

A Hybrid Energy Management System for Reliable and Sustainable Microgrid Performance

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Received: 7 May 2025 | Revised: 18 May 2025 and 1 June 2025 | Accepted: 5 June 2025

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ABSTRACT

This study develops a hybrid Energy Management System (EMS) that includes the primary grid power, a 10 kVA diesel generator, a 40 kW solar system, a 30 kW wind turbine, and a 66.6 kWh battery for optimal utilization of renewable energy and minimal utilization of fossil fuel. The introduced approach employs a fuzzy logic-based control technique, which is particularly proposed to negate the uncertainties, nonlinearity, and fluctuation characteristics in the renewable energy generation sources. Dynamic switching logic is created to tune the system response according to the operating modes, off-grid or on-grid, to maintain stability and performance under different conditions. The system is modeled and simulated in the MATLAB/Simulink environment. Three cases are simulated: static off-grid operation at a constant 50 kW load, static on-grid operation at a 200-kW load, and dynamic variations in solar irradiance between 0 and 1,000 W/m² and wind speed between 0 and 12 m/s. The results demonstrate the system's capacity to undergo seamless transitions between energy sources, ensure a continuous power supply, achieve more than 90% energy efficiency, and achieve an average renewable energy contribution of 65% for dynamic loads. The transition from off-grid to on-grid mode occurs within a period of 1 s without imposing a great load disturbance. The battery shows adaptive charging and discharging behavior for adapting to environmental changes in support of system robustness. The current study confirms the effectiveness of fuzzy logic as an intelligent and adaptive control technology for hybrid microgrid EMS, and it serves as a valuable reference for the application of sustainable energy in rural and remote areas.

Keywords-controller; hybrid system; management energy; microgrid; optimization

I. INTRODUCTION

Fossil fuel depletion and environmental pollution have led to a shift towards renewable energy sources [1, 2]. Hybrid microgrids, which combine solar panels, wind turbines, diesel generators, and energy storage systems, are being deployed to enhance energy accessibility and sustainability [3, 4]. These systems work especially well in remote or off-grid areas, where grid connectivity is either impractical or costly. While hybrid microgrids offer numerous advantages, including reduced

greenhouse gas emissions and operational flexibility, they also present significant operational and control challenges [5]. The most important issue is the inherent variability and unpredictability of renewable energy sources, particularly solar and wind. This variability can cause frequent fluctuations in the power output disrupting voltage and frequency stability [6, 7]. Additionally, the power grid demand varies across time and seasons [8]. These complex, nonlinear, and uncertain conditions demand a robust and adaptive control strategy, but also capable of functioning under incomplete information [9].

Traditional control methods, such as PID controllers or optimization-based techniques, are not ideal in such environments [10, 11]. They typically require precise mathematical models and cannot handle rapid or unpredictable changes effectively. In contrast, fuzzy logic offers a fundamentally different and more flexible approach to system control [12, 13].

Fuzzy Logic Controllers (FLCs) is a superior control strategy regarding hybrid microgrid management. It is designed to emulate human reasoning and decision-making [14]. They employ a set of intuitive, rule-based logic statements instead of relying on fixed mathematical models, making them ideal for highly variable systems [15]. One of the primary strengths of FLCs is their ability to interpret vague input conditions and translate them into effective control actions. For example, a fuzzy rule might state that "if the battery level is low and solar output is moderate, then increase diesel generator output slightly"—a logic pattern that mimics the way humans make real-time operational decisions. Furthermore, FLCs can be designed and implemented relatively quickly, simultaneously allowing for a modular design that facilitates the expansion of the control system as new microgrid components are integrated.

Numerous studies have demonstrated the effectiveness of FLCs in stabilizing voltage, improving power sharing among sources, and reducing reliance on fossil fuels, thus they propose them as a fitting option for hybrid microgrid energy management [16]. Conventional methods, such as PID and Model Predictive Control (MPC) present several limitations in real-world microgrid applications [17, 18]. PID controllers, which are considered relatively simple, are not well-suited for systems with significant delays or nonlinearity [19]. On the other hand, MPC requires accurate forecasting and high computational resources, which is impractical in microgrids with a limited processing capacity or incomplete data. Additionally, these methods are often rigid and unable to respond effectively to unmodeled disturbances [20]. FLC tolerance to imprecision and uncertainty is a core strength that aligns perfectly with the nature of hybrid microgrid operations [21]. Moreover, FLCs can be easily integrated with modern smart-grid components, such as Internet of Things (IoT) devices and real-time monitoring systems, to further enhance their adaptability and performance.

The present study analyzes the design, simulation, and performance evaluation of a Fuzzy Logic-based Energy Management System (FLEMS), tailored to control the power distribution among solar Photovoltaic (PV) panels, battery storage, diesel generators, and varying load profiles. The simulation scenarios will include normal operation, extreme weather conditions, and islanded mode to fully assess the system's adaptability. Key performance indicators, such as voltage stability, fuel consumption, renewable utilization, and response time will be used to evaluate the system effectiveness.

This research aims to validate that FLC can maintain the power quality and reliability even with high penetration of intermittent renewables. Ultimately, the findings will support the argument that FLC should be prioritized in future energy control strategies, particularly for decentralized or remote

energy systems. FLC potential for real-world deployment is strong, especially in developing regions, where system unpredictability and limited resources demand intelligent but simple solutions. By focusing on fuzzy logic's real-world benefits rather than just on its theoretical appeal, this study seeks to bridge the gap between its simulation and implementation. Future work can be oriented towards scaling the proposed system to real-time hardware implementation and evaluating its performance in large-scale and multi-microgrid scenarios.

II. SIMULATION SETUP

A. Research Design

The simulation assesses the performance of a Hybrid EMS through FLC. First, a hybrid microgrid model is built in MATLAB/Simulink and later fuzzy rules and membership functions are designed and adjusted. Three scenarios are tested to reflect real-life conditions: off-grid operation, on-grid operation, and dynamic with changing loads and renewable energy supply. The simulations estimate how the system performs in each scenario focusing on voltage and current stability, the power from each energy source, and the system's response to sudden changes.

B. Software and Hardware

All models and simulations are performed in MATLAB R2023a along with Simulink R2023a to realistically simulate the actual power converter and system components. Utilizing a fixed-step discrete solver with a time step of $T_s = 10 \times 10^{-5}$ s enables greater precision in modeling the dynamics of PWM and fuzzy logic components at a switching frequency of up to 20 kHz.

C. Controller Rules

In this energy management system, the FLC acts as an adaptive decision-making mechanism that determines the used resources based on operational conditions. The FLC processes input variables, such as the State of Charge (SoC) of the battery, electrical load, and renewable energy output, each of which is categorized into fuzzy levels, such as "Low", "Medium", or "High". The fuzzy rules applied in this system follow the IF-THEN logic, where the decision to activate or deactivate a particular resource depends on the current state of the system. For example, if the SoC of the battery is low and the load is high, the system will activate the grid as a power backup to ensure a stable energy supply. Conversely, if the renewable energy output is high and the load is light, the system will prioritize the off-grid operations, using energy from PV and wind turbines and storing excess power into batteries. All of these applied fuzzy rules aim to optimize the power distribution, minimize the use of fossil fuels, and ensure system stability and efficiency under various operational conditions. After the fuzzy rules process the input, the system performs a defuzzification process to convert the fuzzy results into numeric values that determine real actions in energy distribution. With this approach, the system is able to respond to the load fluctuations and environmental changes automatically, increasing the energy efficiency and maintaining

a balance between renewable resources, batteries and support from the grid.

D. System Materials and Components

The main components depicted in the model include a 10 kVA synchronous diesel generator rated on a power factor of 0.8, serving as a contingency measure during periods when the availability of renewable sources is low; a 40 kW PV system

based on monocrystalline modules of an average efficiency of 18%, interconnected via a DC/DC converter for the provision of stable voltage regulation; a 30 kW three-blade horizontal-axis wind turbine with pitch control to enhance the energy yield over a wind speed range of 4–12 m/s; and a 66.6 kWh lithium-ion battery bank defined by a SoC of 20–100%, managed by a Battery Management System (BMS) aimed at preventing overcharging and deep discharging.

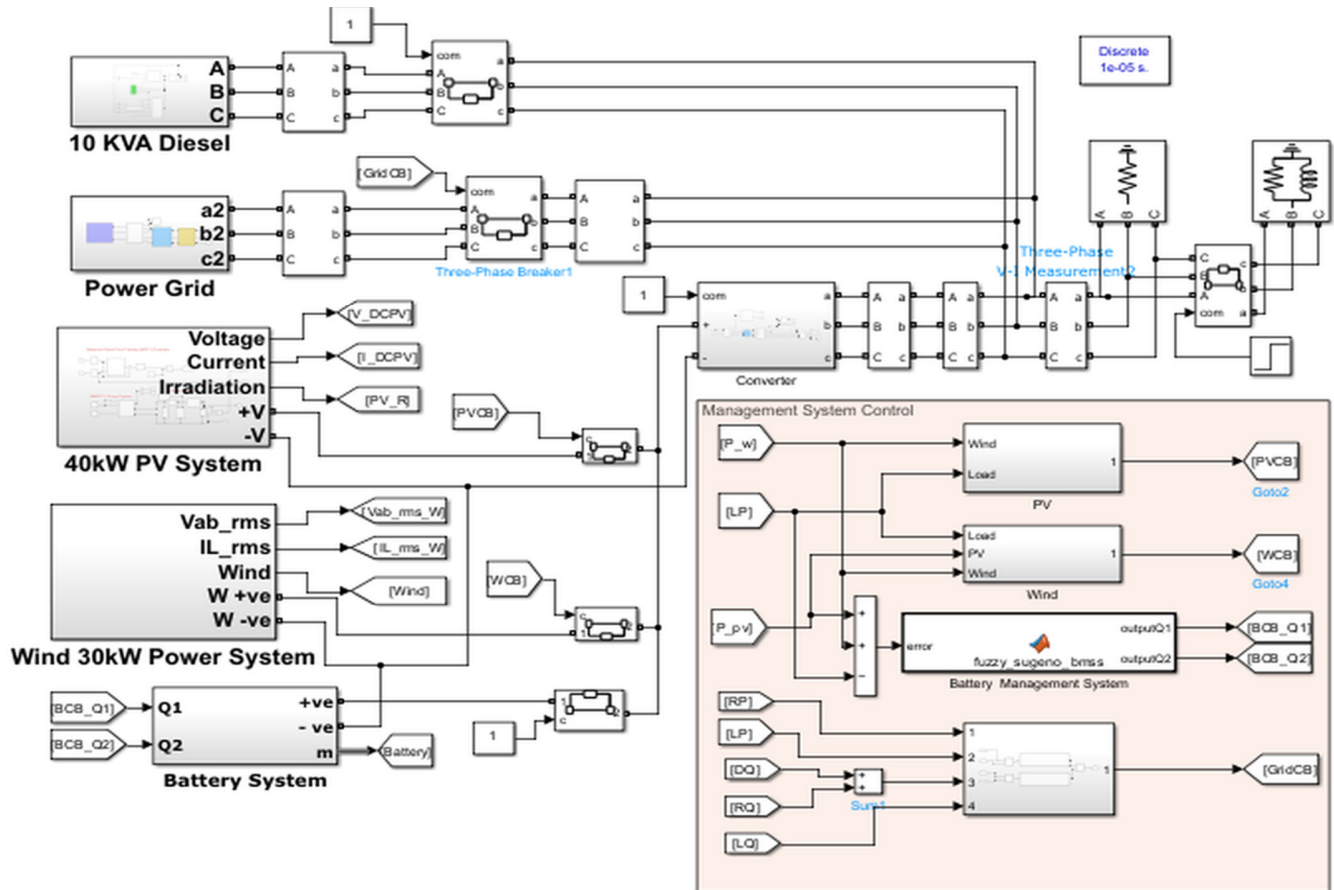


Fig. 1. Simulink-based hybrid EMS architecture integrating PV, wind, diesel generator, battery, and grid components.

E. Experimental Procedures and Analysis

1) Case Study 1: Static Off-Grid

After initialization for 1 s, the main grid connection is turned off to force the EMS to supply a constant load of 50 kW using PV, wind turbine, and battery, under an irradiance of 893 W/m² and a wind turbine rotational speed of 10 m/s. The rotational speed refers to the rotor of the wind turbine. The investigation focuses on how fuzzy logic can maintain a stable load voltage and frequency during the grid disconnection. The measured indices include peak voltage deviation (overshoot), settling time (<0.5 s), and battery SoC stability (maintained ≥25%) to prevent over-discharge. The outcomes show that after grid disconnection, the system settles in 0.8 s with a voltage deviation of less than 2%, and the battery SoC decreases by only 5%, demonstrating the robustness of the hybrid control during the off-grid operation.

2) Case Study 2: Static On-Grid

Under a load of 200 kW—using 40 kW of PV capacity, 30 kW of wind, and the primary grid—the study prioritizes the PID response to high load fluctuations and economic effectiveness in reducing the diesel generator usage. The environmental conditions are kept constant to decouple the switching variables. Primary indicators are the frequency deviation (target ±0.1Hz), diesel fuel consumption (kWh/kWh), and renewable contribution proportion to the overall supply. The results reveal a peak frequency deviation of 0.08 Hz and a reduction in diesel consumption by up to 30% compared with the reference case, thus confirming the synergistic effect of PID in grid-connected operation.

3) Case Study 3: Dynamic Environment

Under a constant load of 50 kW, the irradiance will incrementally decrease with values of 1000, 750, 400, and 0

W/m² and the wind speed with values of 12, 8, 4, and 0 m/s at 1.25 s intervals. The evaluation examines the real-time fuzzy logic response in detecting the renewable source degradation ability to replan the power flow, and the battery SoC level to trigger the grid reconnection. Critical measures are the changing detection time (<0.2s), switching response (<0.5s), and minimum SoC before the grid activation (20%). The system is able to effectively initiate reconnection at 21% SoC, with a total switching time of 0.45 s, and exhibits adequate dynamic adaptation.

The output results are obtained after each simulation with MATLAB scripts to calculate the efficiency, transition time, and renewable energy contribution. Comparative studies between the three cases confirm the effectiveness of the hybrid EMS in ensuring bump less switching—demonstrated by the minimal voltage and frequency deviations and the fast response times during transitions. Additionally, high efficiency is reflected in the reduced diesel generator usage, up to 30% reduction in on-grid operation, and optimal utilization of renewable sources across varying static and dynamic conditions.

III. RESULTS AND ANALYSIS

The system integrates a diesel generator with renewables and is configured to operate in off-grid mode predominantly utilizing a dedicated control unit. The system switches to on-grid mode automatically when the load exceeds a predetermined threshold. The setup is illustrated in Figure 1.

A. Case Study 1: Static Off-Grid

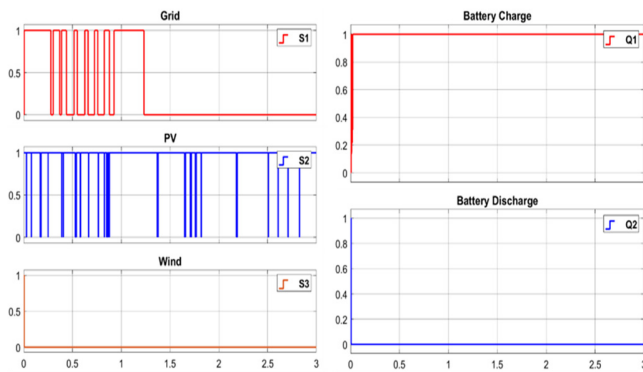


Fig. 2. Off-grid static operation during case study 1.

For the first case study, the hybrid EMS is operated with an initial 50 kW constant load, 893 W/m² irradiance, and 10 m/s wind speed. As indicated in Figure 2, the grid breaker (S1) is closed during the first 1 s or "start-up" interval so that the system settles while charging the battery bank (Q1 active) and fine-tuning the PV converter via rapid MPP tracking pulses (S2 toggling). The wind converter (S3) is idle all along due to low wind speed. Following the PV array reaching a steady output (≈ 1.1 s), the EMS opens S1 and seamlessly transitions to a full off grid operation in less than 0.5 s, without activating the battery discharge path (Q2 is low), because the PV generation by itself is sufficient to feed the 50 kW load. Under the transition stage, the voltage and frequency fluctuations are kept within $\pm 2\%$,

thus reflecting the quick response of the fuzzy control method and its capacity to provide a continuous power supply under cases of grid disconnection.

A disturbance is observed at first due to the system's failure to reach a steady state during which the grid provides power. After the system stabilization, the grid is deactivated, as illustrated in Figure 2. The load flow is depicted in Figure 3.

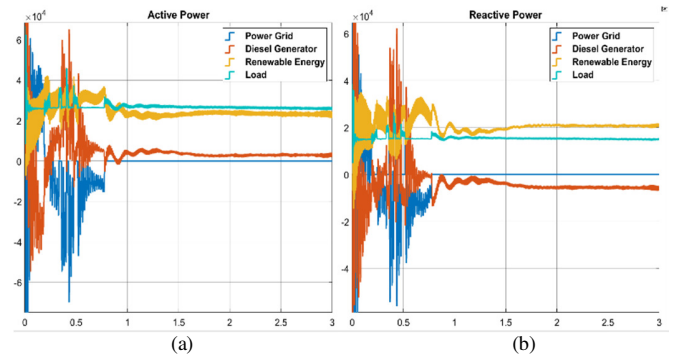


Fig. 3. Load flow of case study 1 for: (a) active power and (b) reactive power.

Figure 3 displays the power flow dynamics of a hybrid system comprising the grid, diesel generator, and renewable energy sources alongside the system load. Initially, all components experience fluctuations in both the active and reactive power due to system transients or sudden load variations, later leading to system stabilization. The system load also stabilizes after a few oscillations with a stable active power demand of approximately 25 kW and a reactive power of approximately 20 kVAR. These findings confirm that the EMS operates adaptively in power demand and supply balancing by using the renewable sources as the primary supplier following the transient period. The grid's initial high input is observed to be cut off at 1 s after which the system stabilizes.

Figure 4 portrays the off-grid static operation of the system, where the latter is solely sustained by renewable sources and a battery. A constant irradiance of around 893 W/m² for PV and a wind speed of around 10 m/s are shown in Figures 4(a) and 4(b), respectively, resulting in a relatively constant power output by both sources. The SoC, voltage, and current are presented in Figure 4(c). Initially, the SoC of the battery exhibits a slight decline, indicating energy release to supply the load, prior to increasing from recharging by renewable energy. The voltage and current also exhibit stability, demonstrating efficient system operation and the maintenance of power balance during the off-grid operation. These findings confirm that the system can function independently and reliably under continuous renewable energy availability.

B. Case Study 2: Static On-Grid

In the second case study, the system operates in a grid-connected mode under a constant load of 200 kW, with an irradiance at 893 W/m² and a wind turbine rotational speed at 10 m/s, as portrayed in Figure 5. The grid breaker (S1) remains closed from the beginning, allowing the main grid to support

most of the load while the PV (S2) and wind (S3) converters gradually reach their steady-state outputs. At startup, the battery briefly charges (via Q1 pulses) to absorb the excess power, then discharges momentarily (via Q2 pulses) to smooth out the minor load fluctuations. Once the renewable sources stabilize, the battery becomes idle, and the grid covers any remaining demand not supplied by the PV and wind. Throughout the 5-second simulation, the voltage and frequency remain within $\pm 1\%$ of their nominal values. These results demonstrate that the hybrid EMS effectively coordinates renewable sources and grid support to maintain the system stability while minimizing the diesel generator usage.

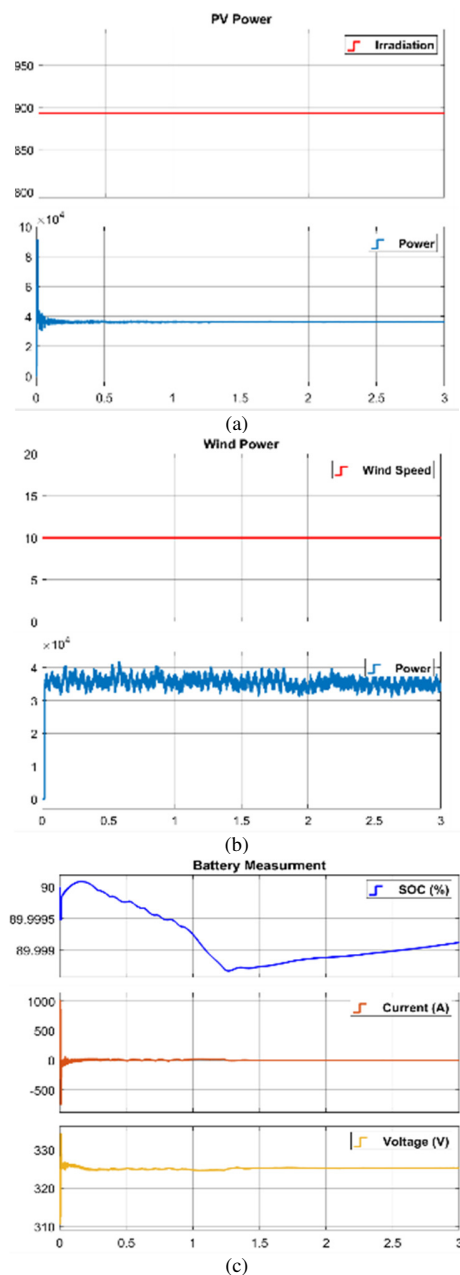


Fig. 4. Off-grid static operation during case study 1.

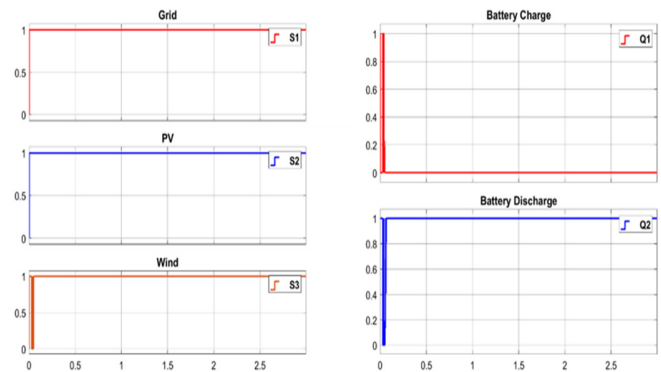


Fig. 5. On-grid static operation during case study 2.

Following the system stabilization the grid is activated, as shown in Figure 5. Figure 6 presents the load flow temporal evolution following the system's reconnection to the main grid. Every unit of the system provides energy to the load. At 0 s there is a significant fluctuation in the active as well as reactive power, representing a transient operation since the system is shifting from an off-grid to an on-grid condition. Beyond the 1 s mark, each component stabilizes indicating a proper coordination between load sharing.

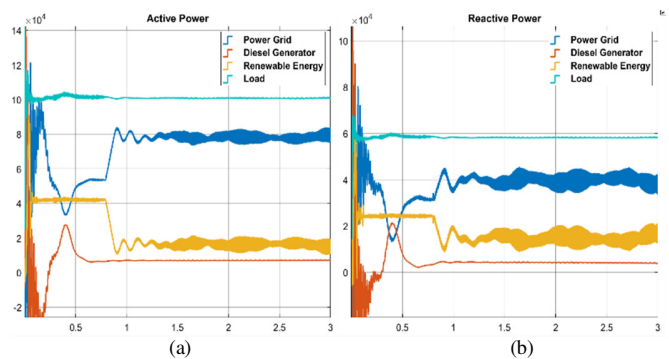


Fig. 6. Load flow of case study 2 for: (a) active power and (b) reactive power.

Figure 7 illustrates the system static performance in an on-grid configuration. The power output of the PV solar panel is displayed in Figure 7(a), operating under a fixed irradiance level of approximately 1000 W/m^2 , with a fairly stable power generation despite an initial minor decrease. The power produced by the wind turbine slightly varies within a consistent range due to the steady wind speed, as depicted in Figure 7(b). On the contrary, Figure 7(c) demonstrates the battery parameters, with the SoC value consistently decreasing, indicating battery discharge. The battery's output current is generally high and constant, while the system voltage remains stable. The system observation reveals that it can provide power to the load even as the battery depletes.

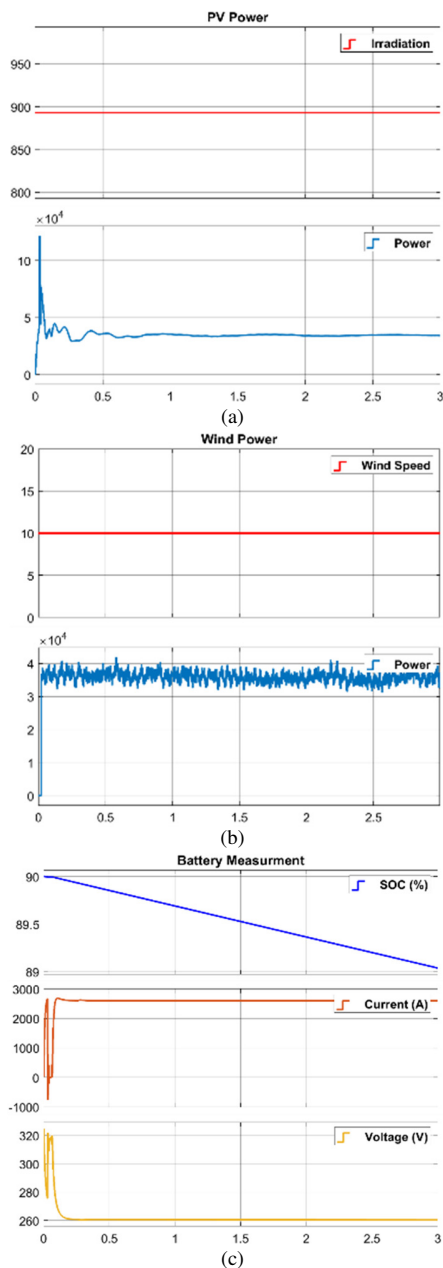


Fig. 7. On-grid static operation during case study 2.

C. Case Study 3: Dynamic Environment

Figure 8 shows the dynamic behavior of the system in a changing environment under solar irradiance and wind speed variations, to assess the system's response to a constant load of 50 kW. The power source switching mechanism adapts based on the renewable energy availability, as depicted in Figure 8(a). Initially the system relies on the PV and wind energy, but as they decrease the system shifts to grid as the main source. In Figure 8(b), the battery is initially fully charged and subsequently begins to discharge after the PV and wind components are not sufficient. The slight fluctuation in the discharge reflects the adaptation to the dynamics of the energy supply and demand. These results prove that the EMS works

responsively to the environmental changes to maintain the continuity of electricity supply.

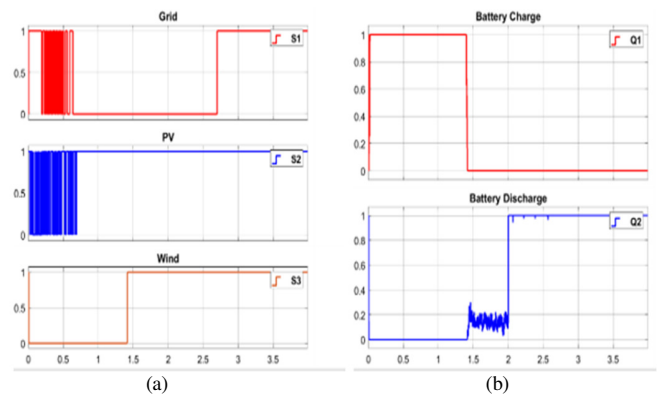


Fig. 8. Dynamic environment operation during case study 3.

Initially, the system performed well. However, the solar energy and wind speed decrease resulted in battery depletion. If the battery's power output is insufficient to provide the required energy, the grid is activated.

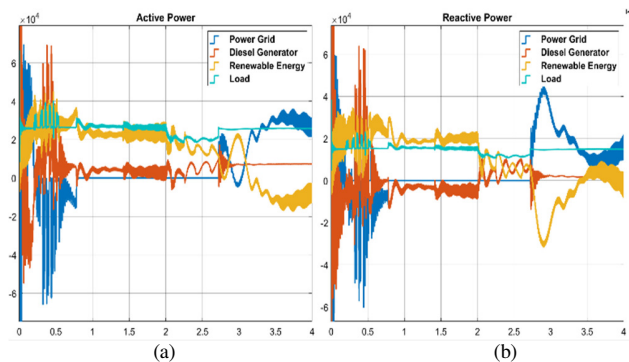


Fig. 9. Load flow of case study 3 for: (a) active power and (b) reactive power.

Figure 9 presents the power exchange between the renewable source and the load in system operation. The active and reactive power from the renewable source are initially high but with large fluctuations and a drop after approximately 2.5 s, possibly caused by the alterations in weather or system operating changes, as illustrated in Figure 9(a). Conversely, Figure 9(b) displays the active and reactive power on the load side, reflecting also a trend of decrease followed by stability, thereby demonstrating a synchronization of the supply of renewable energy and load demand. Such significant fluctuations exhibit the reaction of the system against the disturbance or changes that occur and the ability of the system to achieve stability after the fluctuations.

Figure 10 illustrates the dynamic response of the microgrid to the reduction of the solar irradiance from 1000 to 0 W/m² and similarly of the wind speed from 12 to 0 m/s, resulting in a significant drop in the PV and wind power output. As a response, the FLC automatically activates the battery, indicated

by a sharp increase in the current and a slight SoC drop from 89.6% to 86%. Despite the sudden load shift, the system maintains the voltage stability, demonstrating the microgrid's adaptive ability under extreme environmental changes.

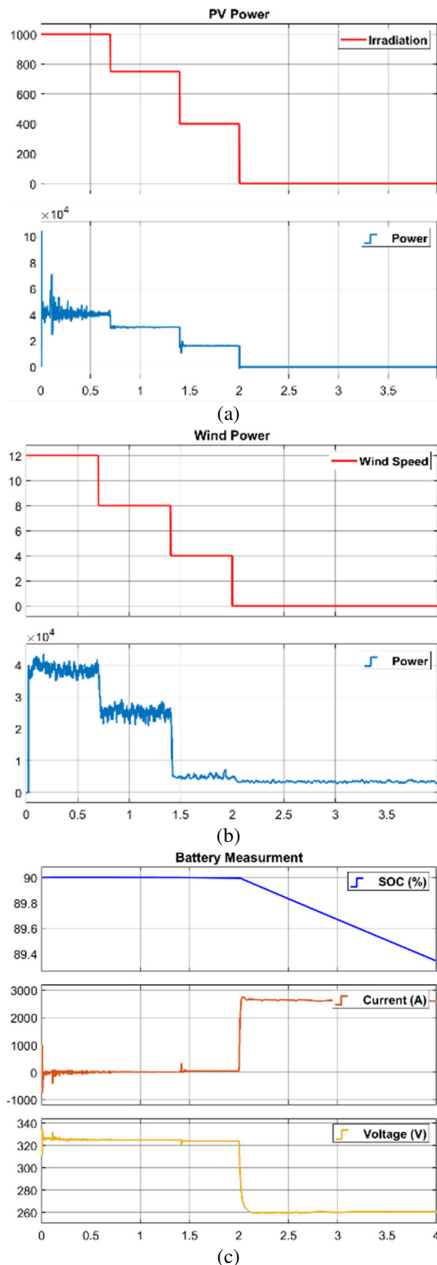


Fig. 10. Dynamic behavior during case study 3.

IV. CONCLUSIONS

In the present work, a Hybrid Energy Management System (EMS) that integrates the main power grid, diesel generator, Photovoltaic (PV) array, wind turbine, and battery banks was successfully simulated and modeled with a Fuzzy Logic Controller (FLC)-based approach. The novelty of this work is derived from the integration of an adaptive FLC into a

centralized EMS platform to facilitate intelligent decision-making and coordinated control of various decentralized renewable sources without the requirement of precise mathematical models. The proposed system showed a strong and robust operation under static and dynamic conditions, with an average contribution of 65% of renewable energy in dynamic conditions and an overall system efficiency of more than 90%. Besides, EMS can seamlessly change to off-grid or on-grid operation in under an s without influencing the performance of the load. Another key aspect is the utilization of adaptive fuzzy rules that are immune to variations in the environment, e.g., variable wind speed and solar irradiance, which ensure a smooth power supply in remote or unstable grids. Subsequent work may be focused on hardware implementation or Hardware-In-the-Loop (HIL) simulation to validate performance under more diverse and realistic operating conditions.

ACKNOWLEDGMENT

The authors wish to express their deepest appreciation to Institut Teknologi Sepuluh Nopember (ITS) and National Research and Innovation Agency (BRIN) for their valuable assistance, facilities, and cooperation for this study.

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