

# IoT-Based Smart Microgrid Energy Management System for Voltage Stability and Reliable Power Distribution

Parikshit Kulkarni  
Department of ECE  
Dharmsinh Desai University  
Nadiad, Gujarat, India

Mahin Khokhar  
Department of ECE  
Dharmsinh Desai University  
Nadiad, Gujarat, India

Prof. Himanshukumar Prajapati  
Department of ECE  
Dharmsinh Desai University  
Nadiad, Gujarat, India

**Abstract**—This paper introduces an IoT based Smart Microgrid Energy Management System for efficient and intelligent energy management using renewable energy sources. The system proposed integrates solar power, battery storage and grid backup supply to provide continuous and reliable power to the different loads. The Arduino Nano is used as the brain to take decisions. The IoT platform has been set up by ESP32 module for monitoring and transmitting the data in real-time through a web-based dashboard. The system is constantly monitoring key variables like voltage, current, battery condition and grid supply status. Based on these parameters, it intelligently controls the energy flow, giving priority to solar power, storing extra energy in the battery and switching to grid backup supply when required. Additionally, the load is split into two stages, critical and non-critical loads. First critical loads are supplied and second non-critical loads are supplied according to the source conditions. For the safety in the laboratory the grid supply is simulated by a DC source, keeping the operational behaviour of a real microgrid system. Experimental results show that the proposed system improves the energy efficiency, reliability and effective real-time monitoring. This system can be improved further for smart grid and large-scale renewable energy applications.

**Keywords:** IoT, Smart Microgrid, Energy Management, Voltage Stability, Renewable Energy, Load Management

## I. INTRODUCTION

The increasing requirement of electrical energy has increased the demand for efficient power management systems. Modern energy systems use communication and control techniques to improve the reliability and efficiency of the system [1], [2]. Multi-source DC systems enable renewable energy applications by providing efficient energy generation, storage and power management.

Energy Management System (EMS) is necessary for proper energy distribution and control. It deals with coordination among power sources, battery storage and load demand while improving the system reliability [3]. Modern communication technologies are also used for the real-time monitoring and control of energy systems [7].

Nowadays, the Internet of Things (IoT) has improved the modern energy systems with continuous data collection, remote monitoring and intelligent control [11]. Advanced energy

management techniques have also been shown to be important for improving system efficiency and reliability [9].

However, there are still many challenges such as efficient load management, cost optimization and real-time system control. Hence, this work aims to develop an IoT based energy management system for improving the performance, reliability and efficiency of the system.

## II. LITERATURE REVIEW

There are many research papers on energy management systems. In [3], a smart system for energy usage improvement was proposed but without real-time IoT monitoring. Similarly, the work in [4] dealt with energy management by centralized control approaches.

A load restoration algorithm was proposed in [5] for energy management systems which improved the system reliability under fault conditions but increased the system complexity. In [6], the integration of renewable energy with limited scalability was discussed through the energy management and operational planning of a PV-based energy system.

In recent years research has been done on IoT based energy management systems. However, a smart IoT based energy system was considered for monitoring and analysis in [8] but detailed performance evaluation of the proposed system was not provided. [10] presented an IoT based energy monitoring system. This work was mainly focused on monitoring and not energy optimization. In [12] a review of artificial intelligence techniques for energy management systems was carried out. This study demonstrated the potential of AI-based solutions; however, these methods need high processing power and complex implementation.

The analysis of reviewed papers indicates that current energy management systems are still grappling with challenges in real-time IoT monitoring, effective control and cost-effective implementation. Therefore, in the present research, a novel IoT based smart energy management system is proposed.

### III. METHODOLOGY

#### A. Description of the Hardware System

The proposed Smart Microgrid Energy Management System using IoT is designed to monitor electrical parameters and automatically manage power flow between solar energy, battery storage and grid backup supply. The system uses embedded hardware and IoT based communication for efficient energy usage and real time monitoring.

The complete system has the following major subsystems:

- Power supply block
- Voltage sensing subsystem
- Current sensing subsystem
- Controlling and processing unit
- Relay switching unit
- IoT communication subsystem

The central processing unit of the system is the Arduino Nano microcontroller. It receives the analog signals from the voltage and current sensors and converts them to digital values continuously using its internal ADC (Analog to Digital Converter). The electrical parameters measured are used by the microcontroller to implement the energy management algorithm to select the best power source to power the load.

For the wireless IoT communication, we used an ESP32 module in our system. The ESP32 transmits real time electrical parameters such as solar voltage, battery voltage, grid voltage, load current etc the data is sent to a cloud platform for remote monitoring and graphical representation.

#### B. Block Diagram of the Proposed System

The block diagram of the proposed iot based Smart Microgrid Energy Management System is shown in Fig. 1. The system consists of three power sources, solar power source, battery storage unit and grid backup power supply. The main energy source is the solar source. The battery and grid supply are secondary and backup sources respectively.

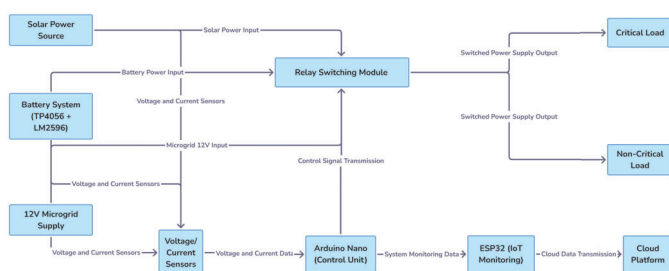


Fig. 1. Block diagram of the proposed Smart Microgrid Energy Management System

The following major functional blocks are the following.

- Solar energy source
- Battery storage system
- Microgrid (12V/grid supply)
- Sensing unit of voltage and current.
- Control unit Arduino Nano.
- Relay switching module

- ESP32 IoT communication module
- Critical loads and non-critical loads

Voltage and current sensors are interfaced to each power sources to monitor the electrical parameters of the system data continuously. The data is then transmitted to the Arduino Nano, which acts as the central processing unit. The measured parameters are processed by the Arduino Nano and intelligent source selection is performed on the basis of predefined threshold conditions.

The output voltage of the solar is controlled using a DC-DC buck converter (LM2596) to a fixed 5V DC voltage, suitable for charging of batteries and operation of the control circuit. This system has a TP4056 charging module for safe charging of the battery and energy storage management.

The relay switching module is controlled by the Arduino Nano to automatically switch between the available power sources and distribute power to critical and non-critical loads. Also, it has an IoT based monitoring system that integrates an ESP32 module. The ESP32 sends data to the cloud platform, allowing remote monitoring and graphical representation of the system performance via a web dashboard.

The proposed system generally provides efficient energy management, real time monitoring and reliable power supply by automatic switching of multiple power sources.

#### C. Voltage Sensing Using REES52

The voltage sensor module is used in the proposed system to measure solar voltage, battery voltage, and grid voltage. The sensor scales the input voltage to a safe level suitable for with the analog input pins of the Arduino Nano for real-time monitoring and processing.

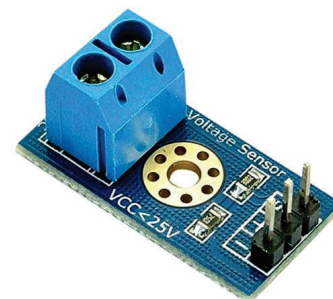


Fig. 2. REES52 Voltage Sensor Module

The ADC conversion relationship is given by

$$V_{ADC} = \frac{ADC \text{ Value}}{1023} \times 5$$

$$V_{in} = V_{ADC} \times \text{Scaling Factor}$$

This method allows safe voltage measurement and protects the Arduino Nano from high voltage levels.

#### D. Current Sensing Using ACS712

The current sensor module is used in the proposed system to measure solar current, battery current, and grid current. The sensor scales the input current to a safe level suitable for with the analog input pins of the Arduino Nano for real-time monitoring and processing. The ACS712 current sensor module used in the proposed system is shown in Fig.3 The

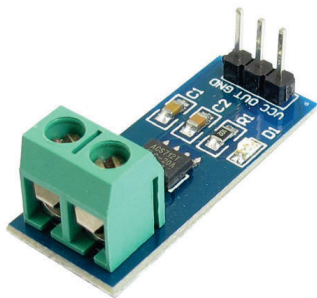


Fig. 3. ACS712 Current Sensor Module

Arduino Nano converts the analog sensor output into digital values using its internal 10-bit Analog-to-Digital Converter (ADC).

The same ADC conversion equation used in the voltage sensor section is applied for the current sensor measurements.

$$V_{ADC} = \frac{ADC \text{ Value}}{1023} \times 5$$

This method enables safe and accurate current monitoring by providing analog output levels suitable for the Arduino Nano analog input pins.

#### E. Control Unit

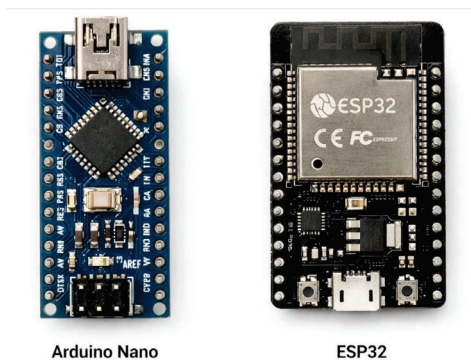


Fig. 4. Arduino Nano and ESP32 modules used as control and communication units

Fig. 4 shows the Arduino Nano and ESP32 modules as the control and communication units of the proposed system. The Arduino Nano serves as the main Processing and controlling unit, and the ESP32 module is used for IoT based wireless communication and remote monitoring.

The Arduino Nano continuously receives voltage and current values from the sensing modules and converts the analog

signals to digital values with its internal Analog to Digital Converter (ADC). The controller follows the energy management algorithm as per the pre-set threshold conditions and controls the relay modules to switch over the solar source, battery supply and grid backup supply automatically. The proposed system is suitable for intelligent power management and continuous power supply to the load.

The ESP32 module is used for communication in the system. It receives data from Arduino Nano and transmits the electrical parameters in real-time to a cloud-based web dashboard using Wi-Fi and HTTP (Hypertext Transfer Protocol) protocols. The data sent includes voltage, current, power and battery state of charge (SOC) that enables continuous remote monitoring and graphical representation of the system performance.

The integration of Arduino Nano for hardware control and ESP32 for IoT communication enhances the overall system performance by combining robust control operation with efficient wireless data transmission.

In short, the stable control and communication unit of the designed iot based smart microgrid energy management system is formed by the coordinated operation of the Arduino Nano and ESP32.

#### F. Relay Switching Circuit

The relay switching circuit is used to select and connect appropriate power source to the load. Arduino Nano is used to control the relays by using the real time system parameters.

Solar power is supplied to the load, if available. If the solar power is not enough, then the system goes to battery supply. If there is no solar and no battery sources, the load is supplied by grid supply.

This mechanism of switching provides for continuous supply of power and for efficient usage of the available power sources.

#### G. IoT Communication Using ESP32

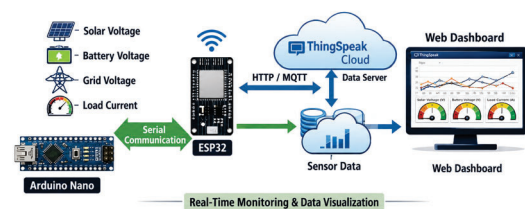


Fig. 5. IoT communication architecture using ESP32 and ThingSpeak cloud

Our system's IoT communication architecture is shown in Fig. 5. The wireless communication interface between the embedded system and the cloud platform is realized by using an ESP32 module, so that the system data can be monitored in real time. The sensing subsystem comprises the measurement of important electrical parameters such as solar voltage, battery voltage, grid voltage and load current. Then the data obtained

from the signals are processed by the Arduino Nano micro-controller, which converts the signals from analog to digital and then the data are sent to the ESP32 module for cloud monitoring.

The processed data are then sent to the ESP32 module via serial communication. The ESP32 is connected to Wi-Fi using HTTP (Hypertext Transfer Protocol) or MQTT protocol (Message Queuing Telemetry Transport) and uploads the data to the web-based dashboard cloud platform. Sensor data is transmitted to web and cloud platforms via HTTP. MQTT is a lightweight protocol for real-time communication between IoT devices and servers.

The data received is stored in the cloud platform and displayed on a web-based dashboard. Users can easily monitor system performance and analyze data from remote locations in real-time. This data can also be saved as an excel sheet for future use.

The integration of ESP32 also provides IoT based monitoring, data logging and efficient system control and improves the overall system performance.

#### H. Energy Management Algorithm

The proposed energy management algorithm ensures the efficient utilization of available energy sources and provides a continuous power supply to the load. The system operation is described as follows:

- 1) Measure solar voltage, battery voltage, grid voltage and load current.
- 2) If solar voltage is higher than threshold voltage, supply power to the load using solar energy.
- 3) If the solar voltage is below the threshold, check the battery voltage.
- 4) If battery voltage is above minimum threshold level, then power the load from battery.
- 5) If there is no solar or battery, or not enough, change the load to the grid power.
- 6) Regular update and upload of system parameters to cloud platform for real time monitoring.

The algorithm is designed to give priority to renewable energy sources, to operate energy efficiently and to switch between power sources smoothly in order to ensure continuous system operation.

#### I. Energy Management Flowchart

The flowchart shows the operation order of the proposed energy management system. The algorithm continuously monitors the solar voltage, battery voltage, grid voltage and load current to decide the best source of power. Solar energy is given priority whenever there is enough power. When the solar power is not sufficient, the system changes to the battery supply and when neither the solar nor the battery can give the power, the load is changed to the grid supply. The algorithm also handles critical and non-critical loads. Critical loads are given the highest priority and non-critical loads are run under the conditions of the available power source. Also, it is sending

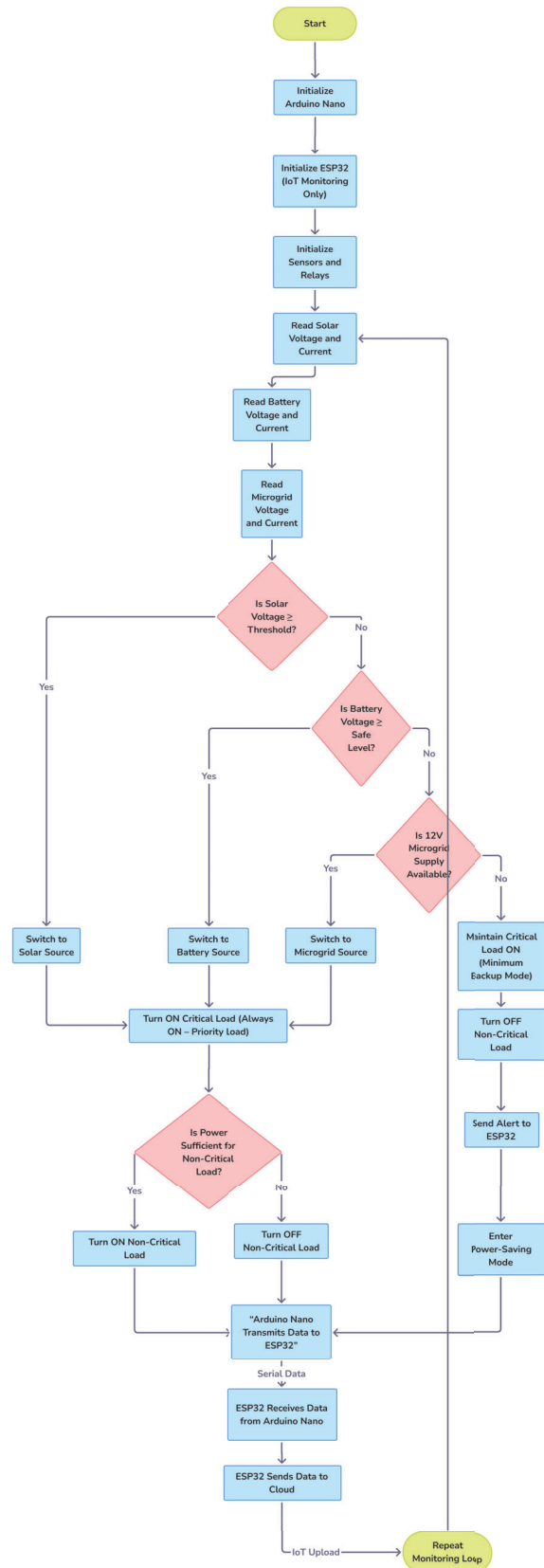


Fig. 6. Flowchart of the proposed IoT-based smart microgrid energy management algorithm

system data to the cloud platform via the ESP32 module for remote monitoring.

#### IV. HARDWARE IMPLEMENTATION

The hardware prototype has three input supply terminals:

- 1) Terminal of solar supply
- 2) Battery supply terminal
- 3) Grid supply terminal

The proposed Smart Microgrid Energy Management System is implemented using an Arduino Nano microcontroller, ESP32 communication module, REES52 voltage sensor, ACS712 current sensor, and relay switching modules. The complete hardware prototype of the developed system is shown in Fig.7. The prototype is assembled on a general-purpose PCB, where all components are interconnected to form an integrated system.

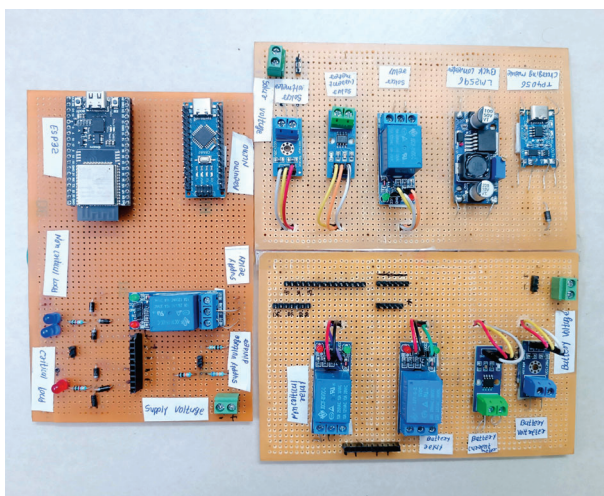


Fig. 7. Hardware prototype of the proposed Smart Microgrid Energy Management System

The solar panel is the main energy source for the system. The voltage sensor measures the voltage that the solar produces and a current sensor measures the current accordingly. Both sensor outputs are scaled to safe levels and connected to the analog inputs of the Arduino Nano and monitored continuously.

The solar power flows into a DC-DC buck converter that regulates the voltage to a stable 5V DC level. This regulated output voltage is given to a TP4056 charging module which is used to charge the battery safely.

The energy is stored in the battery. For this store energy check using voltage and current parameters are continuously monitored through separate voltage and current sensors. When the solar voltage drops below a predefined threshold level, for this condition the control logic activates a relay to switch the load supply from solar to battery. In this condition, the battery acts as the primary power source and provides energy to the load.

If the solar voltage and the battery voltage drop below a certain threshold level, the control logic will activate a relay

to switch the load supply from the battery to the grid. The grid voltage and current parameters are continuously monitored using separate voltage and current sensors. In this situation the grid acts as the primary source of power and supplies energy to the load.

The Arduino Nano is the brain of the system. It continuously checks the sensor data and compares it with the threshold values and controls the relay modules for automatic source switching and continuous power supply.

The processed data from Arduino Nano is sent to ESP32 module for IoT based monitoring. The ESP32 can also upload the real-time voltage and current data to a web-based dashboard for remote monitoring of the system's performance. This provides the capability to continuously monitor all energy sources and load conditions. Therefore, the system operates in a loop, continuously taking measurements of electrical parameters, making decisions based on threshold conditions, and updating the IoT platform for real-time visualization.

The load is classified into two categories. The first one is critical load and the second one is non-critical load. Critical loads are given the highest priority and are always maintained supplied under any conditions. Non-critical loads are controlled based on the availability of power.

#### V. RESULTS AND DISCUSSION

We evaluated the performance of our system using an IoT-based web dashboard and an experimental hardware setup with real-time monitoring. The system performance was evaluated under different operating conditions, such as solar, battery, and grid modes. The system always supplies continuous power to critical loads, and noncritical loads are supplied based on the availability of different energy sources. This means that the critical load is ON in any condition, but the non-critical load is switched between the availability of the sources. The results indicate effective energy management, reliable source switching, and continuous power supply.

##### A. Solar Dashboard

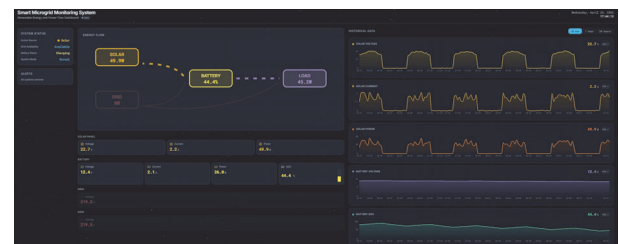


Fig. 8. Web-based dashboard showing solar power generation and system parameters

Fig. 8 shows the web-based dashboard of the microgrid operating in solar mode during the day. In this state, the solar source is the major energy supplier. The solar panel provides power to the connected load (approximately 36.6 W) and charges the battery. A sufficient available grid supply is not used because solar energy meets the load demand. This

mode demonstrates the effective use of renewable energy and energy storage for future use.

### B. Battery Dashboard

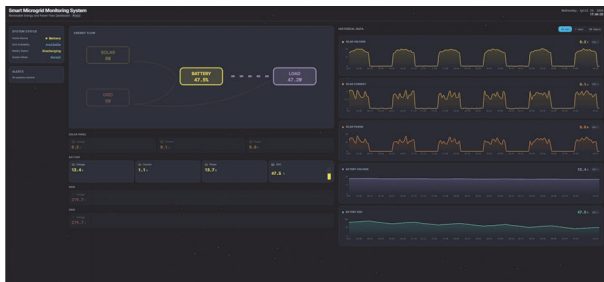


Fig. 9. Web-based dashboard showing battery active mode during low solar conditions

Fig. 9 Dashboard when the system is running on battery under low solar conditions. It was observed that at night, solar power is almost zero, and the load is provided by the battery. The battery was drained to approximately 47.5

### C. Microgrid Dashboard



Fig. 10. Web-based dashboard showing microgrid (grid supply) operation during insufficient solar and battery conditions

Fig. 10 presents the grid-assisted mode operation of the microgrid during the lower voltage available for both solar and battery conditions through the web-based dashboard. Under this condition, the system switched to the grid supply directly supplying the required power (approximately 152.7 W peak) to meet the load demand and maintain system stability. The system parameters, such as voltage and current, are continuously monitored and displayed. The graphs plot the changes in the solar, battery, and load characteristics over time. This mode of operation demonstrates the ability of the system to maintain itself.

### D. IoT-Based Data Logging and Performance Analysis

The recorded system data, including solar and battery voltages and currents, load power, SOC, grid status, and power source, are presented in Table 11. These data are continuously recorded and stored in an Excel sheet through an IoT platform. The stored data help monitor system performance, analyze energy usage, and validate the effectiveness of the proposed

Time	Solar Voltage (V)	Solar current (I)	Battery voltage (v)	Battery current (I)	Load Power(W)	Battery SOC (%)	Grid Available	Active Source	Status
6:00	10.5	0.8	12.5	2	25	70	Yes	Solar + Battery	Charging
9:00	18.5	1.3	12.8	2.5	30	75	Yes	Solar	Charging
12:00	21.5	1.7	13.2	2.2	35	85	Yes	Solar	Charging
15:00	20	1.5	13.1	2	33	82	Yes	Solar	Normal
18:30	12	0.7	12.9	2.3	32	78	Yes	Solar + Battery	Normal
19:30	2	0.1	12.8	2.5	34	75	Yes	Battery	Discharging
22:00	0.0	0.0	12.6	2.4	40	70	Yes	Battery	Discharging
2:00	0	0.0	12.3	2.2	38	60	Yes	Battery	Discharging
4:00	0	0.0	11.8	2.0	35	45	Yes	Grid	Low Battery
5:30	5.0	0.3	12.0	1.8	28	50	Yes	Solar + Grid	Recovery

Fig. 11. Recorded voltage, current, and power values for solar, battery, and grid modes

IOT based smart microgrid energy management system under different operating conditions.

### E. Solar Voltage Variation with Time

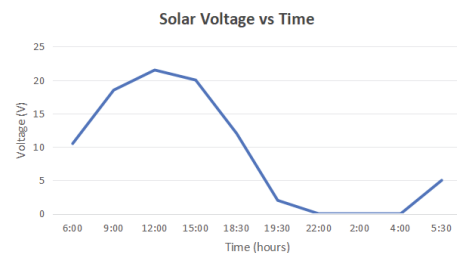


Fig. 12. Solar voltage variation with respect to time

Fig. 12. Observed change in solar voltage with respect to time. It can be seen from the graph that the voltage increases during the day due to high solar irradiance and decreases during the conditions of low sunlight. This indicates that solar power energy generation depends on environmental conditions.

### F. Battery Voltage Variation with Time

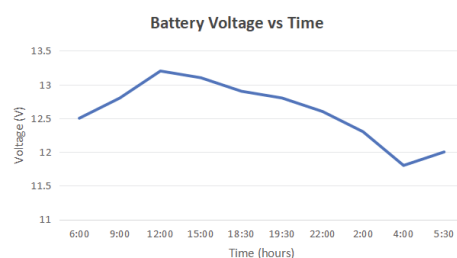


Fig. 13. Battery voltage variation with respect to time

Fig. 13 shows the variation in the battery voltage with time. The graph shows the charging behaviour during periods of solar availability and discharging under low solar conditions, indicating efficient energy use.

### G. Load Power Variation with Time

Fig. 14 shows the variation in load power with time. A stable power delivery to the load is shown in the graph, which demonstrates the reliable system performance. Small variations were observed owing to the switching between the energy sources.

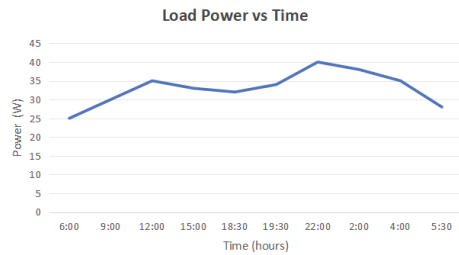


Fig. 14. Load power variation with respect to time

## VI. CONCLUSION

In this study, we presented the design and implementation of an IoT-based Smart Microgrid Energy Management System using Arduino Nano and ESP32. The system constantly monitors the main electrical parameters and performs smart switching between solar, battery, and grid power sources. The proposed system aims to utilize of renewable energy, ensure the reliability of the power supply, and enable real time remote monitoring through a cloud-based platform. The results indicate that the system works efficiently, operates stably, and switches smoothly between energy sources. The system is generally low cost and reliable for small microgrids and improves energy efficiency. It is currently working on a DC power supply. The system is now successfully operational.

## VII. FUTURE SCOPE

The proposed system can be installed in residential, commercial, and small-scale applications to provide a reliable power supply in the future.

This system can be enhanced to provide stable power so that devices continue to function during power cuts. Fast relay switching can be further enhanced to minimize the delay and improve the overall efficiency of system components.

The present system is based on a DC power supply, but it can be extended to an AC power supply for more practical applications. In addition, a mobile or web-based application can be developed to monitor live data, such as voltage, battery status, and energy usage, in real time. This will help users to track the system easily from anywhere and observe which system is active. In general, these improvements will make the system more efficient, use - friendly, and applicable to real-world applications.

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