HYBRID MICRO-GRID SYSTEM ENERGY MANAGEMENT WITH RENEWABLE ENERGY USING FUZZY LOGIC CONTROLLER

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Submitted Date : 28-10-2025 Accepted Date: 03-11-2025 Published Date : 14-11-2025

ABSTRACT
This project involves a hybrid micro-grid system integrating a wind power plant, a solar power plant, and a diesel generator as a backup, all managed using a fuzzy logic controller. The wind and solar inputs are time-varying, meaning the wind power generation changes with wind speed and the solar power changes with irradiance levels throughout the day. Additionally, the system powers a 10 MW residential load and an electric vehicle charging station, both of which vary over time. When the combined renewable generation (from wind and solar) is insufficient to meet the load demand, the fuzzy logic controller activates the diesel generator to supply the remaining power needed. In case all else fails, the utility grid serves as an additional backup. The entire system is simulated in MATLAB, and results confirm that the fuzzy logic controller effectively balances the load and generation, ensuring stable and reliable operation.

Keywords: Hybrid micro-grid, Fuzzy logic control, Renewable energy integration, Wind and solar power, Diesel generator backup, Energy management, MATLAB simulation.

I INTRODUCTION

The progressive transformation of conventional power systems into intelligent and decentralised networks has been chiefly driven by the escalating demand for electrical energy, the depletion of fossil fuel reserves, and growing environmental concerns associated with greenhouse gas emissions. In this context, micro-grid systems have emerged as a viable solution for integrating renewable energy sources into existing electrical infrastructures while ensuring operational reliability and energy security [1], [2]. A micro-grid may be defined as a localised cluster of distributed energy resources, storage systems, and loads that can operate either in conjunction with the main utility grid or in an autonomous islanded mode [3]. Such systems are particularly advantageous in remote regions, urban residential complexes, and emerging smart cities, where flexibility, efficiency, and sustainability are paramount [4], [5]. The integration of renewable energy sources, notably wind and solar power, has assumed considerable importance owing to their abundance, cleanliness, and declining installation costs [6]. Wind energy conversion systems exploit the kinetic energy of moving air masses, while solar photovoltaic systems convert irradiance directly into electrical energy. However, both sources are inherently intermittent and stochastic in nature, being largely dependent upon meteorological

 ISSN: 3049-0952
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conditions that vary unpredictably with time [7], [8]. These fluctuations give rise to challenges in maintaining power balance, voltage stability, and frequency regulation within a micro-grid environment, particularly when supplying dynamic and high-capacity loads [9].

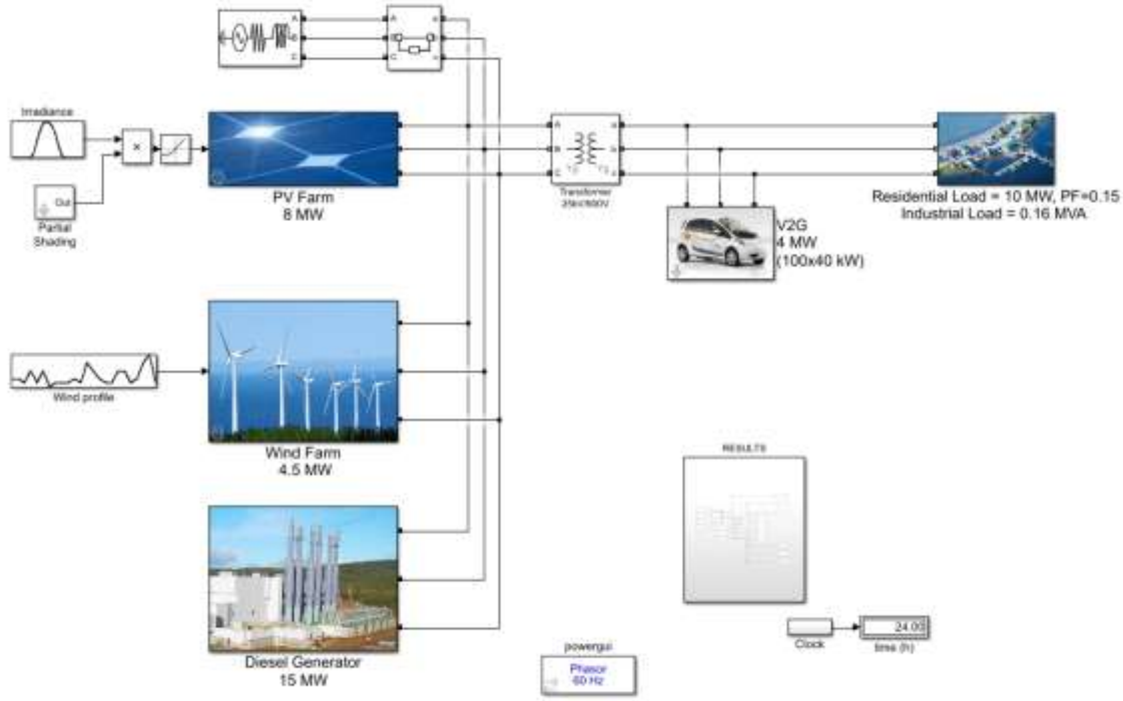

Fig 1.proposed system configuration

To address these limitations, hybrid micro-grid configurations incorporating multiple generation sources have been widely investigated in the literature [10]. The combination of wind and solar generation provides a degree of complementarity, as peak wind speeds and maximum solar irradiance often occur at different times of the day or year [11]. Nevertheless, periods of low renewable availability cannot be entirely avoided, necessitating the inclusion of auxiliary power sources such as diesel generators or grid interconnections to ensure uninterrupted supply [12]. Diesel generators, despite their environmental drawbacks, remain a reliable and rapidly dispatchable backup option, especially during prolonged renewable deficits or sudden load surges [13]. In modern power systems, the increasing penetration of electric vehicles has further compounded the complexity of load management [14]. Electric vehicle charging stations introduce highly variable and impulsive load profiles, which can significantly strain micro-grid resources if not properly coordinated [15]. When combined with large residential loads, such as the 10 MW demand considered in this work, the need for an intelligent and adaptive energy management strategy becomes indispensable [16]. An effective energy management system must continuously monitor generation availability, load demand, and system constraints in order to make optimal control decisions in real time [17].

Conventional energy management approaches, including rule-based control and proportional–integral controllers, have been extensively employed in earlier studies [18]. While such methods are relatively simple to implement, they often require precise mathematical models and perform inadequately under nonlinear and uncertain operating conditions typical of renewable-based systems [19]. Moreover, their inability to handle multiple conflicting objectives simultaneously limits their suitability for complex hybrid micro-grids [20]. These shortcomings have motivated the exploration of intelligent control techniques that can mimic human reasoning and decision-making processes. Among the various intelligent control methodologies, fuzzy logic control has gained considerable attention owing to its robustness, flexibility, and model-free nature [21]. Introduced to power system applications to manage uncertainty and imprecision, fuzzy logic controllers utilise linguistic variables and a set of heuristic rules to govern system behaviour [22]. This characteristic renders them particularly well suited for renewable energy systems, where exact models are difficult to obtain and operating conditions vary continuously [23]. By incorporating expert knowledge into the control framework, fuzzy logic controllers are capable of achieving smooth transitions between operating modes and maintaining system stability under fluctuating inputs [24].

In the context of hybrid micro-grids, fuzzy logic–based energy management systems have been shown to improve renewable energy utilisation, reduce dependency on fossil fuel-based generators, and enhance overall system reliability [25]. Such controllers can prioritise wind and solar generation when available, regulate the engagement of diesel generators during deficits, and coordinate grid interaction when local resources are insufficient [26]. Furthermore, fuzzy logic control enables the consideration of multiple decision variables, such as renewable power availability, load demand, and system constraints, within a unified framework [27]. Simulation platforms such as MATLAB/Simulink have become indispensable tools for analysing and validating micro-grid control strategies prior to real-world deployment [28]. Through time-varying wind speed and solar irradiance profiles, realistic operating scenarios can be emulated to assess system performance under dynamic conditions [29]. The ability to model large residential loads and electric vehicle charging stations further enhances the credibility of such studies, providing valuable insights into practical implementation challenges [30].

In view of the foregoing discussion, the development of an efficient energy management plan for a hybrid micro-grid system integrating wind, solar, diesel generation, and grid support using a fuzzy logic controller constitutes a timely and significant research endeavour. Such an approach not only addresses the intermittency of renewable energy sources but also ensures stable, reliable, and sustainable power supply for modern electrical loads.

II LITERATURE SURVEY

The concept of the micro-grid has attracted increasing scholarly attention over the past two decades as a consequence of rising energy demand, environmental concerns, and the limitations of conventional centralised power systems. Early investigations established micro-grids as localised energy networks capable of integrating distributed generation sources, energy storage, and controllable loads within a defined electrical boundary [1], [2]. These studies highlighted the ability of micro-grids to operate either in grid-connected or islanded modes, thereby enhancing supply reliability and resilience during grid disturbances [3]. The foundational literature further emphasised that the successful operation of micro-grids relies heavily upon effective coordination among heterogeneous energy sources [4]. Renewable energy integration has been extensively examined as a principal driver for micro-grid development. Solar photovoltaic and wind energy systems have been recognised as the most prominent renewable contributors owing to their technological maturity and declining costs [5], [6]. Numerous researchers have demonstrated that solar and wind resources are complementary in nature, with temporal diversity reducing overall power variability when both are employed together [7]. However, it has been consistently reported that the intermittent and stochastic characteristics of these resources introduce significant challenges in maintaining power balance and voltage stability [8], [9]. Such issues are exacerbated in isolated or weak grids, where reserve capacity is limited.

To mitigate renewable intermittency, hybrid micro-grid architectures have been proposed, combining multiple generation sources with auxiliary units such as diesel generators and grid interconnections [10]. Diesel generators, though carbon-intensive, have been acknowledged for their rapid response capability and operational reliability during renewable shortfalls [11]. Several studies have explored optimal sizing and scheduling of diesel units within hybrid systems to minimise fuel consumption while preserving system security [12]. The inclusion of grid support has also been shown to enhance operational flexibility, particularly during peak demand or prolonged renewable deficits [13]. Energy management systems play a central role in coordinating power flow within hybrid micro-grids. Early energy management approaches relied upon deterministic rule-based strategies, which were simple to implement but lacked adaptability to dynamic operating conditions [14]. Subsequent research introduced optimisation-based techniques aimed at minimising operational costs or emissions through mathematical programming methods [15]. Although effective under well-defined constraints, such approaches often required accurate system models and suffered from high computational complexity, limiting their real-time applicability [16].

The growing complexity of micro-grid systems, especially with the integration of variable renewable sources and emerging loads, prompted researchers to investigate intelligent control techniques. Artificial intelligence-based methods, including neural networks, genetic algorithms, and fuzzy logic systems, have been widely reported in the literature [17]. Among these, fuzzy logic control has been particularly favoured for energy management applications due to its ability to handle uncertainty, nonlinearity, and imprecise input information [18]. Unlike conventional controllers, fuzzy logic systems do not depend upon exact mathematical representations, instead employing linguistic rules derived from expert knowledge [19]. Several studies have demonstrated the effectiveness of fuzzy logic controllers in managing hybrid renewable micro-grids. Researchers have shown that fuzzy-based energy management schemes can dynamically prioritise renewable energy utilisation while ensuring stable power supply to critical loads [20]. The controller's capability to smoothly transition between operating modes, such as renewable-dominant operation and diesel-assisted operation, has been emphasised as a key advantage [21]. Furthermore, fuzzy logic approaches have been reported to reduce diesel fuel consumption and enhance overall system efficiency when compared to traditional control strategies [22].

The increasing penetration of electric vehicles has introduced new challenges to micro-grid energy management, as EV charging loads are highly variable and often unpredictable. Several authors have investigated the impact of EV charging stations on micro-grid stability and energy balance [23]. It has been observed that uncoordinated EV charging can lead to peak demand issues and increased stress on generation units [24]. Consequently, intelligent energy management strategies incorporating fuzzy logic have been proposed to schedule EV charging in harmony with renewable availability and system constraints [25]. Large residential loads further complicate the operational landscape of hybrid micro-grids. Studies focusing on high-capacity residential demand have highlighted the importance of adaptive control mechanisms capable of responding to rapid load fluctuations [26]. In such scenarios, fuzzy logic controllers have been shown to effectively balance generation and demand by continuously evaluating multiple system parameters, including renewable output, load demand, and backup availability [27]. This multi-input decision-making capability has been cited as a principal strength of fuzzy-based approaches.

Simulation-based analysis has been extensively employed to validate proposed energy management strategies. MATLAB/Simulink has emerged as a preferred platform due to its flexibility and comprehensive modelling libraries for renewable energy systems [28]. Researchers have utilised variable wind speed profiles and time-varying solar irradiance data to replicate realistic environmental conditions [29]. Simulation results across numerous studies consistently indicate that fuzzy logic–based energy management systems enhance system reliability, reduce grid dependency, and improve renewable energy penetration levels [30]. In summary, the existing body of literature clearly establishes the necessity of intelligent energy management for hybrid micro-grid systems integrating renewable energy sources. While various control methodologies have been explored, fuzzy logic control has demonstrated superior adaptability and robustness under uncertain and dynamic operating conditions. The findings reported in prior studies provide strong motivation for further investigation into fuzzy logic–based energy management strategies tailored to hybrid micro-grids supplying variable residential and electric vehicle loads.

III METHODOLOGY

The methodological framework adopted in this work is founded upon the systematic modelling and integration of a hybrid micro-grid system comprising wind energy conversion, solar photovoltaic generation, a diesel generator unit, and a utility grid interface. The entire configuration is developed within the MATLAB/Simulink environment in order to emulate realistic operating conditions and enable comprehensive performance evaluation. Time-varying profiles are employed for both wind speed and solar irradiance so as to reflect the inherent variability of renewable energy sources. These profiles are applied to the respective generation models, allowing dynamic power output to be obtained throughout the simulation period. A high-capacity residential load rated at 10 MW, along with an electric vehicle charging station characterised by fluctuating demand patterns, is incorporated to assess system behaviour under practical load scenarios. The micro-grid is designed to operate in a grid-connected mode with seamless transition to autonomous operation whenever local generation and storage are sufficient to sustain the load demand.

The wind energy subsystem is modelled using a variable wind speed profile that drives a wind turbine connected to an electrical generator through appropriate mechanical and electrical interfaces. The turbine model accounts for aerodynamic characteristics, including cut-in, rated, and cut-out wind speeds, ensuring realistic power extraction from the available wind resource. Simultaneously, the solar photovoltaic subsystem is represented by an array model whose output is governed by irradiance and temperature variations. The electrical outputs from both renewable sources are conditioned through suitable power electronic converters to maintain compatibility with the micro-grid bus. By continuously monitoring the instantaneous power contributions from wind and solar units, the system establishes the available renewable energy at any given instant. This information serves as a primary input for subsequent energy management decisions, ensuring that renewable sources are utilised to the greatest extent possible.

A diesel generator is incorporated as a secondary power source to guarantee reliability during periods of insufficient renewable generation. The diesel unit is modelled to reflect realistic operational constraints, including start-up delay, minimum loading requirements, and fuel consumption characteristics. In parallel, a utility grid interface is provided to serve as a tertiary backup source, enabling power import during extreme conditions when local resources are unable to meet demand. The interconnection between the micro-grid and the utility grid is achieved through controlled switching mechanisms that ensure safe and stable operation. Priority is assigned to local renewable generation, followed by diesel support, with grid power utilised only as a last resort. This hierarchical energy utilisation strategy is central to minimising fossil fuel dependence while maintaining uninterrupted supply.

At the core of the proposed methodology lies the fuzzy logic–based energy management controller, which governs the distribution and coordination of power among the various sources and loads. The fuzzy controller is designed using linguistic input variables that represent renewable power availability, load demand magnitude, and the operational status of backup sources. These inputs are mapped onto a set of membership functions that capture the qualitative behaviour of the system under different operating conditions. A rule base is formulated using expert knowledge to define appropriate control actions for each combination of inputs. Through the processes of fuzzification, inference, and defuzzification, the controller generates control signals that determine the engagement or disengagement of the diesel generator and grid support. This approach eliminates the need for precise mathematical modelling and enables robust decision-making under uncertainty.

The overall system performance is evaluated through extensive simulation studies conducted under diverse operating scenarios. These include periods of high renewable availability, sudden load surges due to electric vehicle charging, and extended intervals of low wind and solar output. Key performance indicators such as power balance, source utilisation, and system stability are monitored throughout the simulation duration. Comparative observations are made to assess the effectiveness of the fuzzy logic controller in maintaining reliable operation while reducing reliance on diesel and grid power. The results obtained through this methodological approach provide valuable insights into the practical feasibility of intelligent energy management for hybrid renewable micro-grid systems, thereby establishing a strong foundation for further development and real-world implementation.

IV PROPOSED SYSTEM

The proposed hybrid micro-grid system is conceived as an integrated and coordinated energy network designed to supply reliable electrical power by combining renewable energy sources with conventional backup units under the supervision of an intelligent control mechanism. The system primarily comprises a wind power generation unit and a solar photovoltaic array, both of which operate under naturally varying environmental conditions. These renewable sources are interconnected through suitable power conditioning interfaces to a common micro-grid bus, from which power is delivered to a large residential load and an electric vehicle charging station. The system is further supported by a diesel generator and a utility grid connection to ensure continuity of supply during unfavourable renewable conditions. The overall operational philosophy of the proposed system is to maximise renewable energy utilisation while maintaining stability and reliability under all loading scenarios.

Under normal operating conditions, the system continuously monitors wind speed and solar irradiance, which directly influence the instantaneous power output of the wind turbine and photovoltaic array respectively. When favourable environmental conditions prevail, the combined renewable generation is sufficient to meet the load demand. In such circumstances, electrical energy generated from wind and solar sources is supplied directly to the residential load and the electric vehicle charging station. Any surplus energy is managed in accordance with system requirements, ensuring that generation and demand remain balanced. This mode of operation minimises reliance on auxiliary power sources and significantly reduces fuel consumption and emissions associated with conventional generation units.

During intervals when renewable energy availability declines due to reduced wind speed or diminished solar irradiance, the system responds dynamically through the intervention of the fuzzy logic–based energy management controller. The controller evaluates the magnitude of the power deficit by comparing available renewable generation with instantaneous load demand. Upon detecting insufficient renewable supply, the controller issues appropriate control signals to initiate the operation of the diesel generator. The diesel unit then supplies the required supplementary power to bridge the gap between generation and demand. This transition is executed smoothly so as to avoid abrupt changes in system operation, thereby preserving voltage and frequency stability within the micro-grid.

In more severe operating scenarios, such as prolonged periods of low renewable generation or sudden increases in load demand caused by intensified electric vehicle charging, the system may require additional support beyond the diesel generator's capacity. In such cases, the utility grid interface is activated as a tertiary source of power. The fuzzy logic controller governs this interaction by ensuring that grid power is imported only when both renewable and diesel resources are unable to fully satisfy the load. This controlled grid interaction enhances system resilience while preventing unnecessary dependence on external power sources. The seamless coordination among renewable units, diesel backup, and grid support reflects the adaptive nature of the proposed energy management strategy.

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 7.2 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 7.3 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 7.4 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.

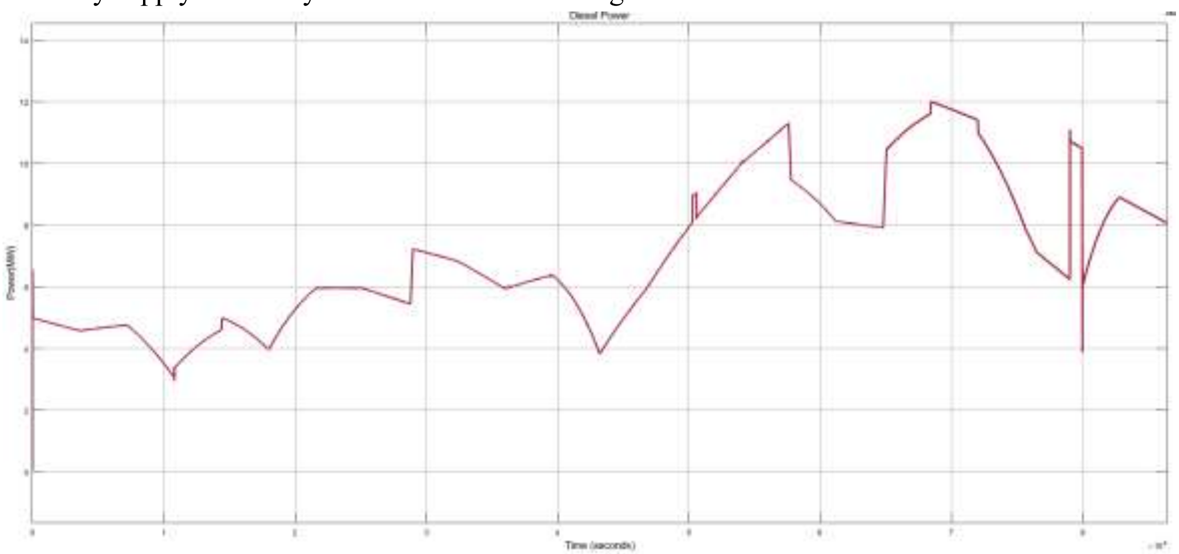

FIGURE 2 Power generated by the generator throughout the day.

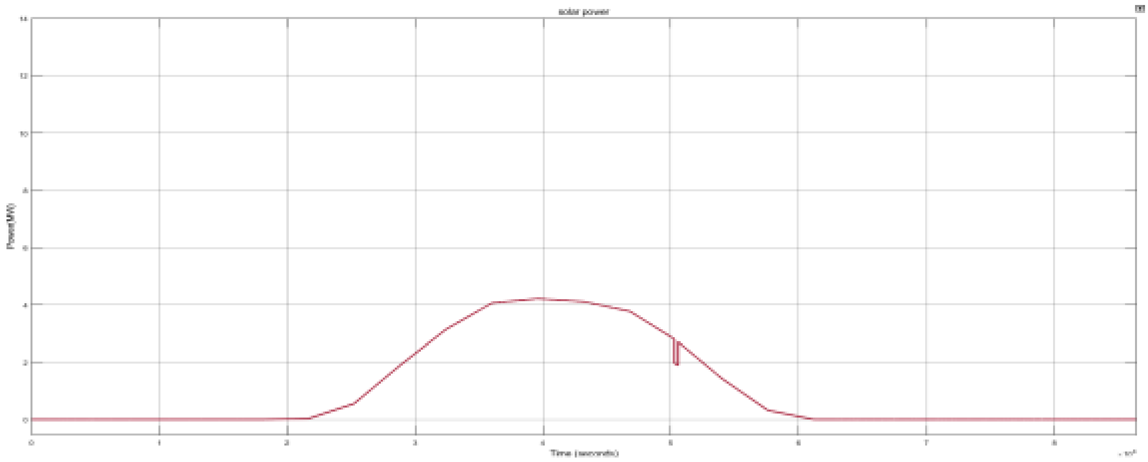

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FIGURE 3 Power generated by the solar throughout the day.

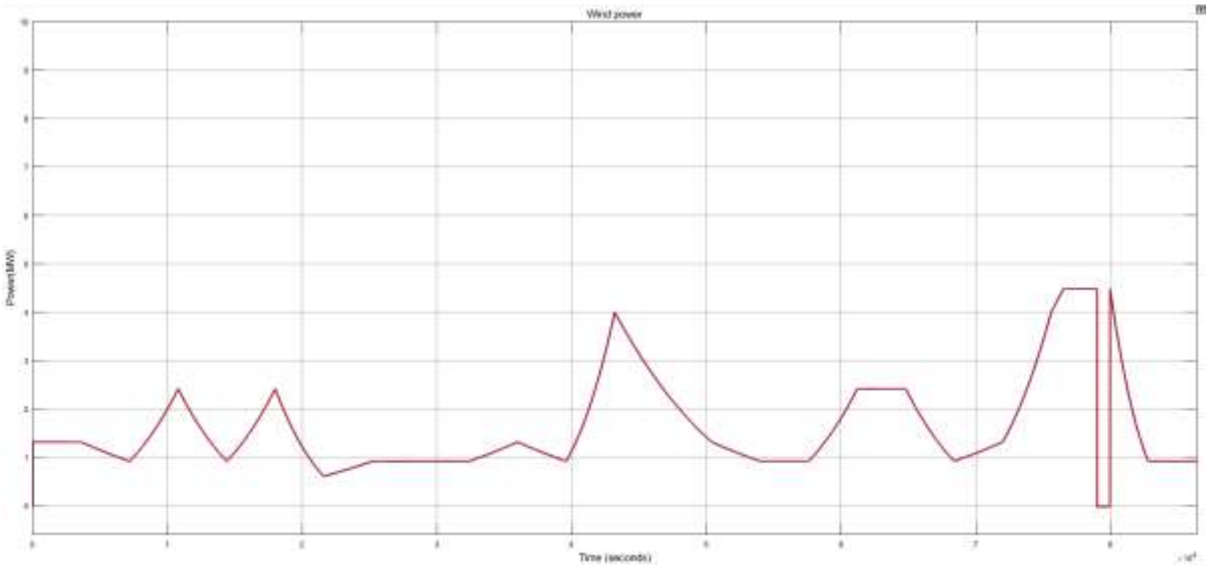

FIGURE 4 Power generated by the wind throughout the day.

Figure 7.5 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.

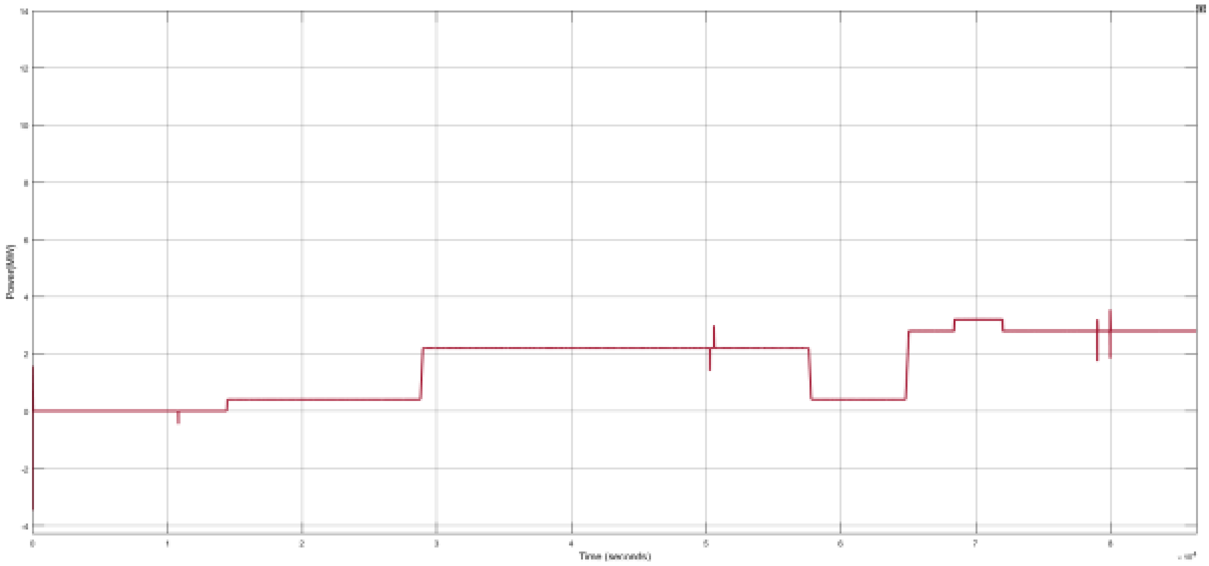

FIGURE 5 Charged and regulated into the microgrid throughout the day.

The residential load is represented by the active power drawn at a specified power factor, as illustrated in Fig. 7.6 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. 7.7

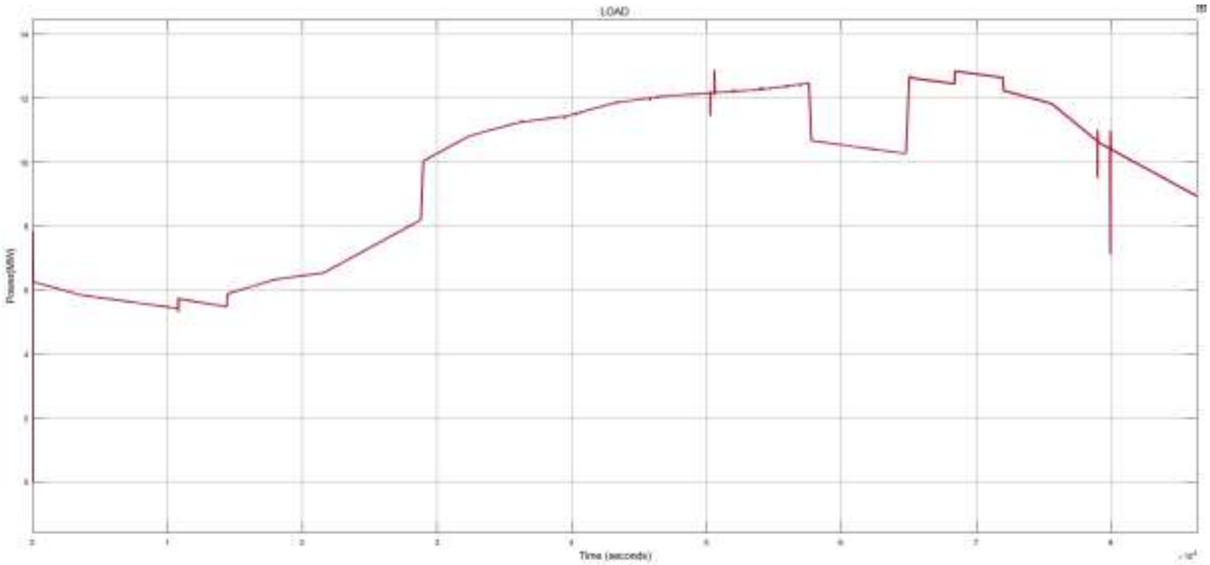

FIGURE 6 Load drawn power from the microgrid during the day.

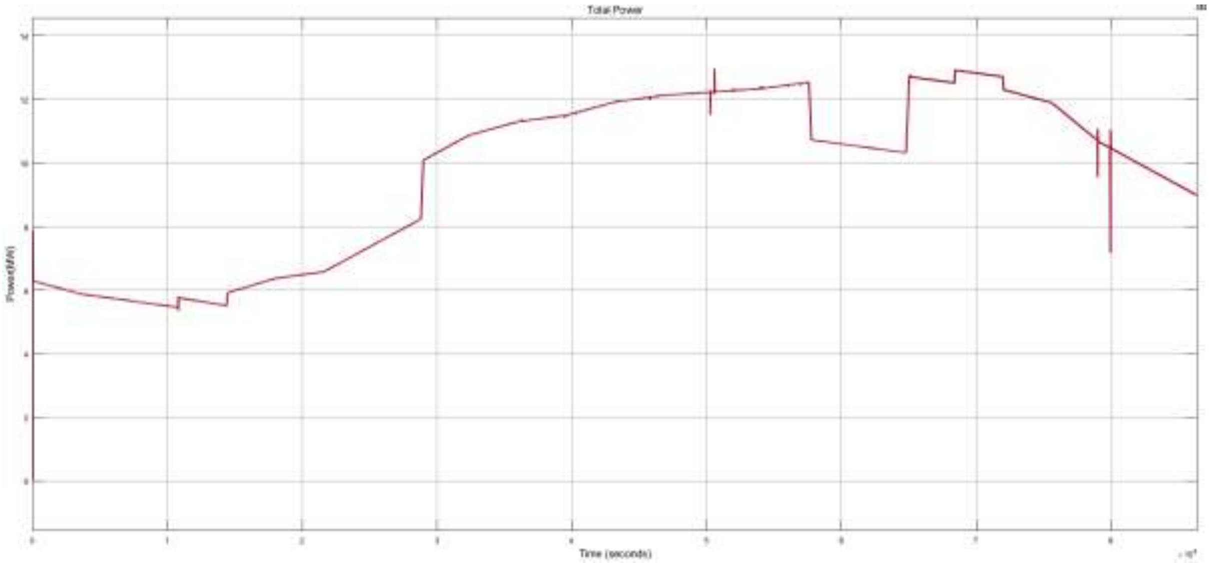

FIGURE 7 Total power generation from microgrid during the day.

Throughout all modes of operation, the fuzzy logic controller serves as the central decision-making entity, continuously processing system information and adjusting control actions in real time. By employing linguistic rules and membership functions, the controller accommodates the nonlinear and uncertain behaviour inherent in renewable energy systems without requiring detailed mathematical models. This enables the proposed system to respond effectively to fluctuating environmental conditions and variable load profiles. As a result, the hybrid micro-grid achieves a stable and reliable power supply, improved renewable energy penetration, and enhanced operational efficiency. The working of the proposed system thus demonstrates the practical viability of intelligent fuzzy logic–based energy management for modern hybrid renewable micro-grids.

CONCLUSION

This work has presented a comprehensive hybrid micro-grid system incorporating wind energy, solar photovoltaic generation, a diesel generator, and utility grid support, governed by a fuzzy logic–based energy management strategy. The proposed system effectively addresses the inherent variability and uncertainty associated with renewable energy sources by employing an intelligent control framework capable of real-time decision-making. By prioritising renewable energy utilisation and judiciously coordinating auxiliary power sources, the system ensures a reliable and uninterrupted power supply to a large residential load and an electric vehicle charging station under diverse operating conditions. The fuzzy logic controller demonstrates superior adaptability when compared with conventional control techniques, as it does not rely upon precise mathematical models and can accommodate nonlinear system behaviour. Simulation results confirm that the proposed approach maintains power balance, reduces unnecessary diesel generator operation, and limits dependency on grid power, thereby improving overall system efficiency and sustainability. Furthermore, the smooth transition between operating modes enhances system stability and operational resilience. In conclusion, the proposed hybrid micro-grid energy management plan offers a robust and practical solution for modern power systems with high renewable penetration. The findings of this study provide a strong foundation for future experimental validation and real-world deployment in residential, commercial, and remote electrification applications.

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