

AI-Based Smart Microgrid Energy Management System

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Abstract: *The AI-Based Smart Microgrid Energy Management System aims to improve energy utilization and power management using IoT and machine learning. The system integrates solar power, battery storage, and transformer supply, with an ESP32 monitoring electrical and environmental parameters. MQTT enables real-time data communication, while a web dashboard supports remote monitoring and load control. Relay-based switching manages power sources according to predefined operating conditions. An LCD displays system status, and a Python-based backend stores data and generates alerts. Machine learning is proposed for estimating battery and transformer health to support predictive maintenance. The system provides a cost-effective approach to smart energy monitoring, automated power management, and reliable microgrid operation.*

Keywords: Smart Microgrid, ESP32, IoT, Energy Management, Solar Energy, MQTT, Machine Learning, Predictive Maintenance

I. INTRODUCTION

The increasing demand for electricity has created a need for efficient energy management, reliable power supply, and improved utilization of renewable energy sources. A microgrid integrates distributed energy resources, energy storage, and controllable loads to improve power management and system reliability [1]. However, effective operation requires continuous monitoring, coordinated control, and appropriate selection of available energy sources [1], [2].

The **AI-Based Smart Microgrid Energy Management System** aims to address these requirements using the Internet of Things (IoT), embedded systems, and machine learning. The proposed system integrates solar power, battery storage, and transformer supply. An ESP32 microcontroller monitors electrical and environmental parameters, while MQTT supports communication between the monitoring hardware and the software platform.

Previous research has demonstrated the application of ESP32-based monitoring and IoT communication in energy management systems [2].

A web-based dashboard provides remote monitoring and load-control functions, while relay-based switching manages power sources according to predefined operating conditions. An LCD displays system information locally, and a Python-based backend stores historical data and generates alerts. IoT-based monitoring and intelligent data analysis are recognized as important approaches for developing advanced microgrid management systems [2], [3].

Weather-related sensor readings can provide additional environmental information for energy-management decisions. Furthermore, machine-learning techniques are proposed to assess battery and transformer health and support predictive maintenance. Recent research reviews highlight the potential of combining IoT, artificial intelligence, and data-driven techniques to improve the monitoring, management, and maintenance of energy systems [3], [4].

The proposed system combines renewable energy monitoring, automated power management, remote accessibility, and predictive maintenance within a unified platform. Its objective is to provide a practical and scalable approach to intelligent microgrid monitoring and energy management. The effectiveness of the predictive maintenance functions will depend on the availability of suitable historical data and validation of the selected machine-learning models.



II. PROBLEM STATEMENT

Conventional energy management systems often face challenges in monitoring multiple power sources, managing loads efficiently, and identifying equipment problems at an early stage. The lack of integrated real-time monitoring and automated control can make it difficult to manage solar energy, battery storage, and grid supply effectively.

Therefore, the problem is to develop an **AI-Based Smart Microgrid Energy Management System** that monitors electrical and environmental parameters, automatically manages power-source switching, and provides remote access through an IoT-based dashboard. The system also aims to generate alerts during abnormal operating conditions and explore machine-learning-based estimation of battery and transformer health to support timely maintenance and improve the reliability of microgrid operation.

III. OBJECTIVES

- To develop an IoT-based system for real-time monitoring of electrical and environmental parameters in a smart microgrid.
- To integrate solar power, battery storage, and transformer supply for effective energy management.
- To implement automatic power-source selection and relay-based load control according to predefined operating conditions.
- To provide remote monitoring and control through a web-based dashboard using MQTT communication.
- To display important system parameters and operating status on an LCD.

IV. LITERATURE SURVEY

The integration of renewable energy sources, IoT technologies, and artificial intelligence has become an important research area in smart microgrids. Previous studies have investigated energy management, real-time monitoring, intelligent control, and equipment maintenance. The following literature review summarizes relevant research and its connection to the proposed system.

Albarakati et al. (2022): Microgrid Energy Management and Monitoring Systems

Albarakati et al. presented a comprehensive review of microgrid energy management and monitoring techniques. Their study examined different control methods and monitoring approaches used to coordinate distributed energy resources. The review highlights the importance of reliable monitoring and coordinated energy management for improving microgrid operation. These findings provide a foundation for integrating solar generation, battery storage, and grid supply into a common monitoring system [1]. <Cite refs={"turn662395search5"}/>

Joshi et al. (2023): AI and Machine Learning for Microgrid Energy Management

Joshi et al. reviewed conventional and artificial-intelligencebased techniques for microgrid energy management. Their research considered centralized, decentralized, and distributed management approaches. The study discussed the potential of machine learning to improve resource utilization and support adaptive energy-management decisions. This work is relevant to the proposed project because it motivates the use of data-driven techniques alongside predefined source-switching rules [2]. <Cite refs={"turn662395search11"}/>

Arévalo et al. (2024): Artificial Intelligence for Microgrid Optimization

Arévalo et al. investigated the application of emerging technologies and artificial intelligence to microgrid operation. Their systematic review covered reinforcement learning, multi-agent systems, predictive modelling, energy storage, and optimization algorithms. The authors also identified challenges associated with real-time implementation and the coordination of distributed energy resources. These findings support the need for a system that combines monitoring, source management, and intelligent analysis [3]. <Cite refs={"turn662395search8"}/>

4. Negi et al. (2025): Digitalization of Microgrids Using IoT Negi et al. examined the role of IoT, cloud computing, bigdata technologies, artificial intelligence, and machine learning in modern microgrids. Their review explained how real-time and historical data can support system operation, management, and maintenance. This research is relevant to the proposed ESP32-



based platform, which uses MQTT communication, a Python backend, historical data storage, and a web dashboard for monitoring and control [4]. <Cite refs={"turn662395search6"}/>

V. ARTIFICIAL INTELLIGENCE FOR MICROGRID DESIGN, CONTROL, AND MAINTENANCE (2025)

A 2025 review published in *Energy Conversion and Management: X* examined AI applications in microgrid design, control, and maintenance. It discussed equipment condition monitoring, fault diagnosis, and prognosis, along with the integration of IoT and other digital technologies. The study supports investigating machine-learning methods for battery and transformer health assessment. However, reliable predictions require suitable operating data and validation of the selected models [5]. <Cite refs={"turn662395search0"}/>

[1] Literature comparison

Ref.	Research focus	Key relevance to the proposed system
[1]	Microgrid monitoring and energy management	Coordination of energy resources
[2]	AI-based energy management	Intelligent decision making
[3]	AI and optimization techniques	Improved management of distributed resources
[4]	IoT and microgrid digitalization	Remote monitoring and data communication
[5]	AI-based control and maintenance	Equipment-health assessment and fault diagnosis

VI. WORKING OF SYSTEM

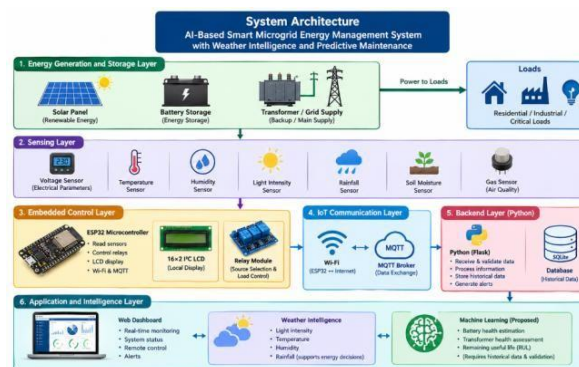


Fig 1: System Architecture

System Initialization

When the system is powered on, the ESP32 initializes the connected sensors, LCD, relay interfaces, and communication services. It establishes a Wi-Fi connection and connects to the MQTT broker to enable data exchange with the monitoring application.

Data Acquisition and Monitoring

The ESP32 collects electrical and environmental information using the connected sensors. These measurements include voltage, temperature, humidity, light intensity, rainfall, soil moisture, and gas-related readings, depending on the installed sensor configuration. The controller processes the sensor readings and determines the operating status of the system.

Energy Source Management

The system considers solar energy availability, battery charge level, and transformer supply status to manage the available power sources. Based on the programmed decision rules, the controller operates relays to select the appropriate source and control individual loads. This approach supports automated switching according to predefined



conditions. 4. Local Display and IoT Communication The LCD displays important system information, such as operating status and selected parameters. Simultaneously, the ESP32 transmits monitoring data to the backend through MQTT over Wi-Fi. Control commands received from the web application can be processed by the controller, which operates the corresponding relays and sends status updates. 5. Backend Processing and Data Storage

The Python-based backend receives incoming data, validates the received parameters, and stores historical records in an SQLite database. A web dashboard presents the available measurements and system status to the user. When monitored values cross configured limits, the backend can generate alerts to indicate abnormal operating conditions.

Weather-Based Energy Management

Environmental readings provide information about conditions that may influence solar-energy availability. Light intensity and other available weather-related measurements can be used as supporting inputs for energymangement decisions. The usefulness of these inputs depends on the installed sensors and the decision logic implemented in the controller.

Predictive Maintenance

Historical operating data can be processed using machinelearning techniques to estimate battery and transformer health. The proposed predictive-maintenance function aims to identify potential deterioration and indicate when inspection or servicing may be required. The reliability of these predictions depends on the quality of the dataset, the selected model, and experimental validation.

Continuous Monitoring and Control

The system repeatedly acquires sensor readings, updates the display, communicates with the backend, evaluates operating conditions, and executes control actions. This continuous process enables centralized monitoring, remote supervision, and automated energy-source management within the microgrid.

VII. SYSTEM DESIGN

1. System Overview

The proposed AI-Based Smart Microgrid Energy

Management System integrates solar power, battery storage, and transformer/grid supply for efficient energy management. An ESP32 monitors electrical and environmental parameters and controls relays according to predefined conditions. Wi-Fi and MQTT enable communication with a Python Flask backend, which stores data in an SQLite database and provides alerts through a web dashboard. Weather-related measurements support energy-management decisions, while machine learning is proposed for battery and transformer health assessment and predictive maintenance.

2. Components Used in the Project

1 ESP32 Microcontroller



Fig 2: ESP32

The main controller that reads sensor data, controls relays, and communicates with the dashboard using Wi-Fi.



2. Solar Panel



Fig 3: Solar Panel

Converts sunlight into electrical energy for the microgrid.

3. DS18B20 Temperature Sensor



Fig 4: DS18B20 Temperature Sensor Measures temperature for equipment and environmental monitoring.

4. DHT11 Sensor

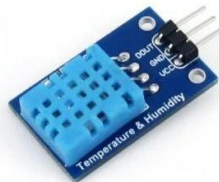


Fig 5: DHT11 Sensor

Measures ambient temperature and relative humidity..

5. LDR Sensor



Fig 6: LDR Sensor

Detects light intensity to help assess surrounding light conditions.

6. Rain Sensor



Fig 7: Rain Sensor

Detects the presence of water or rainfall on its sensing surface.



7. Soil Moisture Sensor

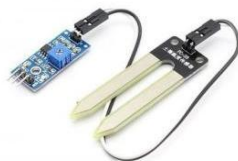


Fig 8 : Soil Moisture Sensor Measures soil moisture and provides additional environmental data..

8. MQ-6 Gas Sensor



Detects combustible gases, particularly LPG-related gases, in the surrounding air.

9. 16×2 I²C LCD Display



Fig 10 : 16×2 I²C LCD Display

Displays selected sensor readings and the current system status..

10. Web-Based User Interface

The web interface provides control buttons for movement and gripper actions. It allows users to operate the robot easily through any web browser.

VII. MATHEMATICAL EQUATIONS

1. Load Power Calculation

Power consumed by the load is calculated as:

$$P = V \times I$$

Assume load voltage = 12 V and current = 2 A

$$\begin{aligned} &= 12 \times 2 \\ &= 24 \text{ W} \end{aligned}$$

2. Solar Energy Calculation

Energy generated by a solar panel is calculated as:

$$E = P \times t$$

Assume solar panel power = 100 W and sunlight duration =

$$\begin{aligned} &4 \text{ hours} \\ &= 100 \times 4 \\ &= 400 \text{ Wh} \end{aligned}$$

3. Battery Energy Calculation

Battery energy is calculated as:

$$E = V \times Ah$$

Assume battery voltage = 12 V and capacity = 7 Ah

$$\begin{aligned} &= 12 \times 7 \\ &= 84 \text{ Wh} \end{aligned}$$

Usable energy at 80% efficiency:

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$$= 84 \times 0.80$$

$$= 67.2 \text{ Wh}$$

4. Battery Backup Calculation

Backup time is calculated as:

$$\text{Backup Time} = \text{Usable Battery Energy} / \text{Load Power}$$

$$= 67.2 / 24$$

$$= 2.8 \text{ hours (168 minutes)}$$

5. Voltage Sensor Calculation

The output voltage of a voltage divider is calculated as:

$$V_{out} = V_{in} \times R_2 / (R_1 + R_2)$$

Assume $V_{in} = 24 \text{ V}$, $R_1 = 100 \text{ k}\Omega$ and $R_2 = 10 \text{ k}\Omega$

$$= 24 \times 10 / (100 + 10)$$

$$= 240 / 110$$

$$= 2.18 \text{ V}$$

6. Battery Percentage Calculation

Battery percentage can be estimated using the measured battery voltage and the selected battery's voltage range:

$$\text{Battery \%} = (V_{\text{measured}} - V_{\text{min}}) / (V_{\text{max}} - V_{\text{min}}) \times 100$$

Assume $V_{\text{measured}} = 12 \text{ V}$, $V_{\text{min}} = 10.5 \text{ V}$ and $V_{\text{max}} =$

$$12.6 \text{ V}$$

$$= (12 - 10.5) / (12.6 - 10.5) \times 100$$

$$= 1.5 / 2.1 \times 100$$

$$= 71.43\% \text{ (estimated)}$$

7. Temperature Monitoring

The temperature difference from a selected safety limit is calculated as:

$$\text{Temperature Margin} = \text{Maximum Allowed Temperature} - \text{Measured Temperature}$$

Assume maximum allowed temperature = 60°C and measured temperature = 45°C

$$= 60 - 45$$

$$= 15^\circ\text{C}$$

The system can generate a warning when the measured temperature reaches the configured safety threshold.

8. System Reliability Calculation

System reliability can be estimated from repeated successful tests:

$$\text{Reliability} = \text{Successful Tests} / \text{Total Tests} \times 100$$

Assume 95 successful tests out of 100 tests

$$= 95 / 100 \times 100$$

$$= 95\%$$

VIII. RESULTS

The proposed AI-Based Smart Microgrid Energy Management System provides a framework for monitoring solar power, battery storage, and grid supply through an ESP32-based controller. Sensor readings are communicated to a Python-based backend using MQTT and displayed on an LCD and web dashboard. The system supports relaybased power-source control, environmental monitoring, data storage, and alerts when configured operating limits are exceeded. Historical data can also be used to develop machine-learning models for battery and transformer health prediction. The system aims to improve energy monitoring and power management; its actual performance and prediction accuracy must be confirmed through experimental testing.



IX. CONCLUSION

The AI-Based Smart Microgrid Energy Management System Maintenance combines IoT technology, sensor monitoring, and automated power control to manage solar energy, battery storage, and grid supply. The ESP32 collects system data, while MQTT and a web dashboard support remote monitoring and communication. Relay-based switching, environmental monitoring, data storage, and alert generation help improve energy management and system supervision. In addition, historical data can support future machinelearning models for predicting battery and transformer health. The proposed system provides a foundation for smarter and more reliable microgrid operation, with its overall effectiveness to be confirmed through practical testing and performance evaluation.

X. FUTURE SCOPE

The proposed system can be improved by integrating advanced machine-learning algorithms to predict battery performance, transformer faults, and maintenance requirements more accurately. Weather forecasting can be incorporated to estimate solar power generation and optimize battery charging and load distribution. Mobile application support, cloud storage, and additional sensors can enhance remote monitoring and system accessibility. Future development may also include real-time energy consumption analysis, improved fault detection, and automatic load prioritization during power shortages. These improvements could make the system more efficient, reliable, and suitable for larger microgrid applications

REFERENCES

1. J. Albarakati et al., "Microgrid Energy Management and Monitoring Systems: A Comprehensive Review," *Frontiers in Energy Research*, vol. 10, Art. no. 1097858, 2022.
2. "Design and Implementation of an Energy Management System Based on Distributed IoT," *Computers & Electrical Engineering*, vol. 109, Art. no. 108775, 2023.
3. P. Arévalo, D. Ochoa-Correa, and E. Villa-Ávila, "Optimizing Microgrid Operation: Integration of Emerging Technologies and Artificial Intelligence for Energy Efficiency," *Electronics*, vol. 13, no. 18, Art. no. 3754, 2024.
4. S. Negi et al., "Microgrids 4.0: Digitalization of Microgrid with IoT and Recent Technology Interventions," *IET Communications*, vol. 19, no. 1, Art. no. e12864, 2025.
5. "Artificial Intelligence for Microgrids Design, Control, and Maintenance: A Comprehensive Review and Prospects," *Energy Conversion and Management: X*, vol. 27, Art. no. 101056, 2025.
6. A Banks and R. Gupta, "MQTT Version 3.1.1," OASIS Standard, 2014.
7. Espressif Systems, *ESP32 Series Datasheet*, Espressif Systems.
8. Espressif Systems, *ESP-IDF Programming Guide*, Espressif Systems.
9. Python Software Foundation, *Python Documentation*, Python Software Foundation.
10. Pallets Projects, *Flask Documentation*, Pallets Projects.
11. SQLite Consortium, *SQLite Documentation*, SQLite.
12. Scikit-learn Developers, *Scikit-learn: Machine Learning in Python—User Guide*, Scikit-learn.
13. A K. S. Sayed et al., "Artificial Intelligence Applications in Smart Grids: A Review," relevant publication details to be verified before citation.
14. International Energy Agency, *Renewables 2024: Analysis and Forecast to 2030*, IEA, 2024.
15. National Renewable Energy Laboratory, *Microgrids and Distributed Energy Resources*, NREL.
16. IEEE Standards Association, *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, IEEE Std 1547-2018.
17. IEEE Standards Association, *IEEE Standard for the Specification of Microgrid Controllers*, IEEE Std 2030.7-2017.



18. DS18B20 Programmable Resolution 1-Wire Digital Thermometer, Analog Devices/Maxim Integrated, Datasheet.
19. DHT11 Temperature and Humidity Sensor, Aosong Electronics, Datasheet.
20. HiveMQ, *MQTT Essentials: A Comprehensive Guide to MQTT*, HiveMQ Technical Documentation.

