Design and Development of Microgrid Monitoring and Controlling Using PLC

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ABSTRACT

Background

Existing small-scale microgrid systems often suffer from unstable renewable energy management, inefficient source switching, and lack of real-time monitoring. To overcome these limitations, this paper presents the design and implementation of a Programmable Logic Controller (PLC)-based monitoring and control system integrating renewable and non-renewable energy sources for reliable microgrid operation. The proposed system incorporates solar photovoltaic (PV), wind energy, and an AC backup supply to ensure continuous power availability under varying operating conditions.

Materials and Methods

The developed hardware system utilizes real-time sensing and data acquisition through an ESP32 controller and Mitsubishi PLC for intelligent monitoring and control of power flow. Power conditioning units including buck and boost converters are used for efficient voltage regulation and battery charging. The PLC-based control strategy performs automatic source switching, battery monitoring, and protection operations to improve system stability and energy utilization.

Results

Experimental analysis demonstrates stable voltage regulation within ±3%, converter efficiency of approximately 89%, and automatic source switching delay of nearly 120 ms. The implemented system successfully maintains reliable operation under varying renewable generation conditions and load demands.

Conclusion

The proposed approach provides a cost-effective, scalable, and efficient solution for residential, industrial, and rural smart microgrid applications.

Index Terms: Microgrid, PLC, Renewable Energy, Energy Management, Smart Grid, Battery Storage.
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Energy, Energy Management, Smart Grid, Battery StorageN

Electrical energy has become one of the most essential requirements for modern society due to rapid industrialization, population growth, and technological advancements. The increasing demand for electricity and the depletion of conven- tional fossil fuel resources have accelerated the adoption of renewable energy sources such as solar photovoltaic (PV) and wind energy in modern power systems [1]. Renewable energy integration not only reduces environmental pollution but also improves energy sustainability and power reliability.

A microgrid is a localized power system consisting of Dis- tributed Energy Resources (DERs), Energy Storage Systems (ESS), and electrical loads operating as a single controllable entity. Microgrids can operate in both grid-connected and islanded modes depending on operating conditions. They areconsidered important components of smart grid systems be- cause they improve reliability, reduce transmission losses, and support efficient utilization of renewable energy resources [2]. However, renewable energy sources such as solar and wind are inherently intermittent and highly dependent on environ- mental conditions. Variations in solar irradiance and wind speed create fluctuations in power generation, affecting voltage stability and continuous power supply. Therefore, efficient monitoring, intelligent control, and proper coordination be- tween renewable and conventional sources are essential for stable microgrid operation.

Most existing PLC-based microgrid systems mainly focus on basic source switching operations and lack intelligent monitoring, fast response mechanisms, and efficient renewable energy utilization. Furthermore, many low-cost systems do not provide proper battery management and real-time data acquisition, resulting in reduced operational efficiency and reliability. Hence, there is a need for a compact, cost-effective, and automated microgrid control system capable of real-time monitoring and intelligent energy management.

In this work, a PLC-based monitoring and control system for a hybrid microgrid is proposed using solar energy, wind energy, and conventional AC supply from the Maharashtra State Electricity Board (MSEB). The renewable DC power generated from solar panels and wind turbines is used to charge a battery storage system through appropriate power conditioning circuits. The stored energy is converted into AC supply using an inverter to power the connected load.

The proposed system provides two AC power sources to the load: inverter AC derived from renewable energy sources and conventional MSEB AC supply. To maximize renewable energy utilization, priority is given to inverter supply. When the battery voltage falls below a predefined threshold value, the system automatically switches the load to the MSEB supply. The automatic monitoring and switching operation is im- plemented using a Mitsubishi Programmable Logic Controller (PLC). An ESP32 controller is used for real-time sensing and data acquisition, while the PLC executes the control logic and manages switching operations. The PLC continuously moni- tors battery voltage, source availability, and load conditions to ensure smooth and reliable power transfer.

Compared to conventional relay-based and microcontroller-based systems, PLC-based control provides higher reliability, fast response, industrial robustness, ease of programming, and compatibility with industrial communication protocols [3]. The proposed system improves renewable energy utilization, en- hances system stability, and provides a cost-effective solution for residential, industrial, and rural microgrid applications.

I. PROBLEM STATEMENT

The demand for electrical energy is continuously increasing due to rapid industrialization, urban expansion, and techno- logical advancements. At the same time, conventional fossil fuel resources are depleting and causing significant environ- mental pollution. To address these issues, renewable energy sources such as solar photovoltaic (PV) and wind energy are increasingly being integrated into modern power systems and microgrids.

However, renewable energy sources are inherently intermittent and highly dependent on environmental conditions such as solar irradiance and wind speed. These fluctuations in power generation create challenges in maintaining voltage stability, power quality, uninterrupted supply, and efficient energy management within microgrid systems.

Existing low-cost microgrid systems often suffer from inef- ficient renewable energy utilization, delayed source switching, poor battery monitoring, and lack of intelligent control mech- anisms. Many systems also lack real-time monitoring, proper protection circuits, and coordinated control between renewable and conventional energy sources. These limitations reduce system reliability, increase power losses, and affect continuous power availability during varying operating conditions.

In addition, improper battery charging and discharging control can reduce battery life and overall system efficiency. The absence of intelligent demand-side management further increases peak load conditions and decreases operational per- formance.

Therefore, there is a need for a compact, cost-effective, and automated PLC-based microgrid monitoring and control system capable of real-time monitoring, intelligent energy management, automatic source switching, and reliable oper- ation under varying load and generation conditions.

Objectives:- The main objectives of the proposed work are as follows:

- To design and develop a PLC-based microgrid monitoring and control system for efficient energy management.
- To integrate renewable energy sources such as solar photovoltaic (PV) and wind energy with conventional AC supply for continuous power availability.
- To implement real-time monitoring and intelligent control of voltage, current, battery status, and source availability using ESP32 and Mitsubishi PLC.
- To develop an efficient battery charging and management system for improving energy storage performance and system reliability.
- To implement automatic source switching between renewable and conventional energy sources based on battery voltage conditions.To improve system protection, operational safety, and voltage stability under varying load and generation conditions.
- To optimize renewable energy utilization and reduce dependency on conventional grid supply through intelligent control strategies.
- To develop a compact, cost-effective, and scalable microgrid solution suitable for residential, industrial, and rural applications.

II. LITERATURE SURVEY

Microgrids have emerged as an effective solution for integrating renewable energy sources and improving power system reliability. Various researchers have investigated different monitoring and control strategies for microgrid operation using Programmable Logic Controllers (PLC), focusing on energy management, source coordination, automation, and load control.

In the paper titled "A Novel Design of Energy Management and Control for Smart Microgrids in Urban Buildings," Y.
V. Pavan Kumar proposed a Smart Energy Management and Control (SEMC) strategy for microgrids integrating renewable energy sources such as photovoltaic (PV), wind power, and fuel cells. The system uses a PLC-based controller to manage available power under different generation and load conditions. A Hardware-in-the-Loop (HIL) platform based on MATLAB/Simulink system reliability. Researchers have further explored the use of hybrid renewable energy systems with advanced monitoring architectures for efficient energy utilization in smart grid applications.

From the literature survey, it is observed that most existing systems primarily focus on source switching and basic energy management. However, many low-cost microgrid systems still lack intelligent monitoring, efficient battery management, fast response control, and coordinated and PLC was implemented for real-time testing. The results demonstrated effective power management and reliable microgrid operation using PLC-based control techniques [4].

Another study titled "PLC Based Microgrid Controller for Disaster Management: A Case in Kodagu" presented a PLC- based hybrid microgrid control system for emergency power restoration during disaster conditions. The proposed system integrates solar, wind, and diesel generators to operate in islanded mode during utility grid failure. The PLC controller manages distributed energy sources and supplies power to critical loads such as shelters and water pumping systems. The study highlighted that PLC-based controllers provide fast source switching, improved operational reliability, and effective load management during blackout conditions [5].

The paper "Application of PLC Based Smart Microgrid" focused on implementing automation and intelligent control in microgrid systems using PLC technology. The proposed system monitored generation and load parameters while controlling switching operations between renewable sources and connected loads. The PLC executed ladder logic programs for real-time monitoring and automatic control functions. The study demonstrated that PLC-based automation improves system flexibility, operational stability, and overall microgrid efficiency. In addition, PLC controllers offer advantages such as industrial reliability, ease of programming, and compatibility with multiple sensors and actuators [6].

Recent research works have also focused on IoT-enabled smart microgrids, intelligent energy management systems, and advanced renewable energy integration techniques.

Modern microgrid systems utilize real-time monitoring, communication-based automation, and smart control algorithms to improve battery management, voltage stability, and operation between renewable and conventional energy sources. Therefore, the proposed work aims to develop a compact, cost-effective, and intelligent PLC-based microgrid monitoring and control system capable of real-time monitoring, automatic source switching, and reliable energy management.

$$V_{out} = \frac{V_{in}}{1 - D} \qquad (4)$$

where D represents the converter duty cycle. Equations (3) and (4) are used for voltage regulation and stable charging operation of the battery system.

D. *Battery Charging Model*

The battery charging power is calculated using Equation (5):

$$P_{battery} = V_{bat} \times I_{charge}$$

III. MATHEMATICAL METHODOLOGY

The proposed PLC-based microgrid system is analyzed using fundamental electrical and power electronics equations to ensure efficient energy management, voltage regulation, battery charging control, and reliable microgrid operation. The mathematical modeling of solar generation, wind generation, converter operation, battery charging, and load management is discussed as follows.

A. *Solar Power Generation*

The output power generated from the solar photovoltaic (PV) system is calculated using Equation (1):

$$P_{solar} = V_{pv} \times I_{pv} \qquad (1)$$

where V_{pv} and I_{pv} represent the solar PV output voltage and current, respectively. Equation (1) is used to estimate the electrical power generated by the solar panel under varying irradiance conditions.

B. *Wind Power Generation*

The power generated from the wind turbine is expressed using Equation (2):

$$P_{wind} = \frac{1}{2} \rho A v^3 C_p$$

where ρ represents air density, A is the swept area of the turbine blades, v is the wind speed, and C_p is the power coefficient of the turbine. Equation (2) represents the wind energy conversion model based on wind speed variation.

C. *DC-DC Converter Operation*

To regulate renewable source voltages for efficient battery charging, buck and boost converter circuits are used in the proposed system.

(5)

where V_{bat} represents battery voltage and I_{charge} represents charging current.

The battery State of Charge (SoC) is estimated using Equation (6):

$$SoC = SoC_{initial} + \frac{1}{C}\int {}_{charge}\, dt \qquad (6)$$

where C_{bat} represents battery capacity. Equation (6) is used for monitoring battery charging and discharging conditions during microgrid operation.

A 12.8 V, 1.5 Ah lithium-ion battery is used in the implemented system. The initial State of Charge (SoC) was maintained at 40%, and the charging current sampling interval was set to 1 second.

E. *Load Power Calculation*

The load power consumption is determined using Equation (7):

$$P_{load} = V_{load} \times I_{load}$$

(7)

where V_{load} and I_{load} represent load voltage and load current, respectively.

F. *Energy Balance Equation*

For stable and continuous microgrid operation, the total generated power must satisfy the load demand and battery charging requirements. The energy balance equation is ex- pressed as:

(2)

$$P_{solar} + P_{wind} + P_{AC} = P_{load} + P_{loss} + P_{battery}$$

(8)

Equation (8) ensures proper coordination between renew- able sources, battery storage, and AC backup supply.

G. *Voltage Sensing*

The voltage divider circuit used for voltage sensing is represented using Equation (9):

$$\frac{R_2}{\quad}$$

Buck Converter (Solar Voltage Regulation): $V_{out} = V_{in} \times_1 + R_2$
(9)

$$V_{out} = D \cdot V_{in} \tag{3}$$

Boost Converter (Wind Voltage Regulation):where R_1 and R_2 represent the resistor values of the voltage divider network. This equation is used to scale higher voltages to safe levels for ESP32 and PLC sensing operations.

H. *Summary*

The mathematical equations used in the proposed system were experimentally validated using practical hardware implementation. The measured converter output voltages and battery charging characteristics closely matched the theoretical calculations with less than 5% deviation.

These mathematical models enable accurate sensing, efficient energy conversion, intelligent battery management, and reliable power flow control, ensuring stable and efficient microgrid operation.

IV. CONTROL ALGORITHM

The proposed system uses a PLC-based intelligent control algorithm for monitoring renewable energy sources, battery status, and load conditions. The control system continuously monitors voltage levels and automatically switches between inverter supply and MSEB supply based on battery conditions.

```
BEGIN

Read solar voltage
Read wind voltage
Read battery voltage

IF battery voltage > threshold THEN
   Connect inverter supply to load
ELSE
   Switch load to MSEB supply
ENDIF

IF renewable source available THEN
   Charge battery
ENDIF

Display voltage and source status on LCD

Repeat continuously

END
```

V. SYSTEM ARCHITECTURE

A. Renewable Energy Integration

As shown in Fig. 2, the proposed microgrid system integrates renewable energy sources including solar photovoltaic (PV) and wind energy generation units. The solar panel output is monitored using a DC voltage sensor and regulated through a buck (step-down) converter to obtain a stable voltage suitable for battery charging. Similarly, the wind energy source is connected through a DC sensor and a boost (step-up) converter to increase the generated voltage to the required charging level. A reverse protection mechanism is incorporated in the charging path to prevent reverse current flow from the battery toward the renewable sources, thereby improving operational safety and system reliability.

B. Non-Renewable Source Integration

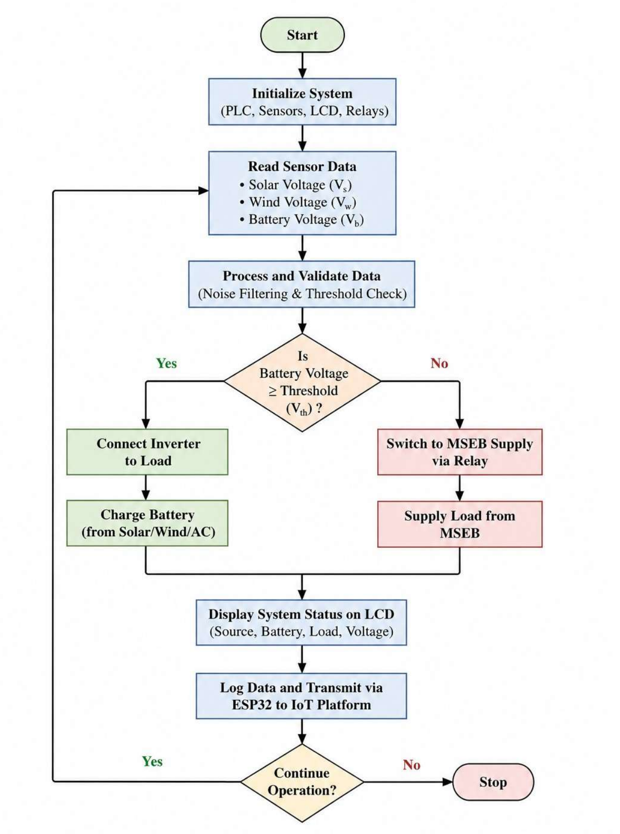


Fig. 1. Flowchart of Proposed PLC-Based Microgrid Control System

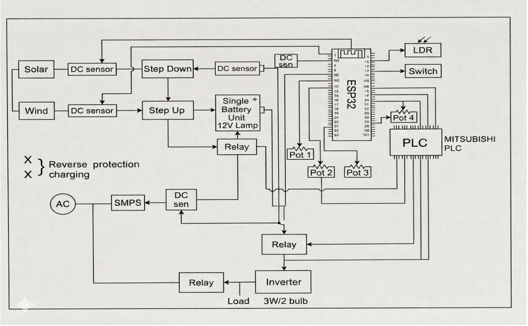


Fig. 2. System Architecture of Implemented Model

An AC supply from the Maharashtra State Electricity Board (MSEB) is used as a backup power source during insufficient renewable energy generation conditions. The AC supply is converted into regulated DC power using a 12 V, 2 A Switched Mode Power Supply (SMPS). The SMPS output is monitored using a DC sensor before being supplied to the battery charging circuit and control system. This arrangement ensures uninterrupted system operation and continuous power availability.

C. Energy Storage System

A 12.8 V, 1.5 Ah lithium-ion battery is used as the energy storage unit in the proposed system. The battery stores energy generated from solar and wind sources and supplies power to the load through the inverter during low renewable generation conditions. Proper charging and discharging control improves battery life, operational stability, and energy utilization efficiency.

D. Sensing and Signal Conditioning

Multiple DC voltage sensors are deployed at various points in the system to continuously monitor source voltage, battery voltage, and converter output voltage. A voltage divider circuit is used to scale higher voltages to safe levels suitable for ESP32 and PLC input terminals. In addition, 10 kΩ potentiometers are used for calibration and adjustment of sensing signals to improve measurement accuracy.

E. Control Architecture

The proposed system employs a two-stage intelligent monitoring and control architecture using ESP32 and Mitsubishi PLC. The ESP32 controller is used for real-time sensing, data acquisition, and preprocessing of sensor signals. The processed data is transmitted to the Mitsubishi PLC, which performs source monitoring, battery management, and switching control operations.

The ESP32 communicates with the Mitsubishi PLC using UART serial communication operating at a baud rate of 9600 bps. Sensor readings are updated every 500 ms and transmitted to the PLC for real-time monitoring and control action. The PLC continuously monitors battery voltage, renewable source availability, and load conditions to ensure reliable microgrid operation.

F. Switching and Protection

Relay modules controlled by the PLC are used for automatic switching between inverter supply and MSEB supply based on battery voltage conditions. The switching mechanism ensures uninterrupted load operation during source transition. Reverse polarity protection and overvoltage protection mechanisms are incorporated to improve operational safety and prevent hardware damage.

G. Load and Power Conversion

An inverter is used to convert the stored DC energy from the battery into AC supply ranging from 110–230 V at 50–60 Hz frequency. The inverter output is used to operate connected AC loads such as 3 W LED bulbs. The implemented system successfully demonstrates stable operation under varying renewable energy conditions.

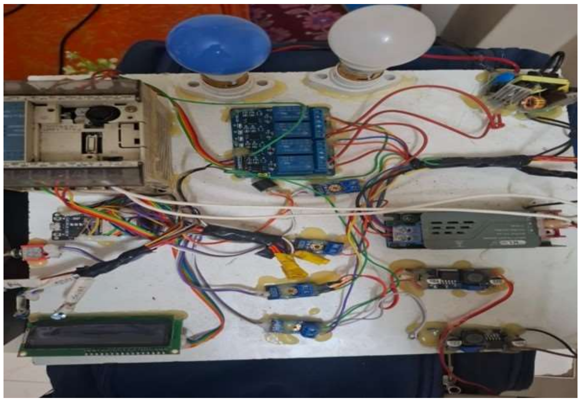
H. Display and User Interface

An LCD display with I2C communication interface is integrated into the system for real-time visualization of operating parameters. The display continuously shows source voltage levels, battery voltage, charging status, and active power source information for user monitoring purposes.

I. System OperationThe proposed microgrid system continuously monitors renewable energy generation, battery conditions, and load demand using coordinated ESP32 and PLC operation. The PLC executes intelligent control logic for automatic source selection, battery charging management, and load supply control. The integrated monitoring and control architecture improves renewable energy utilization, operational stability, and overall system efficiency.

VI. IMPLEMENTED SYSTEM / HARDWARE DESCRIPTION

Fig. 3. Hardware Setup



The proposed system consists of a PLC-based hybrid microgrid setup integrating renewable energy sources, energy storage units, power conditioning circuits, sensing modules, and intelligent control architecture. The hardware implementation is designed to ensure efficient power generation, voltage regulation, real-time monitoring, and automatic control of energy flow, as shown in Fig. 3.

The renewable energy section consists of a polycrystalline solar photovoltaic (PV) panel and a wind energy generation unit. The solar panel acts as the primary renewable energy source and generates DC power under sunlight conditions. A DC motor coupled with a propeller is used to simulate wind energy generation in the laboratory setup. Since both renewable sources produce variable output voltages depending on environmental conditions, proper voltage conditioning and regulation are necessary before battery charging and load operation.

A 12.8 V, 1.5 Ah lithium-ion battery is used as the energy storage system in the proposed microgrid. The battery stores energy generated from solar and wind sources and supplies power to the connected load when renewable generation be- comes insufficient. To ensure continuous operation and reliable backup support, a conventional AC supply from MSEB is connected through a 12 V, 2 A Switched Mode Power Supply (SMPS), which converts AC voltage into regulated DC voltage for charging and control purposes.

The system employs DC–DC power converters for efficient voltage regulation and battery charging. A buck converter module (LM2596) is used to step down the solar panel voltage o a suitable battery charging level. Similarly, a boost converter module (XL6009) is used to increase the voltage generated by the wind source. The converter circuits improve energy transfer efficiency and maintain stable charging conditions under varying renewable energy generation.

For monitoring and sensing operations, multiple DC voltage sensors are deployed at different points in the system to mea- sure source voltage, converter output voltage, and battery volt- age. A resistor-based voltage divider circuit is implemented to scale higher voltages to safe levels suitable for ESP32 and PLC input terminals. In addition, 10 kΩ potentiometers are used for calibration and adjustment of sensor readings to improve measurement accuracy.

The proposed system utilizes an ESP32 microcontroller for real-time data acquisition and preprocessing of sensor signals. The processed sensor data is transmitted to the Mitsubishi PLC through UART serial communication operating at 9600 bps. Sensor readings are updated every 500 ms for real-time monitoring and control. The Mitsubishi PLC acts as the central control unit and executes ladder logic programs for automatic source switching, battery management, and protection operations through a 5 V, 4-channel relay module.

The load section of the implemented system consists of two 3 W LED bulbs representing a small-scale residential load application. An inverter converts the stored DC power from the battery into AC supply ranging from 110–230 V at 50– 60 Hz frequency for operating AC loads.

An LCD display with an I2C communication interface is integrated into the system to provide real-time information such as source voltage, battery voltage, charging status, and active power source conditions. This improves system visibility and user interaction during operation.

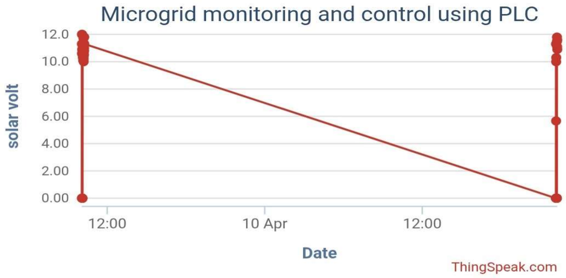


Table I shows the specifications of the major hardware components used in the proposed system.

TABLE I
HARDWARE SPECIFICATIONS OF THE PROPOSED SYSTEM

Component	Specification
Solar Panel	20 W Polycrystalline
Wind Generator	12 V DC Motor
Battery	12.8 V, 1.5 Ah Li-ion
PLC	Mitsubishi FX1N
ESP32	Dual-Core 240 MHz
Buck Converter	LM2596
Boost Converter	XL6009
SMPS	12 V, 2 A
Relay Module	5 V, 4-Channel
Sensor Accuracy	±1%
Inverter Efficiency	89%

Overall, the implemented hardware setup provides a compact, reliable, cost-effective, and efficient solution for real-time monitoring and intelligent control of hybrid microgrid systems using a PLC-based approach.

VII. RESULTS AND ANALYSIS

The proposed PLC-based microgrid system was xperimentally tested under different renewable generation and loadconditions to evaluate system stability, voltage regulation, charging performance, and automatic source switching oper- ation. The obtained results demonstrate reliable operation of the implemented monitoring and control architecture.

The average inverter output voltage was measured as 221.5 V AC with voltage regulation maintained within ±3%. The measured converter efficiency was approximately 89%, while the relay-based source switching delay was observed to be nearly 120 ms. These results validate the effectiveness of the proposed PLC-based monitoring and control strategy.

Battery Voltage vs Time: As shown in Fig. 4, the battery voltage gradually increases during charging operation and remains within the safe operating range of the battery system. The charging profile confirms stable charging performance and efficient energy storage operation under varying renewable energy conditions.

Microgrid Charging Status under PLC Control: As shown in Fig. 5, the charging characteristics vary according to renewable source availability and load demand conditions. The PLC-based charging control logic effectively manages charging and discharging operations to maintain system stability and reliable operation.

Solar PV Voltage Variation with Time: As shown in Fig. 6, the solar PV output voltage changes with variations in solar irradiance and environmental conditions. The regulated solar output successfully contributes power to the microgrid system through the buck converter circuit.

SMPS Output Voltage Characteristics: As shown in Fig. 7, the SMPS output voltage remains comparatively stable throughout operation. The regulated DC output from the SMPS ensures reliable backup charging support during low renewable energy generation conditions.

Wind Generator Output Voltage vs Time: As shown in Fig. 8, the wind generator output voltage varies according to wind speed conditions. The boost converter successfully regulates the wind source voltage for effective battery charging and auxiliary renewable power support.

The standard deviation of inverter output voltage was measured as 2.1 V, indicating stable operation under varying renewable energy generation conditions. The relay transition time between inverter supply and MSEB supply was approximately 120 ms with no noticeable interruption in load operation.

For statistical validation, multiple experimental observations were recorded under varying renewable energy and load conditions. The average inverter output voltage was measured as 221.5 V with a standard deviation of 2.1 V, indicating stable system operation. The average relay switching delay was observed as 120 ms with less than 5% variation during repeated switching cycles. The measured converter efficiency remained approximately 89% under different operating conditions. Experimental results showed that the practical measurements closely matched the theoretical values with a maximum deviation below 5%, validating the effectiveness and reliability of the proposed PLC-based control system.Table II presents the performance comparison between the proposed system and existing PLC-based microgrid control systems.

TABLE II
PERFORMANCE COMPARISON WITH EXISTING PLC-BASED MICROGRID SYSTEMS

Parameter	Existing Systems	Proposed System
Voltage Regulation	±5%	±3%
Converter Efficiency	80–85%	89%
Switching Delay	250–300 ms	120 ms
Monitoring Method	Basic Monitoring	Real-Time Monitoring
Battery Management	Limited Control	PLC Control
Renewable Inte.	Partial Integration	Solar + Wind + AC
Communication Sys.	Conventional Control	ESP32 + PLC UART
Protection Features	Basic Protection	Overvoltage Protection

Table III presents the load testing analysis of the implemented system under different operating conditions.

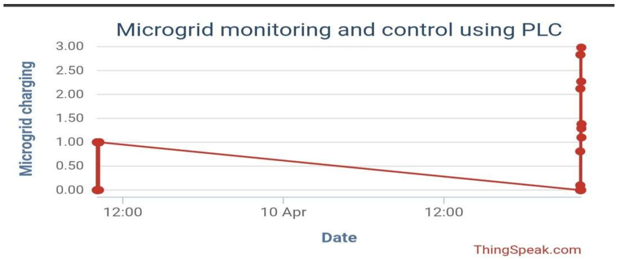


TABLE III
LOAD TESTING ANALYSIS OF THE PROPOSED SYSTEM

Load Condition	Observation
3 W Load	Stable Operation
6 W Load	Stable Operation
9 W Load	Minor Voltage Drop Observed
12 W Load	Stable with Backup Support

VIII. CONCLUSION

This paper presents the design and implementation of a PLC-based monitoring and control system for a hybrid microgrid integrating solar, wind, and conventional AC power sources. The developed system successfully demonstrates effective utilization of renewable energy along with intelligent backup power management to ensure continuous and reliable operation.

The use of power electronic converters such as buck and boost converters enables efficient voltage regulation and safe battery charging under varying renewable generation conditions. The integration of sensors, ESP32, and Mitsubishi PLC provides accurate real-time monitoring, intelligent source coordination, and automatic control of power flow between renewable sources, battery storage, and load.

Experimental analysis confirms that the implemented sys- tem achieves stable voltage regulation within ±3%, con- verter efficiency of approximately 89%, and automatic source switching delay of nearly 120 ms. The relay-based switching mechanism ensures reliable source transition and uninterrupted load operation during low renewable generation conditions.

The proposed system successfully operates small residential loads while maintaining operational stability, protection, and efficient energy utilization. The inclusion of an LCD display further improves system visibility by providing real-time infor- mation regarding source voltage, battery status, and operating conditions.

Overall, the proposed system provides a compact, cost-effective, scalable, and efficient solution for small-scale mi- crogrid applications. It improves renewable energy utilization, reduces dependency on conventional power sources, and en- hances reliable power management through intelligent PLC- based monitoring and control.

The proposed system can be effectively implemented in residential microgrids, rural electrification systems, industrial backup applications, and disaster management systems requir- ing reliable and uninterrupted power supply.

IX. FUTURE SCOPE

Future work may include IoT-based cloud monitoring, GSM alert systems, AI-based energy prediction, SCADA integration, and remote microgrid management for large-scale smart grid applications.

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