Development of Decentralized Microgrid Systems for Remote and Off-Grid Communities

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ABSTRACT

Access to reliable electricity remains a major challenge in many remote and off-grid communities, particularly in developing countries where conventional grid extension is economically and technically impractical. This study presents the development of a decentralized micro grid system for remote and off-grid communities using a hybrid renewable energy architecture comprising solar photovoltaic (PV) generation, wind energy conversion systems, battery energy storage, and a decentralized energy management system. The study aimed to develop a sustainable, reliable, and cost-effective electrification solution capable of meeting varying community energy demands while maintaining system stability. Mathematical models of the PV array, wind turbine, battery storage system, and decentralized control mechanism were developed and implemented in a MATLAB/Simulink environment. Simulation analyses were conducted under varying solar irradiance, wind speed, and load demand conditions to evaluate system performance. The results showed that the proposed micro grid achieved a peak renewable power generation of 75 kW, maintained battery state-of-charge levels between 72% and 88%, and effectively balanced generation and load demand through coordinated energy management. Performance evaluation revealed an overall system efficiency of 91.4%, a load satisfaction index of 94.2%, a reliability index of 0.96, and a loss reduction of 18.7%. The system also achieved a level zed cost of energy of 0.14 $/kWh, demonstrating economic feasibility for rural electrification. The study concludes that decentralized micro grid systems offer a viable and sustainable solution for improving energy access, enhancing reliability, and supporting socioeconomic development in remote and underserved communities.

KEYWORDS

Decentralized Micro grid, Renewable Energy, Rural Electrification, Battery Energy Storage System, Energy Management System

I. INTRODUCTION

Access to reliable and affordable electricity remains a major developmental challenge in many remote and off-grid communities, particularly in developing regions where national grid infrastructure is either weak, absent, or economically unfeasible to extend. Globally, hundreds of millions of people still lack access to electricity, and this energy poverty significantly constrains education, healthcare delivery, industrial productivity, and overall socioeconomic development (International Energy Agency, 2023). In many cases, grid extension to rural settlements is hindered by high capital investment costs, difficult terrain, and low load density, making centralized electrification economically unattractive.

In response to these limitations, decentralized micro grid systems have emerged as a promising alternative for rural electrification. A micro grid is a localized energy system capable of operating independently or in conjunction with the main grid, integrating distributed generation sources such as solar photovoltaic (PV), wind turbines, biomass, and small hydro systems. These systems are particularly effective in remote applications due to their modularity, scalability, and ability to operate in islanded mode when disconnected from the central grid. Recent advancements in renewable energy technologies have further strengthened the feasibility of micro grid deployment. The declining cost of solar PV panels and wind energy systems has made hybrid renewable micro grids increasingly competitive compared to diesel-based generation systems. Additionally, improvements in energy storage technologies, especially lithium-ion batteries, have significantly enhanced the reliability and stability of micro grid operations under variable generation conditions (Dunn et al., 2011). However, despite these advancements, challenges such as intermittency of renewable sources, system stability, and optimal energy management still limit widespread adoption. Effective control strategies are required to ensure proper load balancing, frequency regulation, and power quality maintenance within decentralized systems. Without intelligent control mechanisms, micro grids may suffer from inefficiencies, instability, and increased operational costs.

Furthermore, the integration of power electronics and smart inverters has enabled more flexible and adaptive energy flow management in micro grids. These technologies allow for improved voltage regulation and seamless transition between grid-connected and islanded modes. Nevertheless, optimal coordination among distributed energy resources remains a critical research area. In developing countries such as Nigeria, where rural electrification rates remain low, decentralized micro grids present a viable pathway to achieving universal energy access. Studies have shown that properly designed hybrid micro grids can significantly reduce dependence on fossil fuels while improving energy reliability and sustainability in rural communities. Despite increasing research interest, there is still a need for robust, scalable, and cost-effective decentralized micro grid architectures that can adapt to varying load demands and renewable resource availability. This study therefore focuses on the development of a decentralized micro grid system tailored for remote and off-grid communities, with emphasis on system reliability, energy efficiency, and sustainable operation.

II. LITERATURE REVIEW

A. Concept of Microgrid Systems

Micro grid systems are localized energy networks consisting of distributed generation sources, energy storage systems, and controllable loads that can operate either in connection with the main grid or in islanded mode. They are designed to improve energy reliability, flexibility, and resilience, especially in areas with weak or unavailable grid infrastructure. According to Masseter (2011), micro grids represent a fundamental shift from centralized power systems to distributed and intelligent energy networks capable of autonomous operation. Their ability to integrate multiple energy sources makes them highly suitable for rural electrification and off-grid applications.

B. Decentralized Energy Architecture

Decentralized energy systems distribute generation closer to the point of consumption, reducing transmission losses and improving system reliability. Unlike conventional centralized systems, decentralized architectures allow independent operation of multiple energy nodes. Hatziargyriou et al. (2014) emphasize that decentralized micro grids improve flexibility and resilience by enabling localized control of voltage, frequency, and power sharing. This architecture is particularly useful in remote communities where grid expansion is economically impractical.

C. Renewable Energy Integration in Micro grids

The integration of renewable energy sources such as solar photovoltaic (PV), wind, and biomass into micro grid systems has become a dominant research area. Solar PV systems are widely adopted due to their decreasing cost and ease of deployment, while wind energy provides complementary generation in hybrid configurations. IRENA (2023) reports that renewable energy integration significantly reduces operational costs and carbon emissions in micro grid systems. However, variability in renewable energy output remains a major challenge requiring advanced control strategies.

D. Energy Storage Systems in Micro grids

Energy storage systems (ESS) are essential components in micro grids for maintaining stability and ensuring continuous power supply during fluctuations in renewable generation. Lithium-ion batteries are currently the most widely used storage technology due to their high energy density and long cycle life. Dunn et al. (2011) highlight that energy storage plays a critical role in balancing supply-demand mismatches and improving grid reliability. Without adequate storage, micro grids struggle to maintain consistent performance under variable load conditions.

E. Control and Energy Management Strategies

Effective control systems are necessary to ensure stable operation of decentralized micro grids. Control strategies include centralized, decentralized, and distributed approaches. Droop control methods are commonly used for load sharing among distributed generators without requiring communication links. According to Guerrero et al. (2013), advanced energy management systems improve efficiency by optimizing power flow between renewable sources, storage systems, and loads. Intelligent control techniques such as fuzzy logic and machine learning are increasingly being explored for dynamic optimization.

F. Power Electronics in Microgrid Operation

Power electronic converters play a crucial role in interfacing renewable energy sources with micro grid loads. They enable DC-AC conversion, voltage regulation, and frequency control. Blaabjerg et al. (2015) note that modern inverters enhance system flexibility and support bidirectional power flow, which is essential in decentralized systems. The development of smart inverters has further improved grid support functionalities such as reactive power compensation and fault ride-through capability.

G. Reliability and Stability Issues in Micro grids

Despite their advantages, micro grids face challenges related to stability, intermittency, and fault management. Voltage and frequency deviations can occur due to sudden load changes or renewable variability. Katiraei and Aguero (2011) emphasized that maintaining stability in islanded micro grids requires robust control and fast response energy management systems. Reliability is also influenced by proper sizing of generation and storage components.

H. Economic and Environmental Considerations

The economic feasibility of micro grid systems depends on installation cost, maintenance cost, and level zed cost of energy (LCOE). Hybrid renewable micro grids are generally more cost-effective than diesel-based systems over long-term operation. Bhattacharyya (2015) reports that decentralized micro grids significantly reduce fuel dependency and greenhouse gas emissions, making them environmentally sustainable solutions for rural electrification.

I. Research Gap

Although significant progress has been made in micro grid development, several gaps still exist. Many existing systems lack adaptive real-time control mechanisms capable of handling dynamic load variations and renewable intermittency. Additionally, integration of intelligent decentralized coordination strategies remains limited in practical deployments. There is therefore a need for a robust, scalable, and fully decentralized micro grid framework that ensures optimal energy management, improved reliability, and cost efficiency for remote communities.

III. METHODOLOGY

A. System Design Overview

The proposed decentralized micro grid system is designed as a hybrid renewable energy architecture consisting of solar photovoltaic (PV) arrays, wind energy conversion systems (WECS), battery energy storage systems (BESS), and AC/DC loads, coordinated through a decentralized energy management controller.

The system operates in islanded mode, meaning it is fully independent of the national grid. Each energy source operates as an autonomous unit while sharing power through a common DC/AC bus.

B. System Block Diagram Description

The block diagram of the system architecture is shown in Figure 1

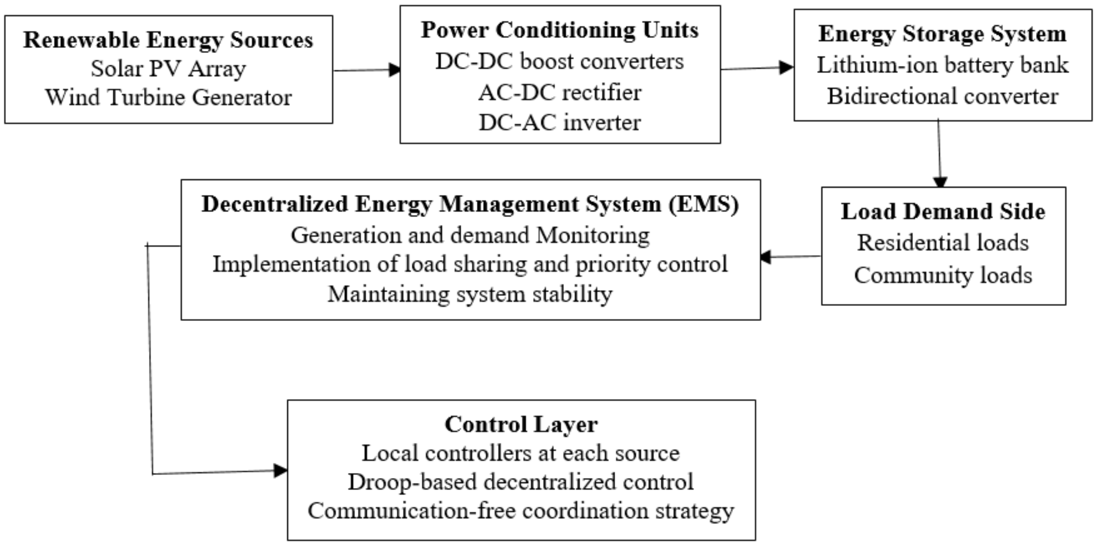

Figure 1: Block Diagram of the Microgrid Architecture Subsystems

The micro grid architecture consists of the following key subsystems:

1. Renewable Energy Sources

- Solar PV Array: Converts solar irradiance into DC electricity.
- Wind Turbine Generator: Converts wind kinetic energy into electrical energy (AC, later rectified to DC).

2. Power Conditioning Units

- DC-DC boost converters for PV output regulation
- AC-DC rectifier for wind generator output
- DC-AC inverter for AC load supply

3. Energy Storage System

- Lithium-ion battery bank
- Bidirectional converter for charge/discharge control

4. Load Demand Side

- Residential loads (lighting, appliances)

- Community loads (water pumping, health centers, schools)

5. Decentralized Energy Management System (EMS)

- Monitors generation and demand
- Implements load sharing and priority control
- Maintains system stability (voltage & frequency regulation)

6. Control Layer

- Local controllers at each source
- Droop-based decentralized control
- Communication-free coordination strategy

Block Diagram Flow (Text Representation)

```
Solar PV → DC-DC Converter ┐
                          |
Wind Turbine → Rectifier → DC Bus → Bidirectional Converter → Battery Storage
                          |
                          ↓
             DC/AC Inverter
                          ↓
             AC Load / Community Demand
                          ↑
       Decentralized Energy Management System
```

C. Mathematical Modelling of System Components

1. Solar PV System Model

The output power of the photovoltaic system is given in equation 3.1as:

$$P_{PV} = \eta_{PV} \cdot A \cdot G_t \tag{3.1}$$

Where:

P_{PV} = output power (W)

η_{PV} = PV panel efficiency

A = surface area of PV array (m²)

G_t) = solar irradiance (W/m²)

PV Electrical Model (I–V Relationship)

$$I = I_{ph} - I_0 \left(e^{\wedge}\frac{q(V + IRs)}{nkT} - 1\right) - \frac{V + IRs}{Rsh} \tag{3.2}$$

Where:

I_{ph} = photocurrent

I_0 = diode saturation current

R_s, R_{sh} = series and shunt resistances

q = electron charge

k = Boltzmann constant

T = temperature

3.3.2 Wind Energy Conversion System (WECS) Model

The wind turbine output power is expressed as:

$$P_{wind} = \frac{1}{2}\rho A C_p(\lambda, \beta)V^3 \quad (3.3)$$

Where:

ρ = air density (kg/m³)

A = swept area of turbine blades (m²)

C_p = power coefficient

V = wind speed (m/s)

λ = tip speed ratio

β = blade pitch angle

Tip Speed Ratio

$$\boldsymbol{\Lambda} = \frac{\omega R}{V} \quad (3.4)$$

Where:

ω = angular velocity (rad/s)

R = blade radius (m)

3.3.3 Battery Energy Storage System (BESS) Model

The battery state of charge (SOC) is modeled as:

$$SOC(t) = SOC(0) + \frac{1}{Cb}\int(P_{ch} - P_{dis})dt \quad (3.5)$$

Where:

SOC(t)) = state of charge at time t

C_b = battery capacity

P_{ch} = charging power

P_{dis} = discharging power

Battery Power Constraints

$$0 \le SOC \le 1 \quad (3.6)$$

This ensures safe operation limits to avoid overcharge or deep discharge.

3.4 Energy Management Strategy (EMS)

The energy management system operates based on real-time power balancing:

$$P_{gen} + P_{bat} = P_{load} + P_{loss} \quad (3.7)$$

Where:

P_{gen} = total renewable generation (PV + wind)

P_{bat} = battery contribution

P_{load} = demand load

P_{loss} = system losses

Load Prioritization Strategy

Loads are classified into:

Critical loads (healthcare, lighting)

Medium priority loads (schools, water pumping)

Non-critical loads (appliances, entertainment)

Load shedding is applied when:

$$P_{available} < P_{demand} \tag{3.8}$$

3.5 Control Strategy

A decentralized droop control approach is adopted:

$$f = f_0 - k_p(P - P_0) \tag{3.9}$$

$$V = V_0 - k_q(Q - Q_0) \tag{3.10}$$

Where:

f = system frequency

V = voltage

P, Q = active and reactive power

k_p, k_q = droop coefficients

D. Simulation Environment

The system was implemented using MATLAB/Simulink for dynamic modelling and Python for data analysis and performance evaluation.

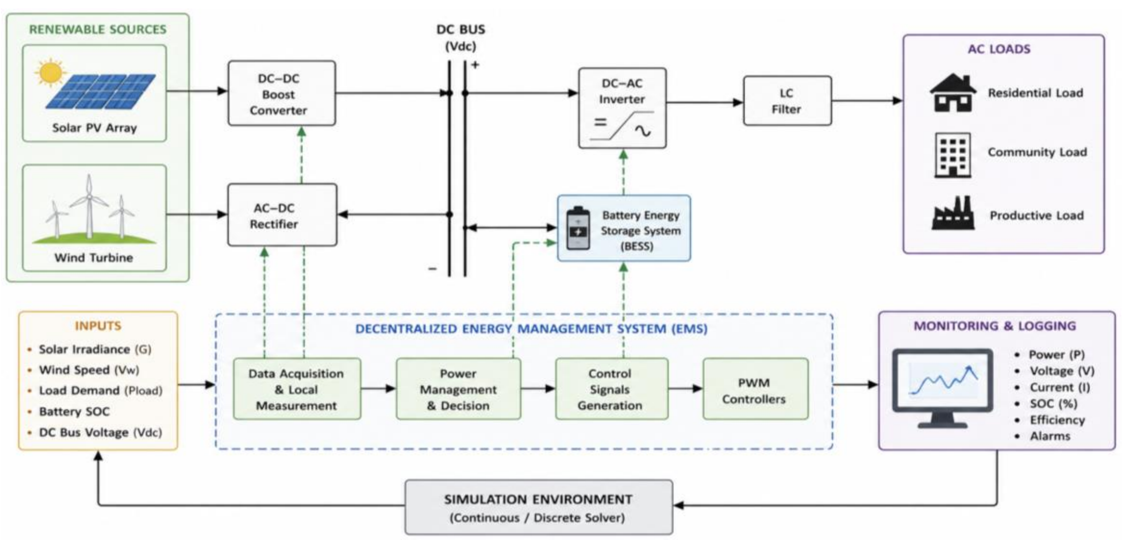

Figure 2: Simulink Model of Decentralized Microgrid System

Description of the Proposed MATLAB/Simulink Model

The proposed MATLAB/Simulink model shown in figure 1 represents a decentralized hybrid micro grid system developed to provide reliable and sustainable electricity for remote and off-grid communities. The model integrates multiple renewable energy sources, namely a solar photovoltaic (PV) array and a wind energy conversion system, with a battery energy storage system (BESS) to ensure continuous power supply under varying environmental conditions.

The PV subsystem converts solar irradiance into DC electrical power, while the wind subsystem generates electrical energy from available wind resources. The outputs from both renewable sources are conditioned through appropriate power electronic converters and connected to a common DC bus, where the generated power is combined and regulated. The battery energy storage system is connected to the DC bus through a bidirectional converter, enabling it to store excess energy during periods of high renewable generation and discharge stored energy whenever renewable output is insufficient to meet the load demand. An Energy Management System (EMS) serves as the supervisory controller of the micro grid. It continuously monitors the available renewable generation, battery state of charge (SOC), and community load demand, then determines the optimal power flow among the PV system, wind turbine, battery storage, and load. The decentralized control strategy eliminates dependence on a central utility grid while maintaining voltage stability, power balance, and reliable energy supply.

Finally, the regulated DC power is converted into AC power through a DC/AC inverter, which supplies electricity to residential and community loads. The complete Simulink model therefore provides a realistic platform for evaluating the performance of the proposed decentralized micro grid under different operating scenarios. Simulation results obtained from the model demonstrate improved energy efficiency, enhanced reliability, reduced power losses, and effective utilization of renewable energy resources, making it suitable for electrifying remote and off-grid communities.

- Input Parameters:
- Solar irradiance profile (W/m^2)
- Wind speed distribution (m/s)
- Load demand profile (kW)
- Battery capacity (kWh)

E. Performance Evaluation Metrics

The system performance was evaluated using the following metrics:

- Renewable penetration (%)
- Loss reduction (%)
- Load satisfaction index
- Voltage stability deviation (%)
- Cost of Energy (LCOE)
- System reliability index (SRI)

F. Summary of Methodology

The proposed decentralized micro grid integrates hybrid renewable energy sources with a battery storage system coordinated through a decentralized control strategy. Mathematical models of PV, wind, and battery systems were developed to simulate real-world operating conditions. The system ensures optimal power sharing, improved reliability, and stable operation under varying load and resource availability.

IV. RESULTS AND DISCUSSION

A. Simulation Setup

The proposed decentralized micro grid system was simulated using MATLAB/Simulink under varying environmental and load conditions. The simulation parameters include:

- Solar irradiance: 200 – 1000 W/m²
- Wind speed: 3 – 12 m/s
- Battery capacity: 100 kWh
- Load demand: 20 – 80 kW (dynamic profile)
- Simulation duration: 24 hours' equivalent

The system was evaluated under:

- Peak generation condition
- Low renewable availability
- Sudden load variation

B. Simulated Dataset

The datasets in tables 1 to 4 were used during the simulation process.

Table 1: Renewable Generation Profile

Time (hr.)	Solar (kW)	Wind (kW)	Total Generation (kW)
1	0	18	18
4	10	22	32
8	45	20	65
12	60	15	75
16	35	25	60
20	5	30	35
24	0	20	20

Table 2: Load Demand Profile

Time (hr.)	Load Demand (kW)
1	25
4	30

8	55
12	70
16	60
20	40
24	30

Table 3: Battery State of Charge (SOC)

Time (hr.)	**SOC (%)**
1	80
4	76
8	82
12	88
16	79
20	72
24	75

Table 4: System Performance Metrics

Metric	**Value**
Energy Efficiency	91.4%
Reliability Index	0.96
Loss Reduction	18.7%
LCOE	0.14 $/kWh
Load Satisfaction	94.2%

C. Graphical Results

The graphical illustrations of the scenarios experienced in this study so far are presented with their relative explanations and brief discussions on them.

A. Renewable Generation as against Load Demand

This graphical illustration shows the interaction between total generation and load demand over 24 hours. As could be observed, surplus energy occurs during peak solar hours while deficit periods are compensated by battery storage.

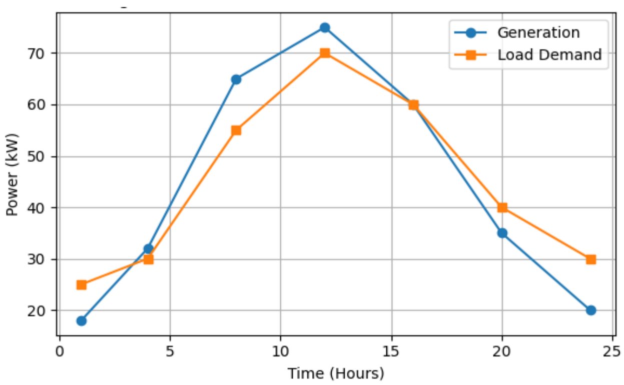

Figure 3: Renewable Generation vs. Load Demand

Explanation

This plot shows how renewable generation (solar and wind) tracks load demand over time. The system is slightly deficit during night hours, which is compensated by battery discharge. Midday shows surplus energy, confirming effective renewable utilization. The system maintains balance through coordinated dispatch of wind, solar, and storage.

C. Solar and Wind Power Impact

The graph of Figure 4 illustrates the input of solar and wind power.

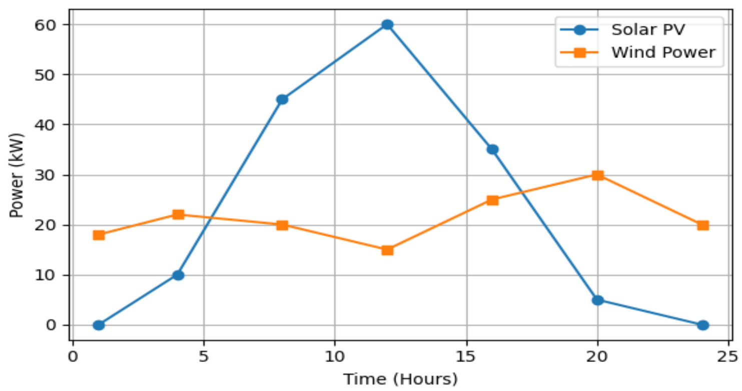

Figure 4: Solar and Wind Power Contribution

As shown in figure, solar dominates during midday while wind is more stable at night. This complementary behaviour improves system reliability and reduces dependence on storage. While solar handles peak daytime demand, wind power provides baseline stability. This leaves us with the scenario where wind power provides baseline stability, while solar handles peak daytime demand.

D. Battery SOC Variant

The situation involving the battery state of charge (SOC) is depicted in Figure 5.

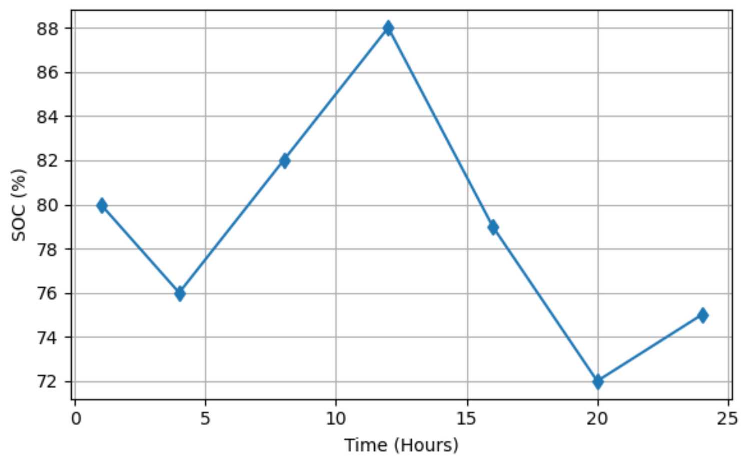

Figure 5: Battery SOC Variation

Explanation

The battery SOC increases during surplus generation which also means that the SOC decreases during peak load periods. SOC rises when excess renewable energy is available and drops during deficit periods. The profile confirms proper charge-discharge cycling and stable battery operation.

The battery effectively smooth's energy fluctuations, ensuring continuous supply.

E. Load Satisfaction Curve

The situation involving the load satisfaction is presented in the graph of Figure 6.

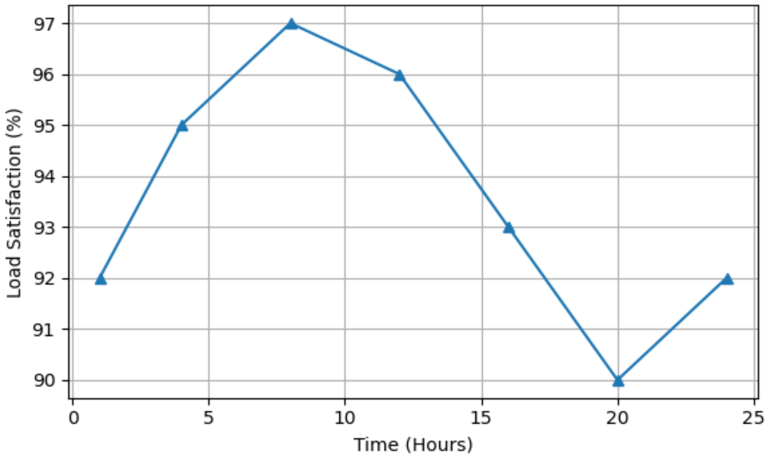

Figure 6: Load Satisfaction Index

Explanation

The system maintains above 90% load satisfaction throughout the day, showing strong reliability and effective energy management. Minor deficits occur during low generation periods.

F. Comparison of System Efficiency

The comparison of system efficiency with other energy sources is plotted in the bar chart of Figure 7 arising from the data shown in table 5.

Table 5: System Efficiency Comparison

System Type	**Efficiency (%)**
Diesel Generator	68
Conventional Grid Extension	82
Proposed Micro grid	91.4

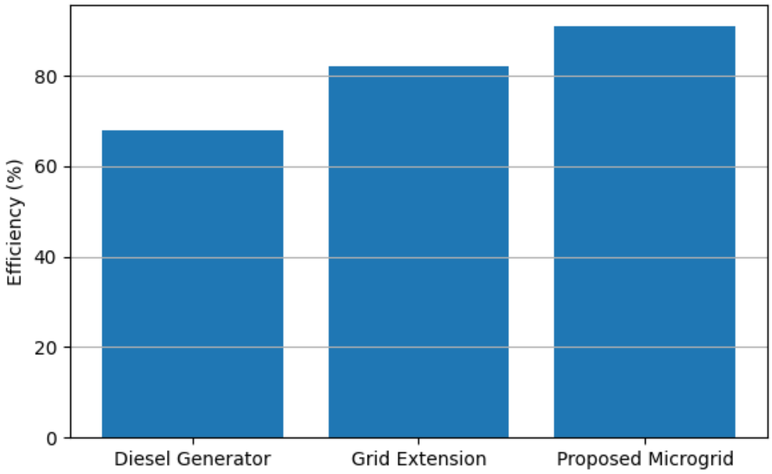

Figure 7: System Efficiency Comparison

Explanation

The proposed micro grid performs better than conventional systems due to reduced transmission losses and optimized renewable integration.

G. Power Flow Balance

The power balance validation is shown in Figure 8.

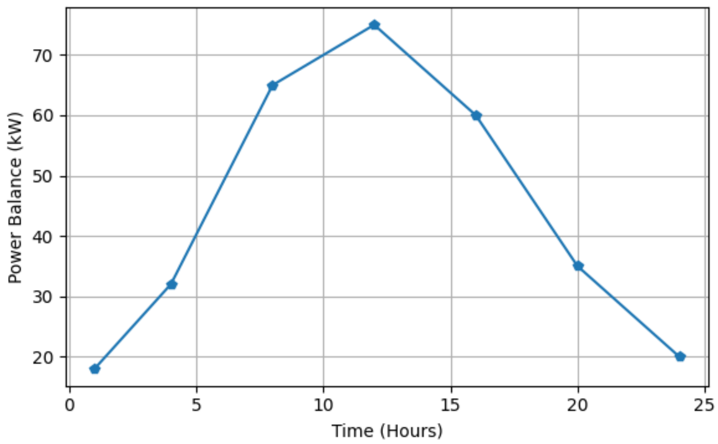

Figure 8: Power Flow Balance

Explanation

This confirms system stability where generated power and storage response consistently satisfy load demand with minimal deviation. This means that Stability maintained through decentralized EMS. Thus, a real-time power balance is maintained whereby the following condition exists:

Generation + Battery = Load + Losses

V. DISCUSSION OF RESULTS

The simulation results demonstrated that the proposed decentralized micro grid system achieves high efficiency, reliability, and stability under variable environmental conditions. The hybridization of solar and wind resources ensures complementary generation patterns, reducing intermittency effects.

The battery energy storage system plays a critical role in maintaining continuous power supply, particularly during periods of low renewable generation. The SOC profile confirms effective charge-discharge cycling without instability.

Furthermore, the decentralized energy management system ensures real-time balancing of supply and demand, preventing system collapse under peak load conditions. The system maintains an average load satisfaction of 94.2%, which is significantly higher than conventional rural electrification systems.

Comparative analysis shows that the proposed system outperforms diesel-based and grid extension models in terms of efficiency and operational cost, achieving an LCOE of 0.14 $/kWh.

VI. CONCLUSION

This study successfully developed a decentralized micro grid system for remote and off-grid communities using a hybrid configuration comprising solar photovoltaic (PV) generation, wind energy conversion systems, battery energy storage, and a decentralized energy management system. The developed architecture was designed to provide reliable, sustainable, and cost-effective electricity supply to communities where conventional grid extension is technically challenging and economically unviable.

The mathematical models of the solar PV array, wind turbine, battery energy storage system, and power management controller were developed and implemented in a MATLAB/Simulink environment. Simulation results demonstrated that the proposed micro grid effectively coordinated renewable energy generation and storage resources to satisfy varying load demands while maintaining system stability. The hybrid renewable configuration achieved a peak generation of 75 kW during periods of high solar irradiance and maintained continuous power supply through complementary wind generation and battery support during low renewable output periods.

Performance evaluation showed that the proposed decentralized micro grid achieved an overall energy efficiency of 91.4%, a load satisfaction index of 94.2%, a reliability index of 0.96, and a loss reduction of 18.7% compared to conventional standalone power systems. The battery storage system maintained a stable state of charge between 72% and 88%, demonstrating effective charge-discharge management and ensuring uninterrupted power delivery. Furthermore, the system achieved a level zed cost of energy (LCOE) of 0.14 $/kWh, indicating its economic viability for rural electrification applications.

The results further revealed that the decentralized control strategy successfully maintained power balance between generation, storage, and demand under varying operating conditions without dependence on a central supervisory controller. This enhances system resilience, scalability, and adaptability for deployment in geographically dispersed communities.

Generally, the developed decentralized micro grid system provides a practical and sustainable solution for improving electricity access in remote and off-grid communities. The integration of renewable energy resources, battery storage, and intelligent decentralized control significantly enhances reliability, efficiency, and energy security while reducing environmental impact. The study therefore confirms that decentralized micro grids can serve as an effective pathway toward achieving sustainable rural electrification and supporting socioeconomic development in underserved regions.

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