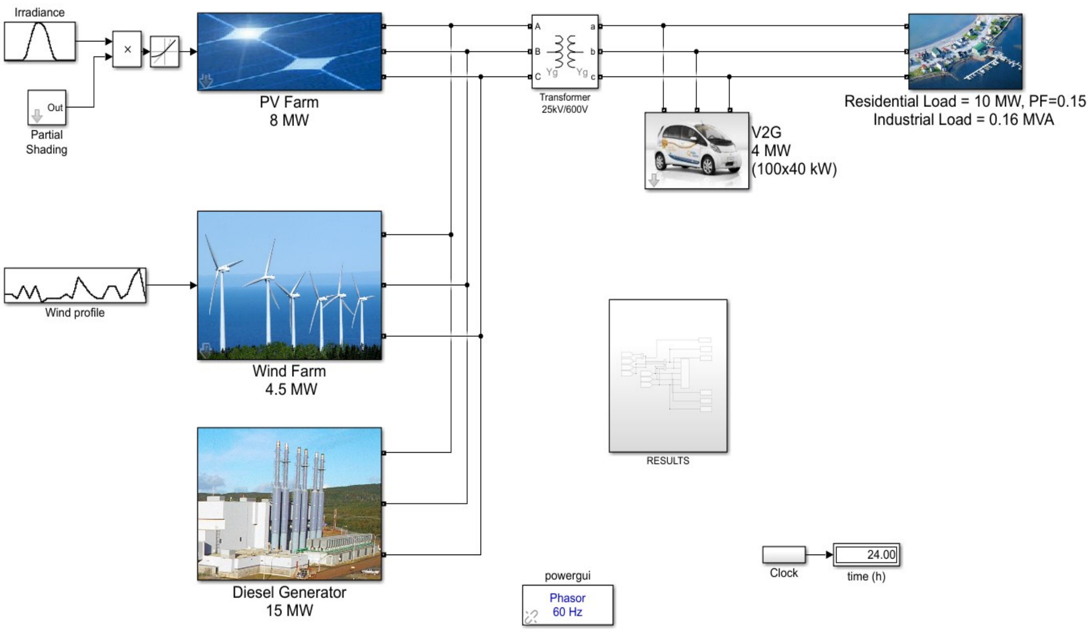

FIGURE 1. MATLAB/SIMULINK circuit of the proposed system

EXISTING RESULTS (LOAD POWER 14MW)

Microgrid systems rely on the precise management of fundamental quantities like current and voltage, which are represented by sinusoidal waveforms with a frequency of 50 Hz. However, these fundamental variables lose their sinusoidal features due to various factors, resulting in the presence of undesired harmonic components in the microgrid system. The exponential growth of EVs results in a surge in power demand, posing an additional burden on the microgrid. Consequently, there is an increase in the variability of the microgrid. The diesel generator within the microgrid maintains equilibrium between the electricity consumed and the power generated. You can determine the discrepancy in the grid frequency by comparing it to the rotor speed of the synchronous machine. Figure 2 presents the total energy output of the diesel generator over the course of the day. The drawbacks of diesel generators are their exorbitant cost and their detrimental impact on the environment. Nevertheless, when renewable energy sources are unable to meet the energy demand, the utilization of a diesel generator becomes necessary to generate the required energy. The microgrid consists of two renewable energy sources. First and foremost, the PV plant generates energy in direct proportion to the level of irradiation present in the surrounding environment. Figure 3 presents the diurnal energy output of solar panels. The solar farm in the microgrid generates direct current by harnessing solar irradiation. The material composition of the panels, the amount of solar irradiation they absorb, and the prevailing climatic conditions all influence the energy output. The wind farm produces electrical power in direct proportion to the strength of the wind. The turbine produces its maximum power output once the wind speed reaches its designated value. The microgrid deactivates the wind power when the wind speed exceeds its maximum threshold, until it returns to its standard level. Figure 4 displays the daily energy production of the wind farm in the microgrid. The use of wind power plants in microgrids is steadily rising owing to their status as a renewable energy source, uncomplicated design, and notable efficacy. Wind farms, in contrast to other conventional power facilities, exhibit distinct characteristics. The primary benefit of EVs is their ability to utilise V2G applications. This application is exclusively applicable to electric cars. Essentially, it enables the car to directly supply electricity to the distribution microgrid.

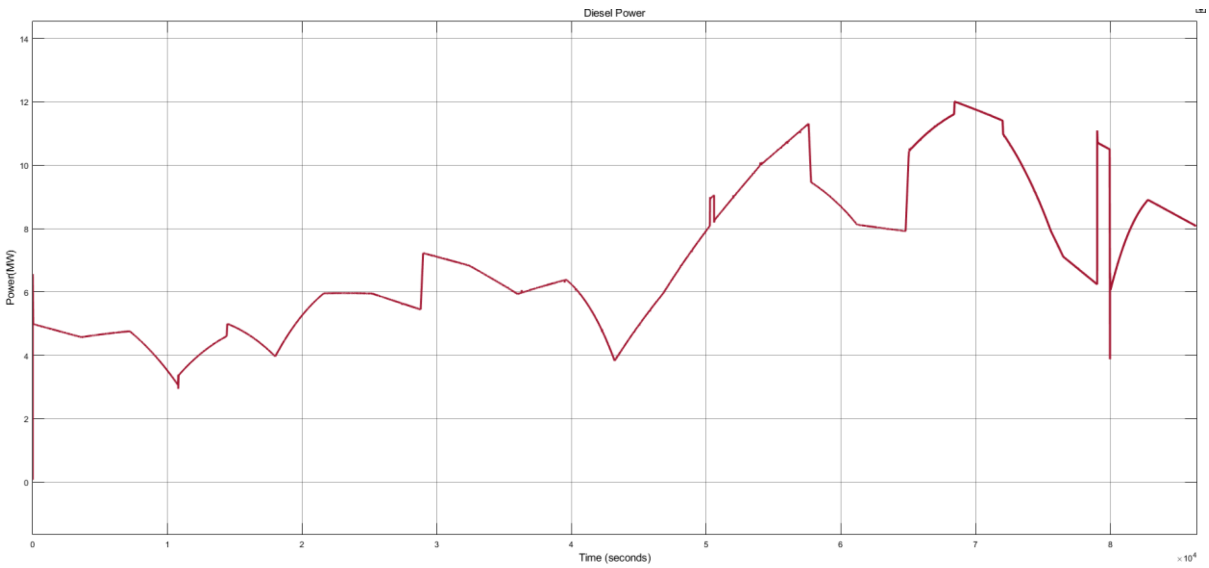

FIGURE 2 Power generated by the generator throughout the day.

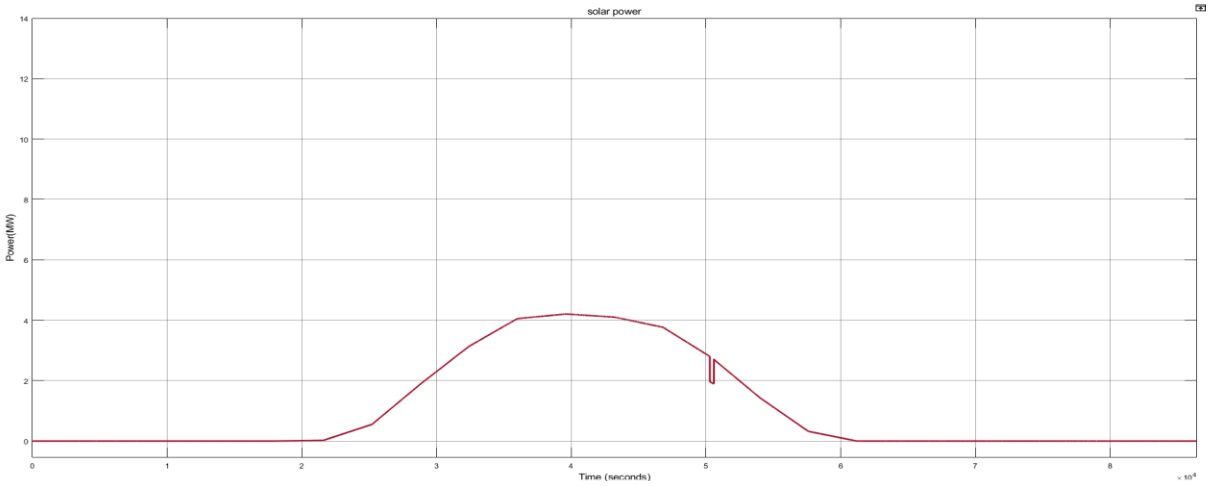

FIGURE 3 Power generated by the solar throughout the day.

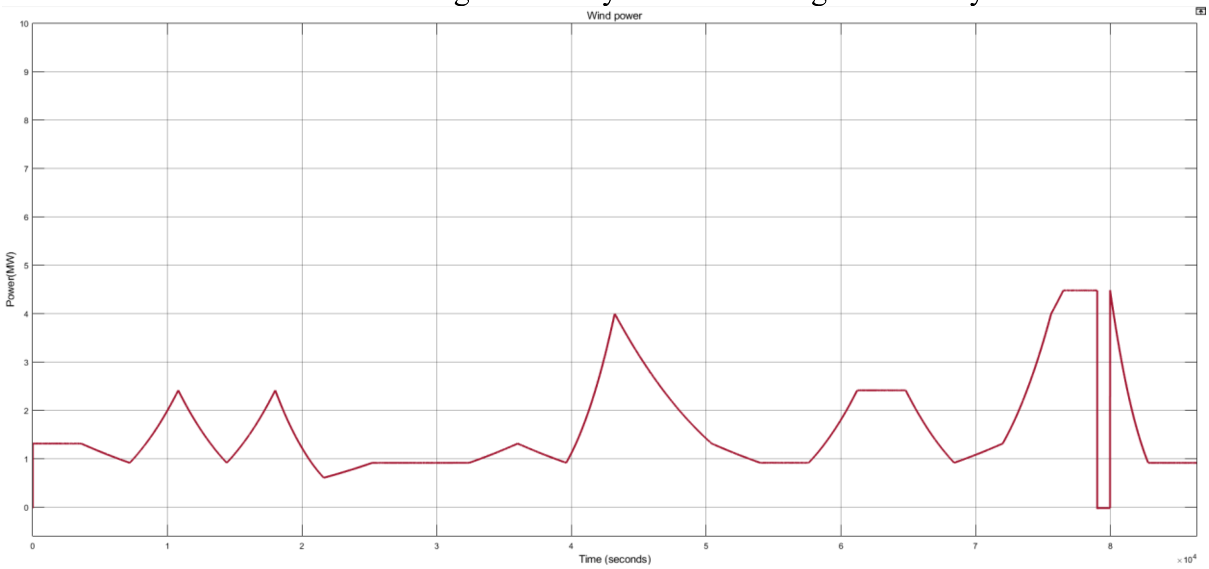

FIGURE 4 Power generated by the wind throughout the day.

Figure 5 shows the power value that the EV transmits and controls to the microgrid throughout the day. V2G refers to the process of transferring electrical energy from the battery systems of EVs to the microgrid. Within the electrical system, the batteries of EVs function as a means of storing energy. Car-to-grid technology enables the charging and discharging of a car battery based on various signals, such as energy output or consumption. The utilisation of electric vehicle charging results in a rise in the electrical demand per transformer during periods of high energy consumption inside the microgrid. This poses significant challenges to achieving energy equilibrium. Charging many EVs in the same phase leads to a phase imbalance in the microgrid. Spontaneous charging of EVs poses significant issues within the microgrid. Charging many EVs at the same time can result in a decrease in voltage at the connectors of the chargers. EVs draw a significant amount of active power from the network during charging, leading to power losses within the microgrid. V2G technology serves two primary objectives. It manages the battery charge and utilises the available power to stabilise the grid during transient events. V2G technology guarantees the immediate accessibility of current decentralised energy storage systems. A multitude of battery types are introduced into the market.

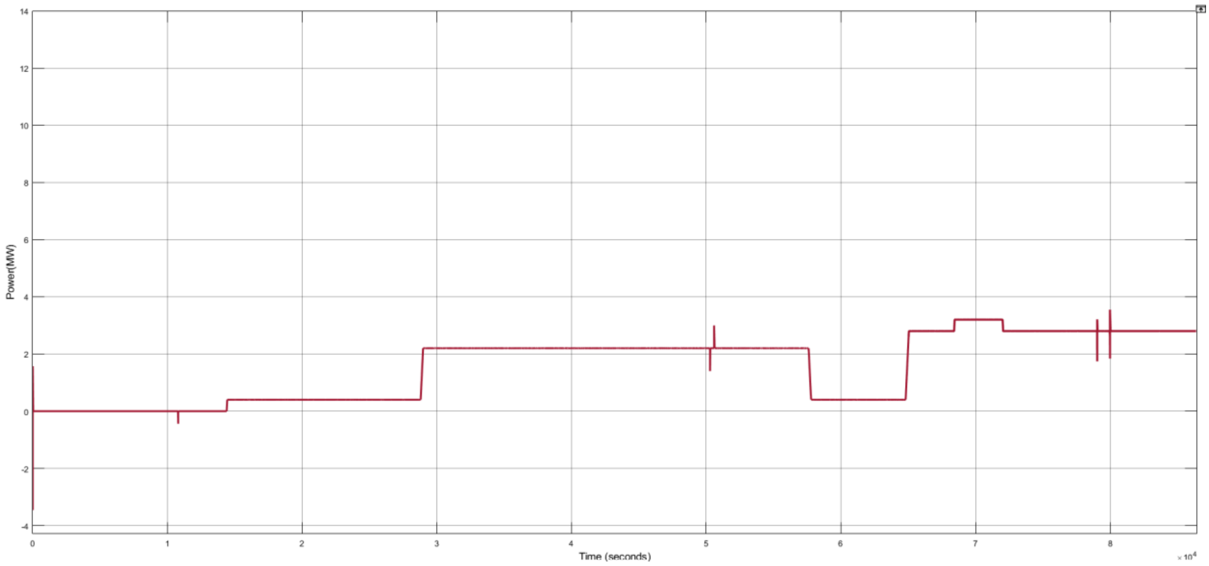

FIGURE 5 Charged and regulated into the microgrid throughout the day.

The residential load is represented by the active power drawn at a specified power factor, as illustrated in Fig. 6 The total power generated is represented by the active power generated from the microgrid, and the power generated is equal to or more than the load. That means there is an equilibrium between demand and generation, as shown in Fig. 7

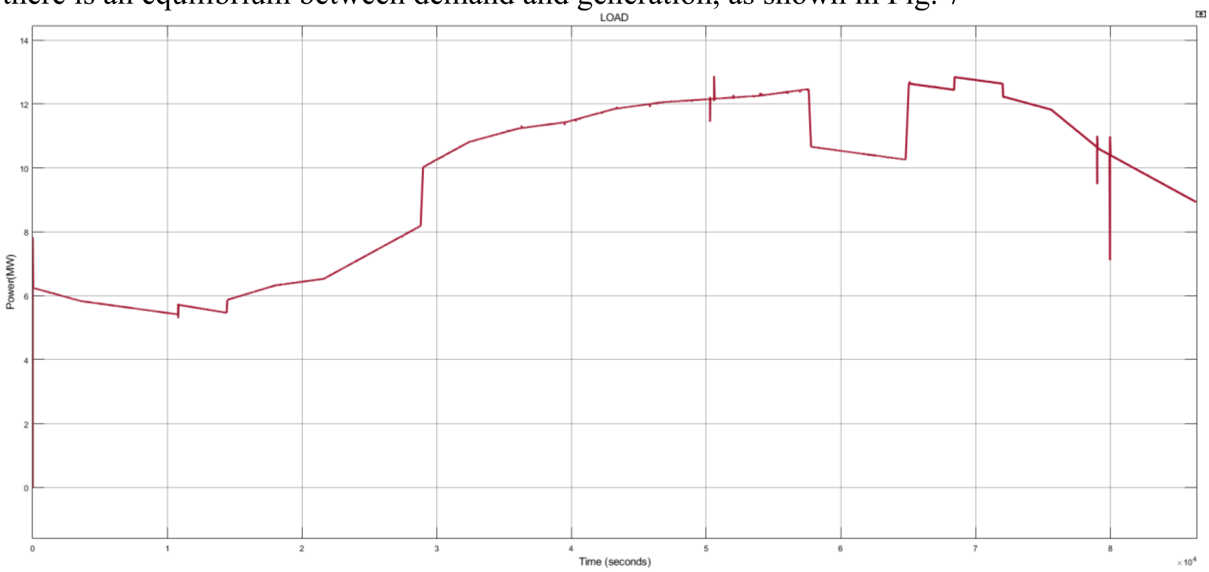

FIGURE 6 Load drawn power from the microgrid during the day.

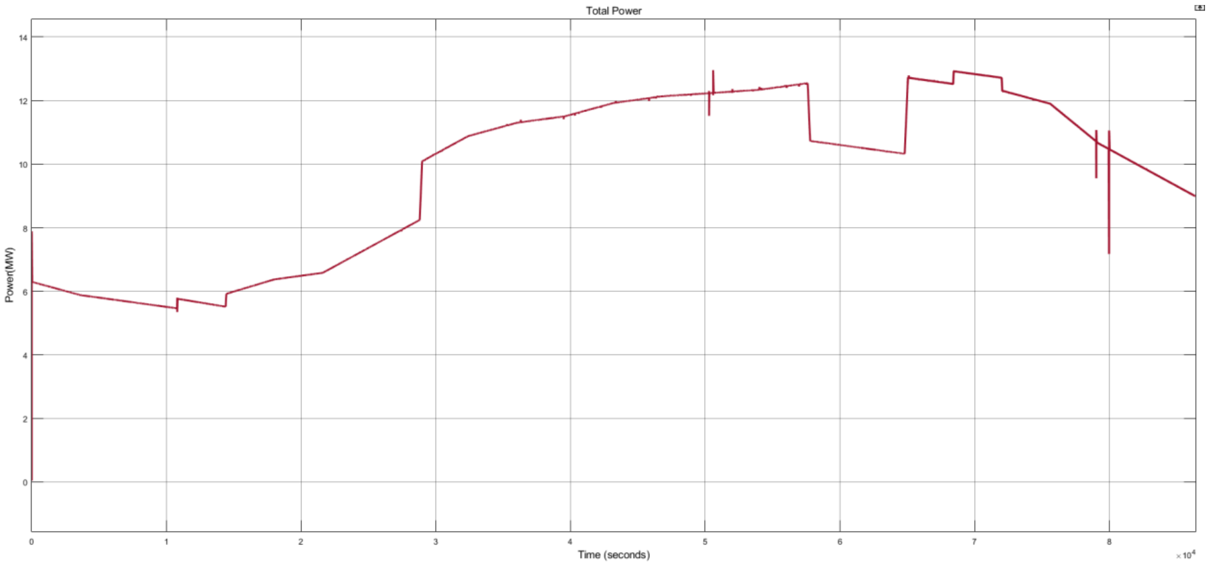

FIGURE 7 Total power generation from microgrid during the day.

EXTENSION RESULTS (LOAD POWER 18MW)

Figure 8 presents the total energy output of the diesel generator over the course of the day. The drawbacks of diesel generators are their exorbitant cost and their detrimental impact on the environment. Nevertheless, when renewable energy sources are unable to meet the energy demand, the utilization of a diesel generator becomes necessary to generate the required energy. The microgrid consists of two renewable energy sources. First and foremost, the PV plant generates energy in direct proportion to the level of irradiation present in the surrounding environment. Figure 9 presents the diurnal energy output of solar panels. The solar farm in the microgrid generates direct current by harnessing solar irradiation. Figure 10 displays the daily energy production of the wind farm in the microgrid. The use of wind power plants in microgrids is steadily rising owing to their status as a renewable energy source, uncomplicated design, and notable efficacy.

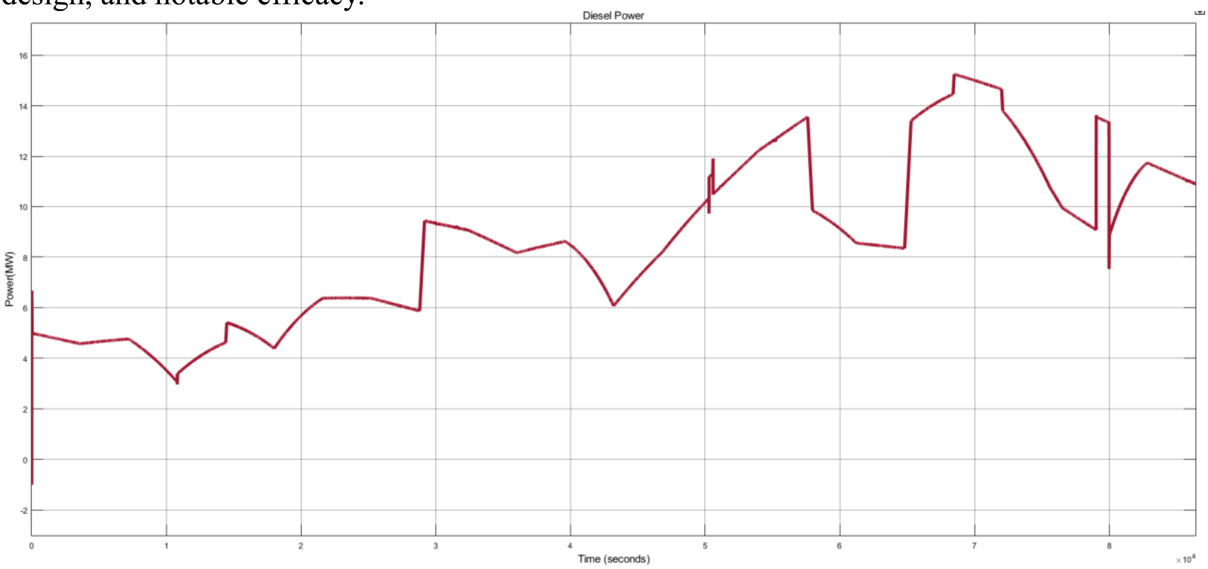

FIGURE 8 Power generated by the generator throughout the day.

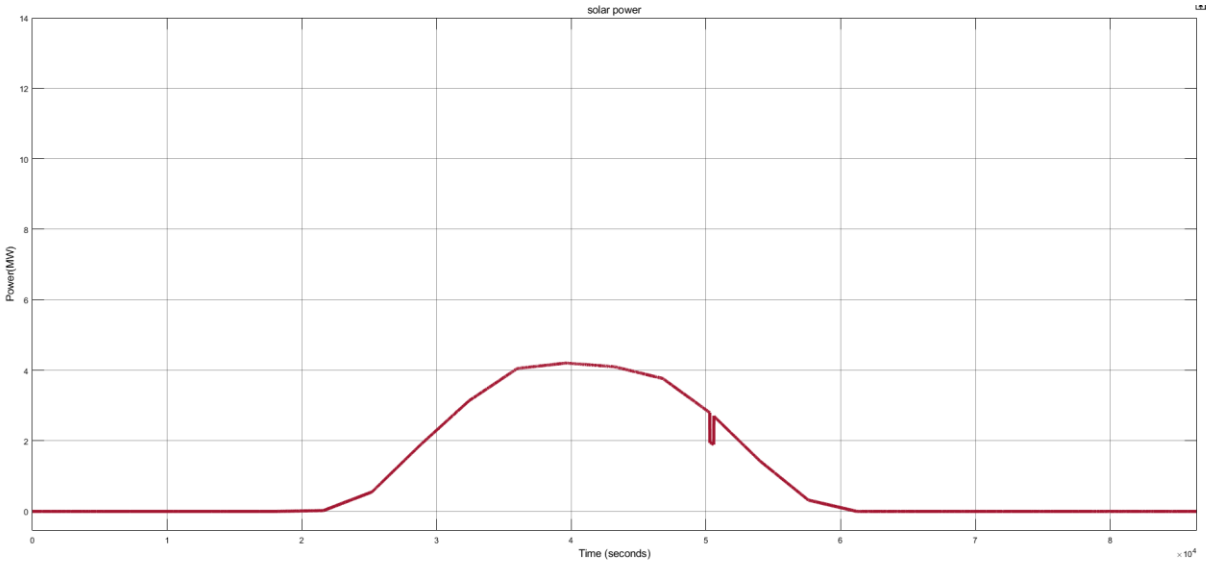

FIGURE 9 Power generated by the solar throughout the day.

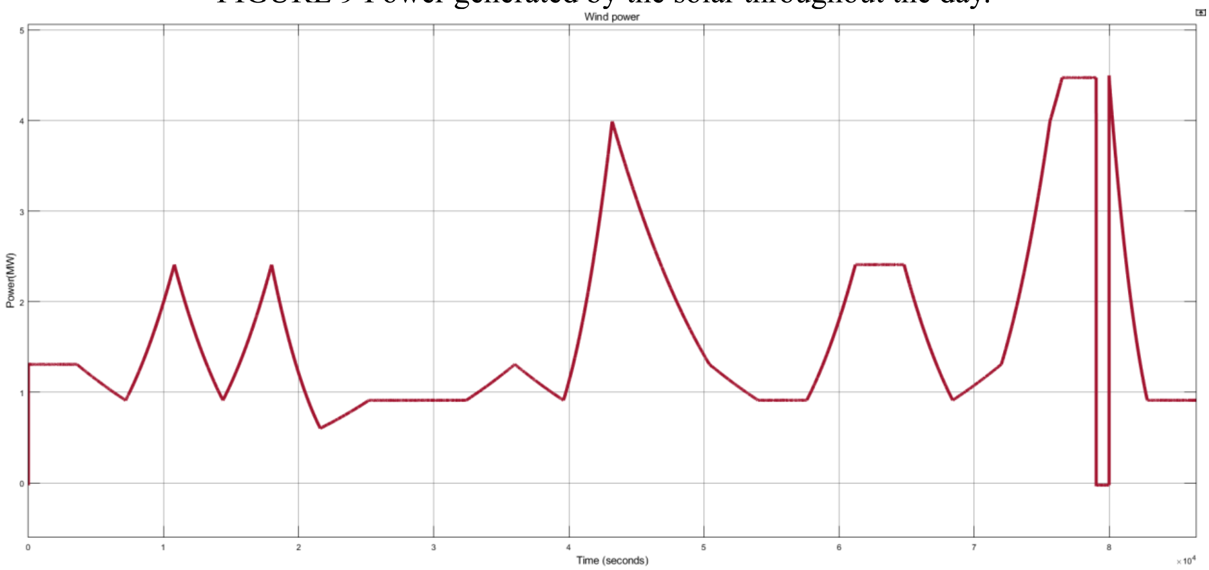

FIGURE 10 Power generated by the wind throughout the day.

Figure 11 shows the power value that the EV transmits and controls to the microgrid throughout the day.

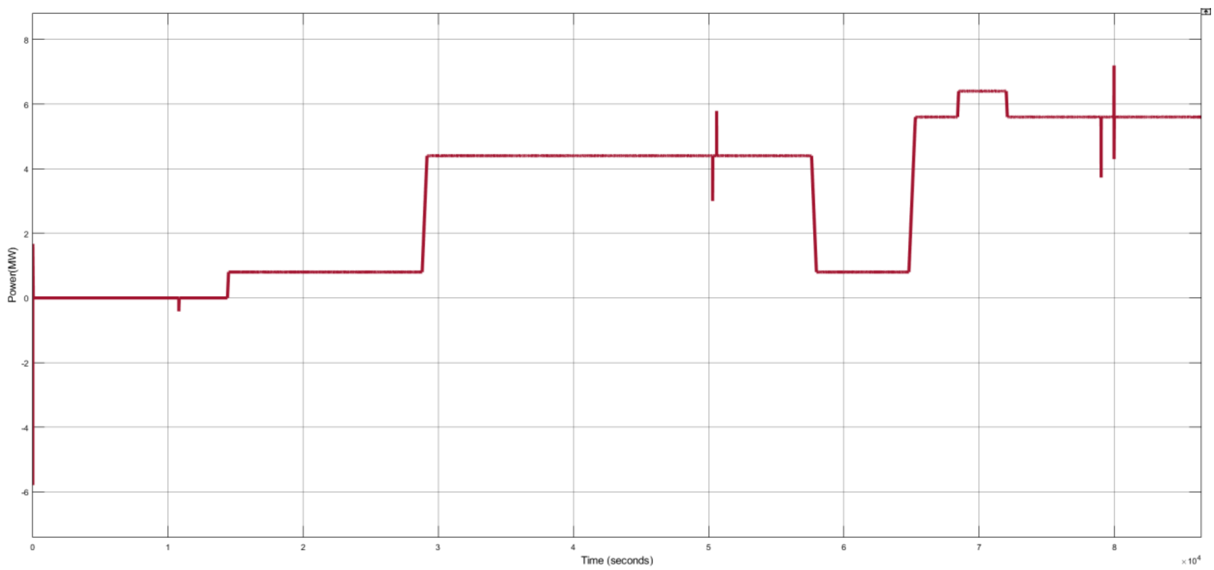

FIGURE 11 Charged and regulated into the microgrid throughout the day.

The residential load is represented by the active power drawn at a specified power factor, as illustrated in Fig. 12 The total power generated is represented by the active power generated from the microgrid, and the power generated is equal to or more than the load. That means there is an equilibrium between demand and generation, as shown in Fig. 7

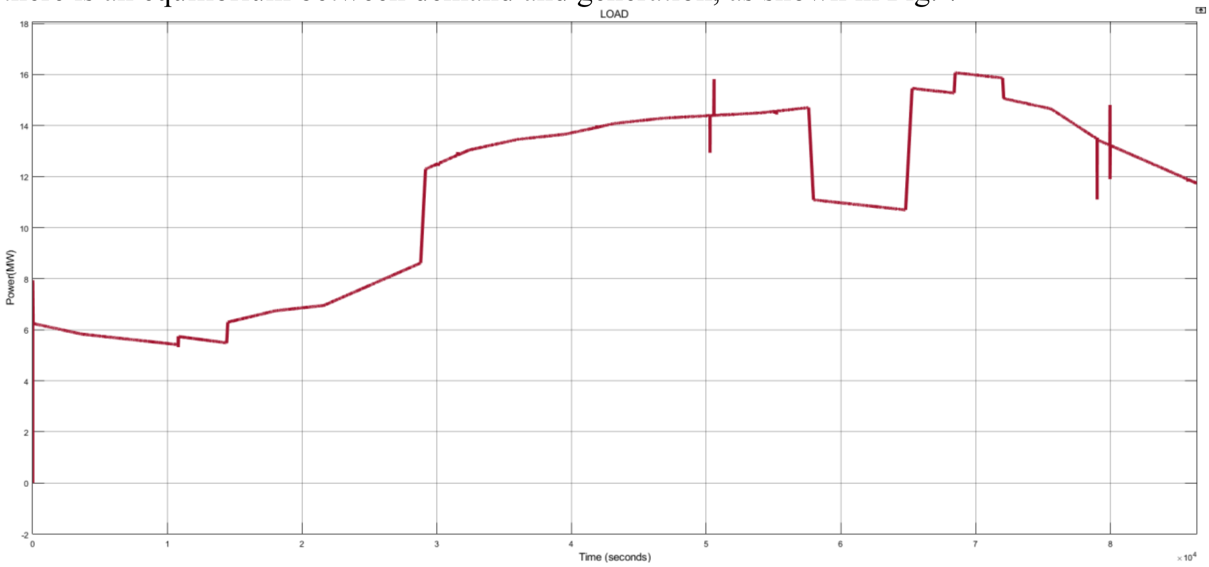

FIGURE 12 Load drawn power from the microgrid during the day.

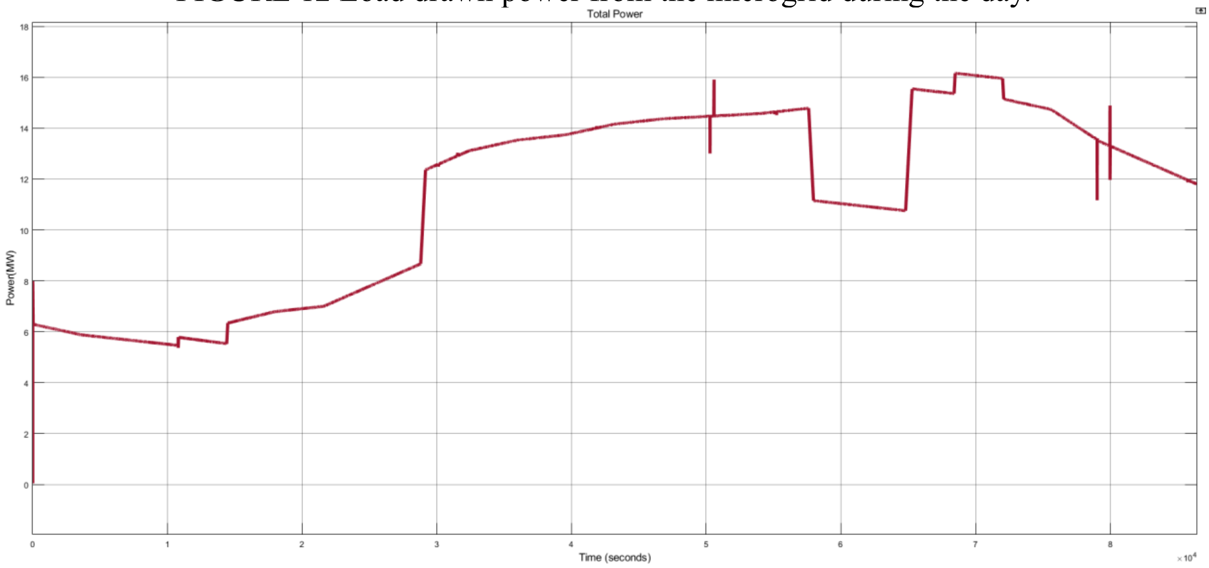

FIGURE 13 Total power generation from microgrid during the day.

CONCLUSION

The integration of Electric Vehicles (EVs) into distribution networks is an inevitable trend, bringing both challenges and opportunities. As EV adoption grows, the increased electricity demand places additional strain on distribution systems. To address these challenges, techniques such as reactive power compensation are employed to regulate voltage levels within microgrids. By improving power factor and minimizing transmission losses, reactive power support enhances overall system efficiency. EVs integrated into microgrids can actively contribute by providing reactive power adjustments, further stabilizing grid performance. This study focuses on analyzing the operational dynamics of standalone microgrids, with a particular emphasis on various EV charging strategies. It considers key uncertainties, including fluctuating load demands, solar irradiation, and wind patterns, which are critical for optimizing microgrid performance. Given the rapid expansion of EV adoption, it is essential to investigate their impact on power quality, particularly regarding harmonic distortions. Implementing effective mitigation strategies is crucial to maintaining grid stability and ensuring seamless compatibility with existing electrical infrastructure. The increasing prevalence of EVs is also driving a proportional rise in charging station deployments, reflecting the growing need for accessible and efficient charging solutions. The rapid transformation of the transportation sector underscores the urgency of advancing EV technologies, which have a profound impact on both power systems and environmental sustainability. As EVs continue to reshape mobility, their seamless integration into energy networks requires strategic planning and innovative solutions to maximize benefits while minimizing disruptions to grid operations and environmental impacts.

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