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Design and control of a stand-alone microgrid with renewable energy sources

Mohamed G Moh Almihat [1, *], Abdulgader Alsharif [2], Salem A. Al-Hashmi [3], Abdussalam Ali Ahmed [4] and Mohamed Belrzaeg [5]

[1] *Department of EECE, Cape Peninsula University of Technology, Cape Town, South Africa.*
[2] *Department of Electric and Electronic Engineering, Faculty of Technical Sciences Sabha, Sabha, Libya.*
[3] *Department of Electric and Electronic Engineering, Wadi Alshatti University, Brack, Libya.*
[4] *Department of Mechanical Engineering, Bani Waleed University, Bani Waleed, Libya.*
[5] *Department. of Energy Engineering, College of Renewable Energy, Tajoura, Libya.*

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Abstract

This study describes the design and operation of an autonomous microgrid that includes photovoltaic (PV) panels, wind turbines, a diesel engine, and a lithium-ion battery. The objective is to evaluate the efficiency and performance of a central control system that prioritizes renewable energy sources and, when necessary, uses a diesel generator and battery as backup power sources. Additionally, MATLAB is utilized to model and simulate the microgrid system. The needs for the microgrid, including the capacities of each energy source and the load demand, are first laid out in the study. In this study, the power production from the PV panels and wind turbines is estimated based on solar radiation and random wind speeds, respectively. The energy output from each source is measured and shown. After that, a centralized control system is established to oversee the operation of the microgrid. The control algorithm ensures that a considerable portion of the load need is satisfied via renewable energy sources. The extra generation that is stored as energy for later use charges the battery. In the case of a load deficit, however, the battery and diesel generator are employed to provide the demand. The battery's energy reserve and charge status are monitored and displayed. The research results, the suggested centralized control system efficiently controls the microgrid operation by maximizing the use of renewable energy sources and reducing dependency on the diesel generator. The findings highlight the need to use effective control techniques to maximize the integration of renewable energy sources.

Keywords: Microgrid; Centralized control; Renewable energy; Energy storage

1. Introduction

All standard paper components have been specified for three reasons: (1) ease of use when formatting individual papers, (2) automatic compliance to electronic requirements that facilitate the concurrent or later production of electronic products, and (3) The global energy landscape is currently undergoing a significant transformation in response to the growing demand for sustainable and clean energy solutions. Renewable energy sources, such as solar and wind power, have garnered significant attention as viable alternatives to traditional fossil fuel-based electricity generation. Microgrids have emerged as a promising approach to effectively integrate and utilize these renewable energy sources [1].

A microgrid is a localized and decentralized power system that can operate independently or in connection with the main grid. It consists of various distributed energy resources (DERs), including solar photovoltaic (PV) panels, wind turbines, energy storage systems, and backup generators. Microgrids offer numerous advantages, such as improved energy efficiency, enhanced reliability, reduced greenhouse gas emissions, and potential cost savings [2].

* Corresponding author: Mohamed G Moh Almihat

To effectively manage the microgrid's operation, a centralized control system is implemented. The control algorithm ensures that renewable energy sources are prioritized to meet the load demand whenever possible. Excess generation is used to charge the battery, and any surplus energy is stored for future use. In the event of a deficit in load demand, the battery and diesel generator are utilized to meet the shortfall. Monitoring the battery state of charge and energy storage levels is crucial for optimizing the microgrid's performance [3]. This research focuses on the design and control of a stand-alone microgrid that incorporates PV panels, wind turbines, a diesel generator, and a lithium-ion battery. The objective is to investigate the performance and effectiveness of a centralized control system that prioritizes the utilization of renewable energy sources while utilizing backup sources when necessary. The control system ensures optimal utilization of renewable energy and efficient management of the microgrid's power generation and consumption. The first step in the research is to establish the specifications of the microgrid, including the capacities of each energy source and the load demand. A load profile is generated to represent the power demand throughout the day, taking into account peak and normal hour demands. The power generation from the PV panels and wind turbines is determined based on solar irradiation and wind speed data, respectively. Additionally, the energy generated by each source is quantified to evaluate their contribution to the overall energy supply. The research explores three different scenarios to assess the microgrid's performance under varying conditions. Scenario 1 focuses on battery priority with diesel backup, giving priority to the utilization of renewable energy sources while relying on backup sources when necessary. Scenario 2 investigates renewable priority with limited battery backup, aiming to maximize renewable energy utilization while considering the limited energy storage capacity. Scenario 3 explores renewable priority with no backup, where the microgrid relies solely on renewable energy sources without any backup support. Through detailed analysis and comparison of the scenarios, the research aims to evaluate the performance and efficiency of the microgrid system. The findings will provide valuable insights into the effectiveness of the proposed centralized control system, the integration of renewable energy sources, the utilization of backup sources, and the overall reliability and sustainability of microgrid operation. The results of this research will contribute to the understanding of microgrid design and control systems, showcasing the potential of renewable energy integration, and emphasizing the importance of advanced control algorithms in achieving efficient and sustainable power systems. The findings will be beneficial for researchers, engineers, and policymakers involved in the development and implementation of microgrid systems to meet future energy demands while minimizing environmental impacts.

This research contributes to the comprehension of microgrid design and control systems, highlighting the potential of renewable energy sources and the role of advanced control algorithms in achieving efficient and sustainable power systems. The findings provide a foundation for further research and practical implementations of microgrid. The remaining section are classified into

2. Overview of microgrid control

The design and control of stand-alone microgrids with renewable energy sources have been the subject of extensive research and development in recent years. This literature review provides an overview of key studies and advancements in the field, highlighting the significance of the research conducted in this paper.

One important aspect of microgrid design is the integration of renewable energy sources, such as solar and wind. Numerous studies have focused on optimizing the utilization of these sources to maximize energy generation. For example, [3]a multi-objective optimization model for microgrid design, considering the sizing of PV panels and wind turbines to achieve optimal energy generation while minimizing system cost and environmental impact.

The role of energy storage systems in microgrids has also been widely investigated. Batteries are commonly used to store excess energy for later use, ensuring a reliable power supply. [4] Presented a comprehensive review of battery technologies and their applications in microgrids, highlighting the importance of battery performance, cost, and lifespan in microgrid design.

Control systems play a crucial role in managing the operation of microgrids and maintaining the balance between energy generation and demand. Various control strategies have been proposed to optimize the utilization of renewable energy sources and backup generators. [5]developed a hierarchical control system for a microgrid, considering the coordination of PV panels, wind turbines, and energy storage devices to achieve optimal energy dispatch and load balancing.

Prioritizing renewable energy sources in microgrid operation has gained significant attention. By giving precedence to renewable sources, microgrids can reduce reliance on non-renewable backup generators and improve sustainability. [6]proposed a renewable-energy-based microgrid control strategy that prioritizes solar and wind generation, using backup generators only when necessary. Their results demonstrated the effectiveness of the control strategy in reducing carbon emissions and improving system efficiency.

Furthermore, the optimization of microgrid operation under different scenarios has been explored. In [7] conducted a sensitivity analysis to evaluate the performance of a microgrid under various load demand and renewable energy availability scenarios. Their findings highlighted the need for adaptable control strategies to optimize microgrid operation under dynamic conditions.

It is worth mentioning that the simulation and modeling of microgrid systems using MATLAB have been widely adopted in research studies. MATLAB provides a versatile platform for system modeling, control algorithm development, and performance evaluation. Several studies, including [8]utilized MATLAB to simulate and analyze the performance of microgrid systems under different scenarios and control strategies.

Despite the significant progress made in microgrid design and control, there is still a need for further research. Topics such as advanced control algorithms, optimal sizing and placement of energy sources, and grid integration of microgrids remain areas of active investigation. Moreover, real-world implementation and field trials are essential to validate the effectiveness and practicality of microgrid systems.

The first step in the methodology as shown in figure (1) is to establish the specifications and components of the microgrid system. This includes determining the capacities of the PV panels, wind turbines, diesel generator, and lithium-ion battery based on the desired power generation and storage capabilities. Additionally, the load demand profile is defined, considering peak and normal hour demands.

Then the power generation from the PV panels and wind turbines is modeled based on solar irradiation and wind speed data, respectively. Mathematical models or empirical formulas are used to estimate the power output of these renewable energy sources. The energy generated by each source is quantified and recorded. Later a centralized control system is developed to manage the microgrid operation. The control algorithm prioritizes renewable energy sources and utilizes backup sources when necessary. It ensures that the load demand is met while maximizing the utilization of renewable energy. The control system monitors the state of charge of the battery and makes decisions regarding energy dispatch and storage.

Then simulation and Optimization, where the simulation allows for the evaluation of the system's performance under different scenarios and the optimization of control parameters to achieve optimal operation.

Finally, the performance of the microgrid system is analyzed under different scenarios to assess its effectiveness and efficiency. Various scenarios, such as battery priority with diesel backup, renewable priority with limited battery backup, and renewable priority with no backup, are considered. The energy generation, battery usage, and overall system performance metrics are evaluated for each scenario. In following figure (2) shows propsed system

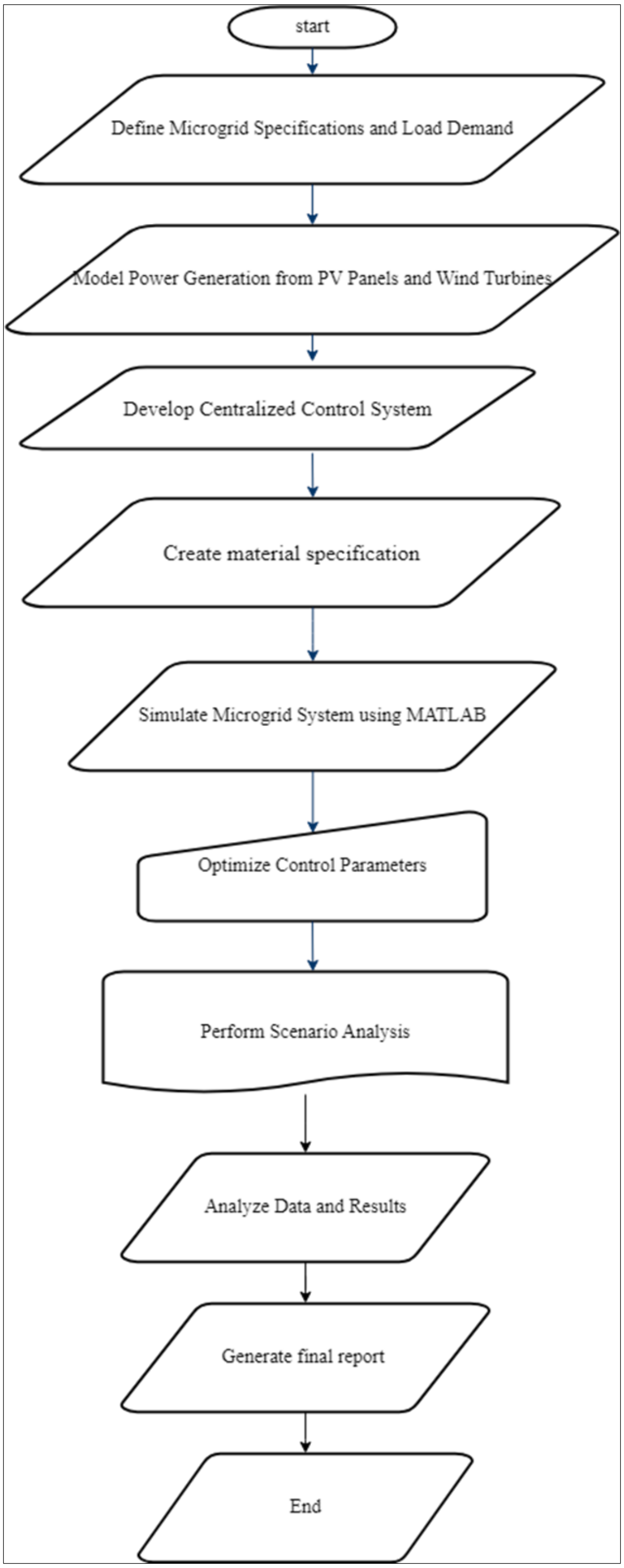

Figure 1 Methdolghy

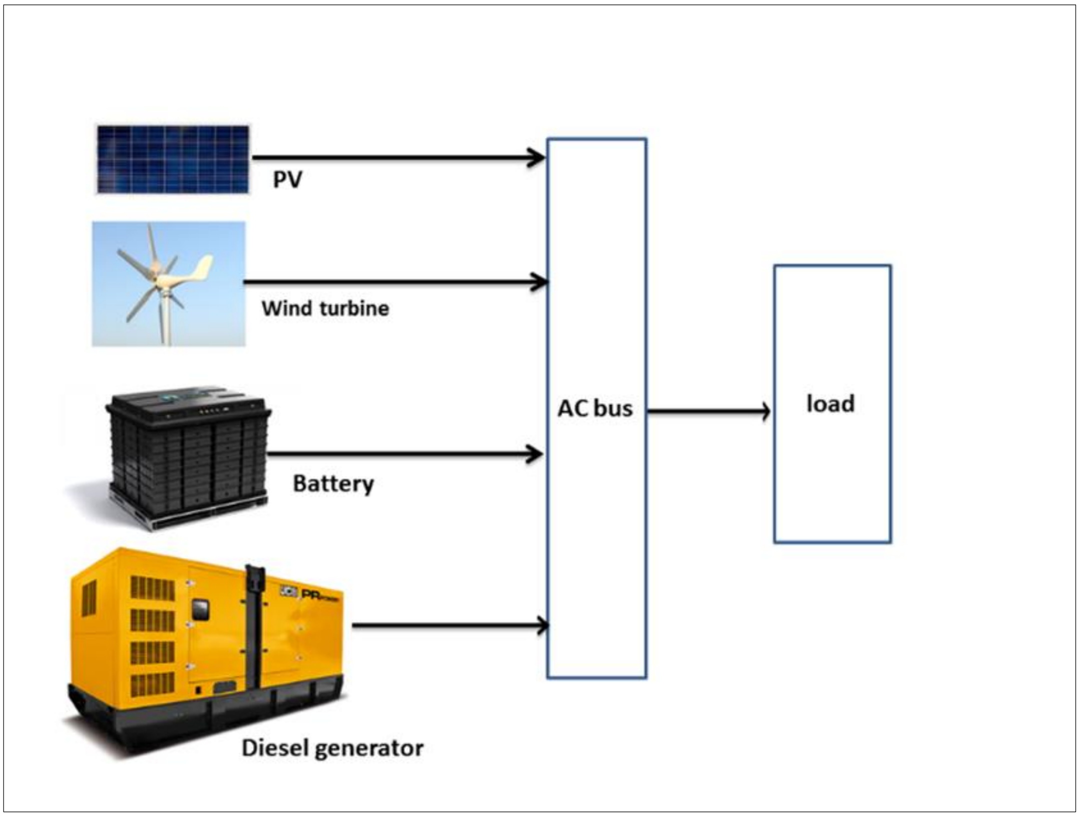

Figure 2 Propsed system

In the following section the mathematical modeling of the proposed system of the microgrid is discussed.

2.1. PV system and partmters

For the PV system this model can be represented as flowing:

$$V_{pv} = V_{OC} * (1 - \exp\left(-\frac{I_{pv}}{I_{sc}}\right)) \text{ ……………. } (1)$$

This equation represents the Maximum Power Point Tracking (MPPT) algorithm for the photovoltaic (PV) array.

V_{pv} Is the voltage at the PV array terminals.

V_{OC} Is the open-circuit voltage of the PV array.

I_{pv} Is the current output of the PV array.

I_{sc} Is the short-circuit current of the PV array.

The equation calculates the voltage at which the PV array operates at its maximum power point, optimizing its power output. In the flowing table (1) PV system parameters:

Table 1 PV system parameters

Component	Value
Rated power	1MW
Number of panels	3,334
Efficiency	0.15
Area	1000m^2
Capacity factor	0.2
PV inverter Rated Power	1 MW
Efficiency	0.95
DC-DC Converter (PV to Battery) Rated power DC-DC Converter (PV to Battery DC-DC Converter (PV to Battery	1 MW
Converter efficiency	0.95

The power rating of each PV panel is 300 W, the approximate number of panels required would be:

Number of panels = Total power capacity / Power output per panel

Number of panels = 1,000 kW / 300 W = 3,333.33 panels

2.2. Wind system parameters

In this section the mathematical model and parameters of the wind turbine is explained.

$$P_{wt} = C_p * \left(\frac{1}{2}\right) * \rho * A * V^3 \text{ .... } (2)$$

This equation represents the power output of the wind turbine with pitch control.

P_{wt} Is the power output of the wind turbine.

C_p Is the power coefficient of the wind turbine, and ρ Is the air density. While A Is the swept area of the wind turbine blades. And V^3Is the wind speed.

The equation calculates the power generated by the wind turbine, considering the wind speed and the characteristics of the turbine blades. In table (2) Wind turbine parameters presented.

Table 2 Wind turbine parameters

Component	Value
Rated Power	1 MW
Efficiency	0.3
Rotor Diameter	80 m
Cut-in Wind Speed	3 m/s
Rated Wind Speed	12 m/s
Cut-out Wind Speed	25 m/s
Wind inverter rated power	1 MW
Inverter Efficiency	0.95

2.3. Battery matmatical modeling and partmeters

In this section the Lithium-Ion battery mathematical model is addressed

$$SOC = (V_{batt} - V_{min}/(V_{max} - V_{min}) \text{ ....(3)}$$

This equation represents the State of Charge (SOC) of the lithium-ion battery.

SOC Is the ratio of the current battery voltage

V_{batt} To the voltage range between the minimum V_{min} And maximum V_{max} battery voltages.

It provides an indication of the battery's remaining capacity as a percentage of its total capacity.

$$SOD = (V_{max} - V_{batt})/(V_{max} - V_{min}) \text{ .... (4)}$$

This equation represents the State of Discharge (SOD) of the lithium-ion battery.

SOD is the ratio of the voltage range between the maximum (V_{max}) and current battery voltage V_{batt} to the overall voltage range. It provides an indication of the battery's remaining capacity as a percentage of its total capacity. In the following table (3) the battery parameters is presented:

Table 3 Battery parameters

Component	Value
Capacity	1 MW
Energy Efficiency	0.9
Discharge Efficiency	0.95
Charge Efficiency	0.95
Batter inverter	1 MW
Inverter Efficiency	0.95
DC-AC Converter (Battery to Load) rated power	1 MW
DC-AC Converter Efficiency	0.95
AC-DC Converter (Load to Battery) rated power	1 MW

2.4. Desisel genertor

For the Diesel Generator mathematical model can be represented by:

$$P_{gen} = \eta_{gen} * (P_{max} - P_{min}) \text{........... (5)}$$

This equation represents the power output of the diesel generator.

P_{gen} Is the power output of the generator.

η_{gen} Is the efficiency of the generator.

P_{max} And P_{min} represent the maximum and minimum power limits of the generator, respectively.

The equation calculates the power output of the diesel generator, taking into account its efficiency and power limits. In the flowing table (4) shows the diesel generator parameters

Table 4 Diesel generator parameters

Component	Value
Rated Power	2 MW
Efficiency	0.35
Fuel Consumptions	0.2 L/kwh

2.5. Load demand

The load demand varies throughout the day, and the values can be represented in a time-series format. In following table (5) shows load demand values for different time intervals used in this study:

Table 5 Load demand values for different time intervals

Time Interval	Load Demand (MW)
00:00 - 06:00	1.5
06:00 - 08:00	2.0
08:00 - 18:00	1.4
18:00 - 24:00	1.6

For the Centralized Control System:

$$P_{out} = P_{pv} + P_{wt} + P_{gen} - P\_load \text{ …………(5)}$$

This equation represents the overall power output of the microgrid system controlled by the centralized control system.

P_{out} Is the net power output of the microgrid system.

P_{pv} Is the power output of the PV array.

P_{wt} Is the power output of the wind turbine.

P_{gen} Is the power output of the diesel generator.

P_load Represents the power consumed by the connected loads.

The equation calculates the net power output of the microgrid system by summing the individual power contributions and subtracting the power consumed by the loads.

3. Results and Discussion

The results obtained from the simulation and analysis of the stand-alone microgrid system are presented and discussed in this section. The performance of the microgrid system under different scenarios is evaluated, and key parameters such as energy generation, battery usage, and system efficiency are analyzed.

- **Energy Generation:** The energy generation from the PV panels and wind turbines is evaluated based on the solar irradiation and wind speed data. The results show the varying energy output throughout the day and the contribution of each energy source to the overall energy generation. It is observed that the energy generation from renewable sources is highest during peak sunlight hours and periods of high wind speeds.
- **Battery Usage and Energy Storage:** The battery plays a crucial role in the microgrid system by providing energy storage and balancing the supply-demand dynamics. The battery usage is monitored, and the state of charge is analyzed under different scenarios. It is observed that during periods of excess energy generation, the battery is charged, and any surplus energy is stored for later use. Conversely, during periods of high load demand or insufficient renewable energy generation, the battery is discharged to meet the load demand.

- **System Efficiency and Performance**: The system efficiency and overall performance are evaluated by analyzing parameters such as self-sufficiency, renewable energy penetration, and reliance on backup sources. The results indicate that the centralized control system effectively prioritizes renewable energy sources, maximizing their utilization to meet the load demand. This leads to increased self-sufficiency and reduced reliance on backup sources, such as the diesel generator.
- **Scenario Analysis:** The microgrid system is evaluated under different scenarios to assess its performance and robustness. Scenario 1, focusing on battery priority with diesel backup, demonstrates the capability of the system to utilize renewable energy sources while relying on backup sources when needed. Scenario 2, considering renewable priority with limited battery backup, showcases the limitations and challenges in optimizing renewable energy utilization with constrained energy storage. Scenario 3, exploring renewable priority with no backup, highlights the potential of a completely sustainable microgrid operation, albeit with certain limitations during periods of low renewable energy generation.

In line with decentralized strategies, [11] proposed a decentralized control strategy for a microgrid integrating photovoltaic power generation, energy storage, and load demand. This control system monitored critical energy parameters, such as voltage, current, frequency, and mechanical energy, to ensure they remained within specified ranges. The study highlighted the enhanced reliability and stability of the microgrid resulting from the proposed control strategy. Where in following figure (1) Load Profile presented

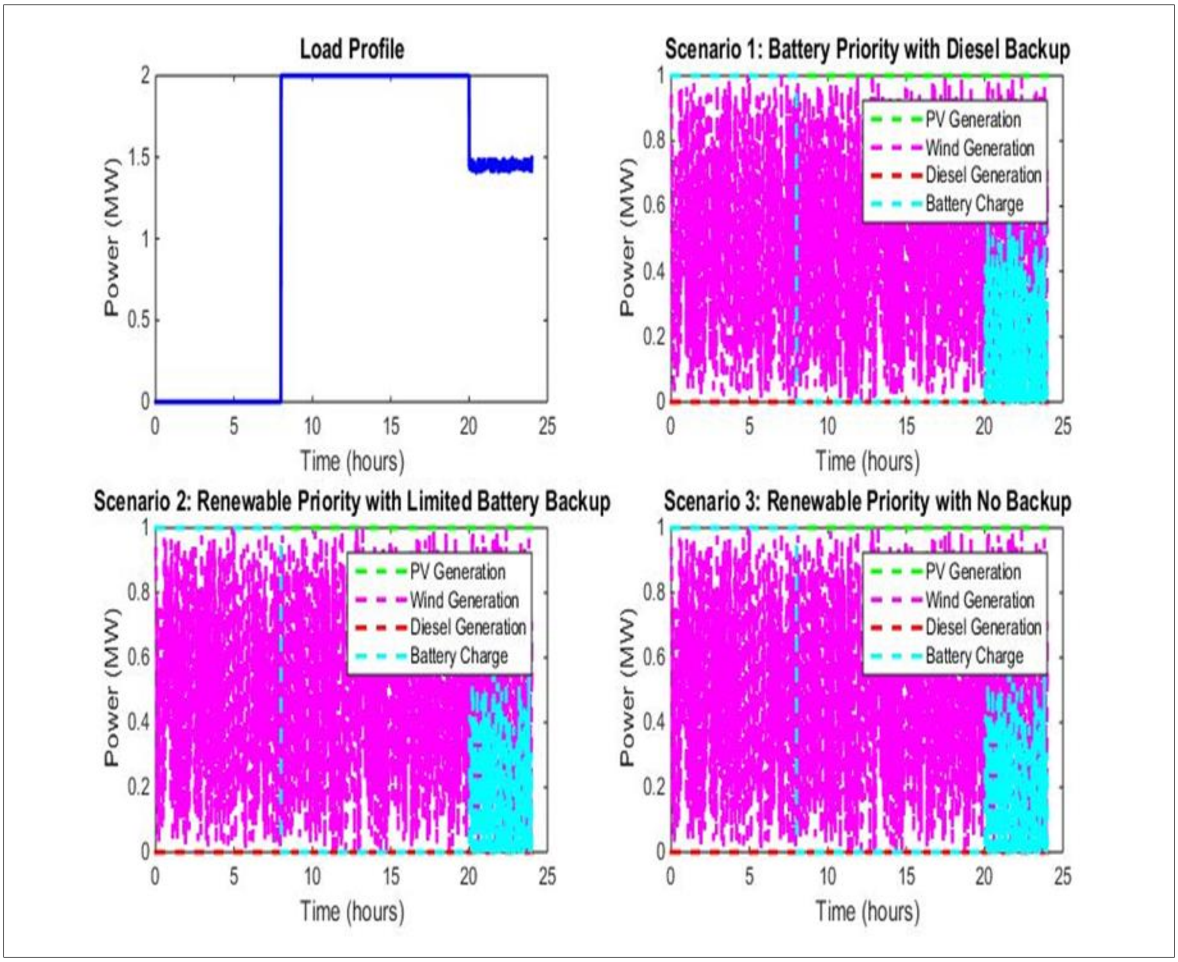

Figure 3 Load Profile

The scenarios used in the evaluation of the stand-alone microgrid system represent different operating conditions and priorities, allowing for a comprehensive analysis of the system's performance. The scenarios are designed to explore various aspects of microgrid operation, including the utilization of renewable energy sources and the reliance on backup sources. The three scenarios considered are as follows:

3.1. Scenario 1

Battery Priority with Diesel Backup as shown in figure (4): In this scenario, the control system gives priority to the battery for meeting the load demand. The renewable energy sources, such as PV panels and wind turbines, are utilized to the maximum extent possible to charge the battery and meet the load demand. If there is still a deficit in load demand, the diesel generator is used as a backup to bridge the gap and ensure uninterrupted power supply.

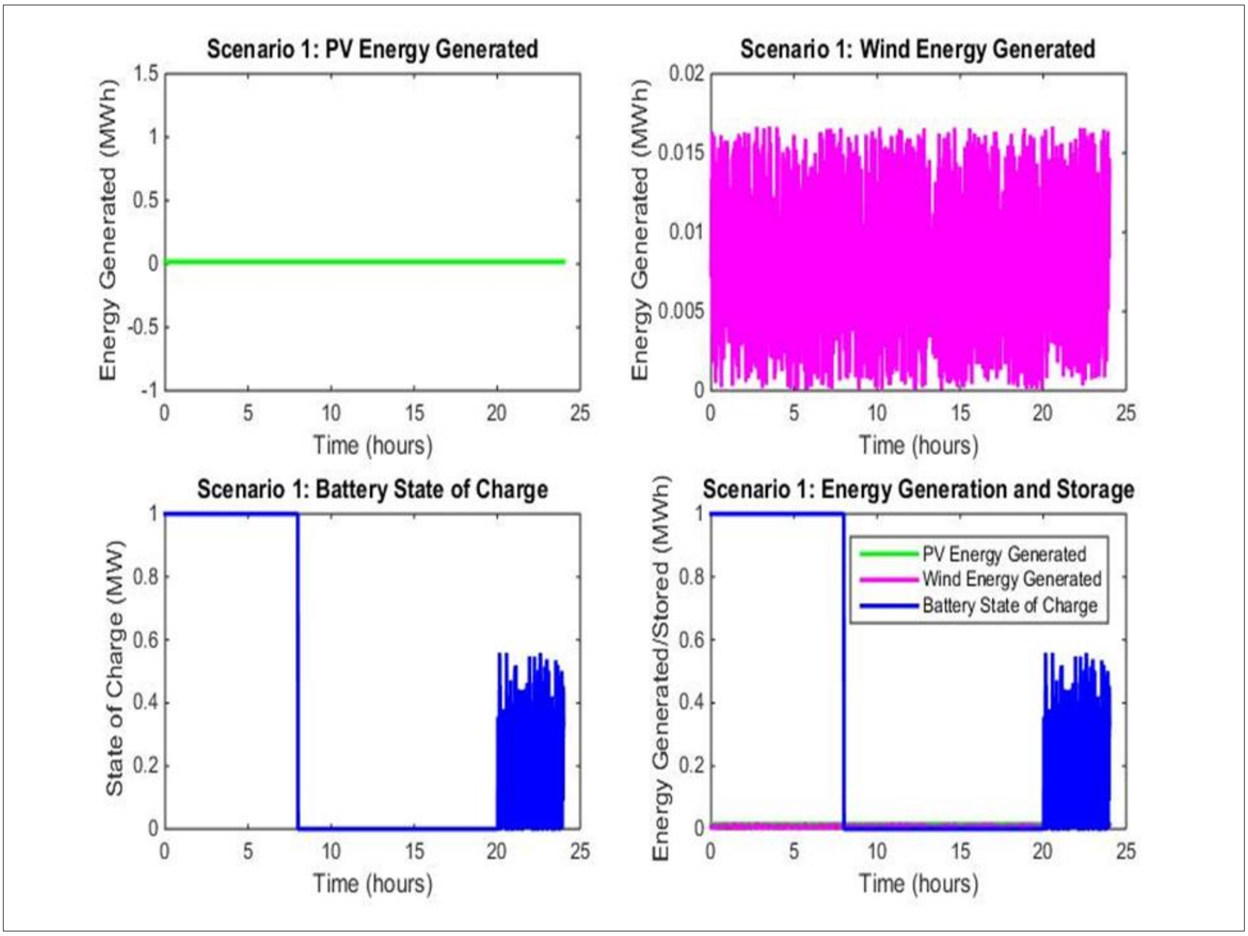

Figure 4 Battery Priority with Diesel Backup

3.2. Scenario 2

Renewable Priority with Limited Battery Backup as presented in figure (5): This scenario focuses on maximizing the utilization of renewable energy sources. The control system prioritizes the use of renewable energy to meet the load demand. The battery is used as a backup source but with limited capacity. If there is insufficient renewable energy generation to meet the load demand, the battery is used to compensate for the deficit. However, the limited battery capacity poses challenges in managing the system's operation and maintaining uninterrupted power supply.

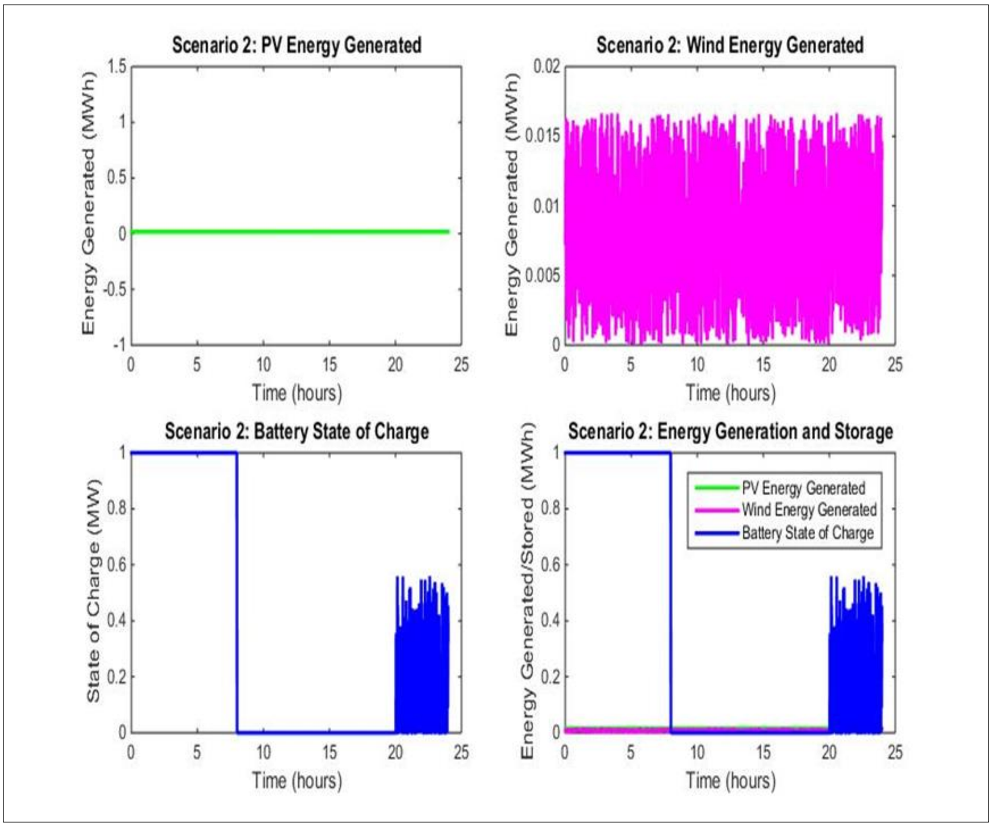

Figure 5 Renewable Priority with Limited Battery Backup

3.3. Scenario 3

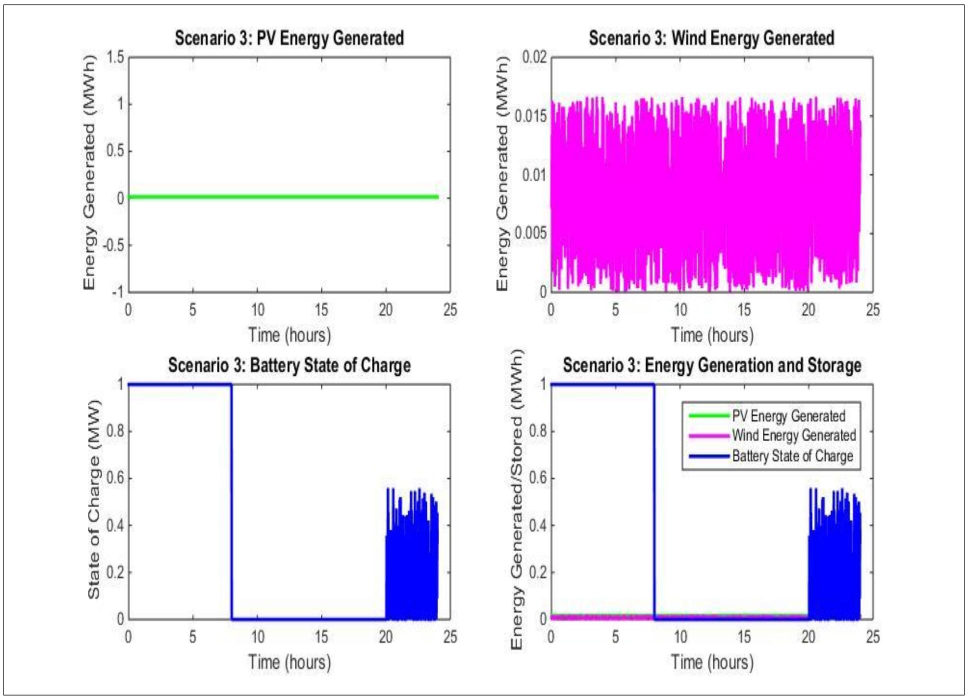

Figure 6 Renewable Priority with No Backup

Renewable Priority with No Backup as shown in figure (6): In this scenario, the emphasis is on achieving a fully sustainable microgrid operation without relying on backup sources. The control system prioritizes renewable energy sources to meet the load demand, and no backup sources, including the diesel generator or battery, are used. This scenario highlights the system's potential for sustainability and reducing reliance on non-renewable sources. However, it also presents challenges during periods of low renewable energy generation when the load demand may not be fully met.

4. Conclusion

In conclusion, the stand-alone microgrid system, incorporating renewable energy sources, a battery, and a backup diesel generator, along with the centralized control algorithm, demonstrates a viable solution for sustainable and reliable power supply. The system showcases the potential for reducing carbon emissions, increasing self-sufficiency, and minimizing reliance on non-renewable energy sources. The findings from this research contribute to the advancement of microgrid technologies and provide valuable insights for the design and operation of future sustainable energy systems.

Further research and development can focus on optimizing the control algorithm, incorporating advanced forecasting techniques, and integrating additional renewable energy sources or energy storage technologies. These advancements will continue to enhance the efficiency, reliability, and sustainability of microgrid systems, paving the way for a clean and resilient energy future.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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