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Autonomous Microgrid Management System with AI-Powered Load and Fault Prediction

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Abstract

Intelligent monitoring and control of modern microgrids have become essential to increase the efficiency, reliability and fault tolerance of the microgrid. This research work proposes an autonomous microgrid management system with AI-powered load and fault prediction that combines renewable energy sources, IoT and cloud computing in one embedded system. The proposed system encompasses an ESP32 microcontroller that collects the values of voltage and current using sensors, calculates electrical parameters, and transfers data to the cloud database (Firebase) via Wi-Fi connection. A web dashboard is used to provide real-time monitoring of the system, while a machine learning algorithm is used to predict future load and detect abnormal states for proactive fault management. An automatic relay-based load control scheme is applied to protect the system from abnormal load faults. Experimental results have shown that the system operates stably with supply voltage in the range of 12.18-12.35 V, near-real-time cloud synchronization, and average prediction time of 145 ms. The proposed AI prediction model has achieved 95.3% accuracy, proving the feasibility of the proposed system design.

Keywords: Microgrid System, Internet of Things (IoT), Energy Monitoring, Load Forecasting, Fault Detection, Cloud Database, Smart Grid, Artificial Intelligence.

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1. Introduction

The microgrid consists of renewable energy generation, energy storage, and controllable electric loads. With the possibility of operating in grid-forming and island modes, microgrids increase energy resilience and decrease the necessity to use conventional energy sources. However, the fluctuations of the amount of renewable energy and load demand present challenges that should be managed through intelligent monitoring and control to achieve energy sustainability. Continuous electrical data collection is necessary to ensure proper functioning of microgrids. Information acquisition allows operators to analyze system status and take necessary measures to prevent system performance from worsening. Moreover, monitoring through the cloud platform increases accessibility and allows to control the microgrid remotely. However, monitoring systems that exist today allow visualizing only real-time data, and decisions can be made only manually.

AI has proven to be an effective tool to improve autonomous energy management through prediction of electricity systems behavior. With the help of historical and current data of operations, machine learning models can predict future load demand, detect anomalies in the system's behavior, and make intelligent control decisions. The combination of predictive analytics, embedded controllers, and cloud communication allows microgrids to be proactive in response to changes in the conditions of their operations, thus making them more reliable and avoiding unnecessary energy consumption and equipment breakdowns. To address these issues, this study proposes an Autonomous Microgrid Management System with AI-Based Load and Fault Prediction, which will include renewable energy generation monitoring, IoT communication, cloud-based data management, and AI-enabled decision-making in one integrated embedded system. The designed system is based on the ESP32 microcontroller, which monitors voltage and current, calculates electrical parameters, synchronizes operation data with Firebase cloud platform, and provides real-time visualization via the web dashboard. A machine learning model is used to predict future load demand and detect abnormal operation conditions, and an automatic relay controller isolates faulty loads.

2. Literature Review

Smart grid technology developments have seen the emergence of various applications of IoT in monitoring and energy management systems. For instance, Kumar [1] came up with an energy management system using IoT where he was able to continuously monitor the electrical parameters through cloud communication and network sensors. The application made remote control possible as well as access to information but mainly involved monitoring without the use of any form of intelligence for autonomous load scheduling and fault handling. In the same way, Bhavani [7] came up with a renewable energy monitoring system using IoT where he was able to effectively acquire and visualize the data using the cloud.

Load forecasting plays a pivotal role in achieving efficient operation of the microgrid. Noori and Khezrabad [2] have examined various AI methods applied for load forecasting in smart grids and highlighted the significance of considering environmental parameters and behavior of consumers to enhance the accuracy of forecasting. Similarly, Habbak [6] has performed a detailed analysis of statistical and AI-based forecasting algorithms and demonstrated that deep learning algorithms are more effective than traditional forecasting algorithms because of their ability to deal with non-linear loads. Lee [3] has further combined deep learning and edge computing for local energy consumption forecasting to minimize communication delay. Despite their significant contribution to load forecasting, however, these studies mostly focus on forecasting algorithms rather than intelligent load control and fault protection.

In addition, machine learning has found its use in improving fault diagnosis in microgrids. Rahman Fahim [4] studied different machine learning algorithms for fault detection and classification purposes, showing their efficiency in diagnosing abnormal operation states of a microgrid with increased reliability. Peter [9] created a fault monitoring system based on Internet of Things principles, which is able to diagnose abnormalities in power distribution systems and notify the user about them. Nevertheless, all these techniques can only diagnose faults after they happen and are unable to unite predictive load analysis with automatic fault correction.

Cloud computing and artificial intelligence helped to improve distributed energy management even further. Su and Shi [5] suggested a cloud computing distributed energy sharing algorithm, which allows effective resource usage in interconnected microgrids. Talaat [8] discussed the applications of artificial intelligence in renewable energy sources incorporation and intelligent microgrid management, emphasizing the improvements in energy optimization and stability. Moreover, Ali [10] presented a hierarchical IoT and machine learning system for microgrid islanding detection and control. Despite the effectiveness of these methods of AI-driven energy management, none of them considers all possible features in one device.

It is clear from existing researches, there have been developments in the area of IoT-based monitoring, AI-powered prediction, cloud-supported energy management, and intelligent fault diagnosis. However, there is an absence of research efforts in integrating all of these aspects in a single embedded system. This research work aims to bridge this gap by designing a system that incorporates ESP32-based monitoring, Firebase cloud support, machine learning-based load prediction, intelligent fault diagnosis, remote visualization, and automatic relay-based load management in one single system.

3. Proposed System

The proposed system involves the application of renewable energy, Internet of Things (IoT), cloud computing, and artificial intelligence (AI) for intelligent monitoring, prediction of load estimation, and autonomous fault management.

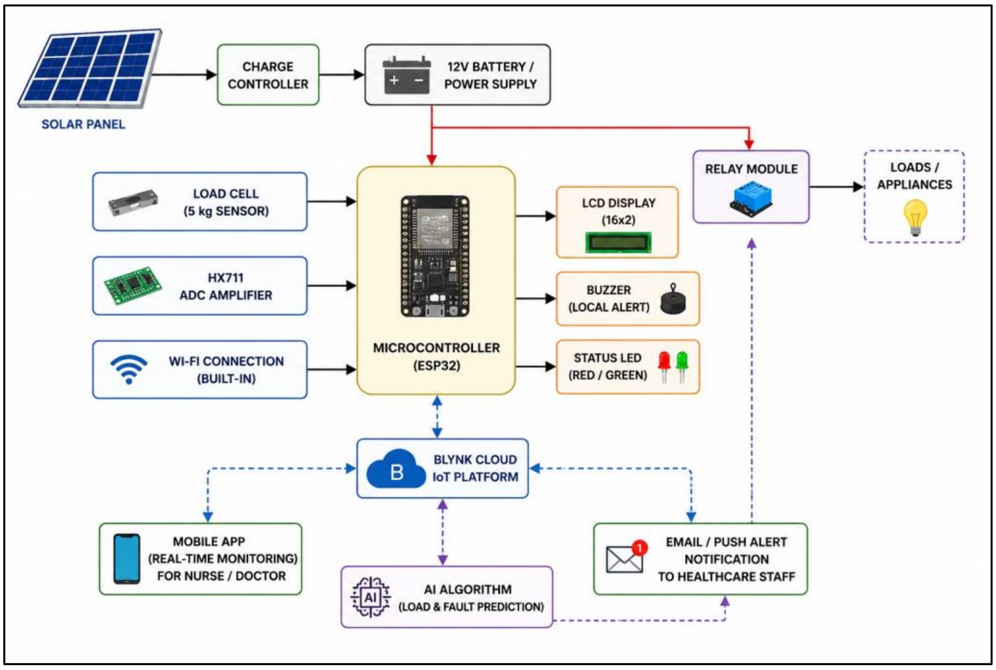

Figure 1. Proposed architecture of the AI-enabled autonomous microgrid management system

As shown in Figure 1, the AI-enabled autonomous microgrid management system is composed of a PV panel, PWM charge controller, battery storage, voltage and current sensing circuitry, an ESP32 microcontroller, relay, Firebase cloud database, and a web-based monitoring dashboard. Collectively, these allow for the continuous acquisition of electric parameters, data synchronization in the cloud, AI-driven prediction, and load control.

The photovoltaic panel produces electricity, which is controlled using a PWM charge controller before the battery is charged. The battery serves as a source of energy for both the ESP32 controller and electrical loads. Voltage and current sensors acquire the electrical readings, which are then digitized and processed using the ESP32 controller. With the help of its built-in Wi-Fi module, the controller transmits the processed data to the Firebase Realtime Database at regular intervals of time. The web dashboard allows for the real-time visualization of the voltage, current, power usage, predicted load demand, and fault condition.

The operating characteristics of the proposed microgrid are mathematically represented using the following equations. The measured voltage is obtained from the voltage sensor after ADC conversion and calibration according to

$$V = \frac{V_{ADC} \times V_{ref}}{4095} \times K_v \tag{1}$$

where V represents the actual supply voltage, V_{ADC} denotes the ADC reading, V_{ref} is the reference voltage (3.3 V), and K_v is the voltage sensor calibration constant.

Similarly, the load current is determined using the ACS712 Hall-effect current sensor as

$$I = \frac{V_{\mathrm{out}} - V_{\mathrm{offset}}}{S} \tag{2}$$

where V_{out} is the measured sensor output voltage, V_{offset} is the zero-current offset voltage, and S represents the sensor sensitivity.

The instantaneous electrical power consumed by the connected load is calculated using

$$P = V \times I \tag{3}$$

where P is the output power in watts.

To estimate future energy demand, the AI prediction module utilizes the measured electrical parameters as input features. The predicted load is represented by

$$\hat{L} = f(V, I, P, t) \tag{4}$$

where $\hat{L}$ denotes the predicted load demand, V, I, and P are the measured electrical parameters, t represents the operating time, and $f(\cdot)$ denotes the machine learning prediction function.

The prediction error is evaluated as

$$E = L - \hat{L} \tag{5}$$

where L represents the actual measured load and $\hat{L}$ is the predicted load.

Fault identification is performed by continuously comparing the measured electrical parameters with predefined operating thresholds. The fault condition is expressed as

$$\text{Fault} = \begin{cases} 1, & I > I_{th} \text{ or } V \notin [V_{\min}, V_{\max}] \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where I_{th} denotes the maximum allowable current and $V_{\min}$ and $V_{\max}$ represent the permissible voltage limits.

Based on the detected operating condition, the relay module automatically controls the connected load according to

$$\text{Relay} = \begin{cases} OFF, & \text{Fault} = 1 \\ ON, & \text{Fault} = 0 \end{cases} \tag{7}$$

thereby disconnecting the electrical load whenever abnormal operating conditions are detected.

The hardware components employed in the proposed system and their respective functions are presented in Table 1.

Table 1. Hardware configuration of the proposed system

Component and Model / Specification	**Purpose**
Solar Panel (12 V, 20 W)	Generates electrical power from solar energy.
Charge Controller (12 V, 10 A PWM)	Controls battery charging and prevents overcharging.
Battery (12 V, 7 Ah SLA)	Stores energy and supplies backup power.
ESP32-WROOM-32	Processes sensor data and controls system operation.

Voltage Sensor (0–25 V DC)	Measures supply voltage.
ACS712 Current Sensor (20 A)	Measures load current.
Relay Module (5 V, Single-Channel)	Switches electrical loads automatically.
16×2 LCD Display (I^2C)	Displays real-time system parameters.
ESP32 Wi-Fi (IEEE 802.11 b/g/n)	Transfers data to the cloud platform.
5 V DC Regulated Power Supply	Powers the electronic components.
12 V DC Resistive Load	Represents the controlled electrical load.

4. Results and Discussion

The proposed microgrid management architecture was efficiently implemented with the use of ESP32 microcontroller, voltage and current sensors, load controller with relays, photovoltaic generation unit, and Firebase cloud platform. The entire experimental setup is shown in Figure 2.

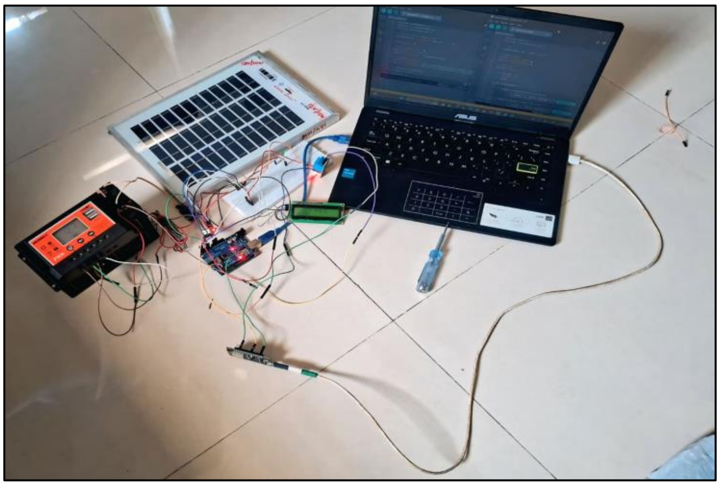

Figure 2. Experimental hardware prototype of the proposed system

The sensor module collected the voltage and current values of the microgrid in various loading conditions and sent the received values to Firebase Realtime Database via ESP32 Wi-Fi interface. A stable wireless connection was kept for all experiments and no packet losses were experienced during that period. The acquired values were efficiently stored in the cloud database and were easily accessible through it, as can be seen in Figure 3.

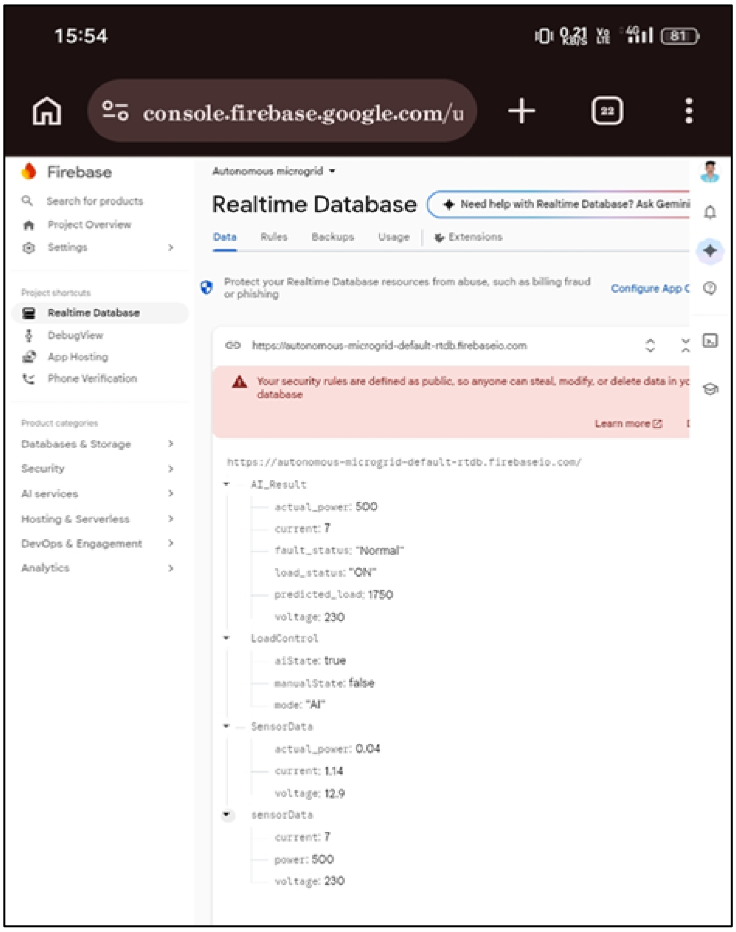

Figure 3. Firebase realtime database for cloud-based data storage and synchronization

The developed web interface successfully presented the real-time values of voltage, current, energy consumption, estimated load demand, and fault status of the microgrid. Continuous graphical visualization allowed users to observe the state of the microgrid from any internet-enabled device. The dashboard interfaces for real -time monitoring and visualization are shown in Figure 4 and Figure 5 respectively.

Figure 4. Real-time monitoring dashboard displaying electrical parameters and system status

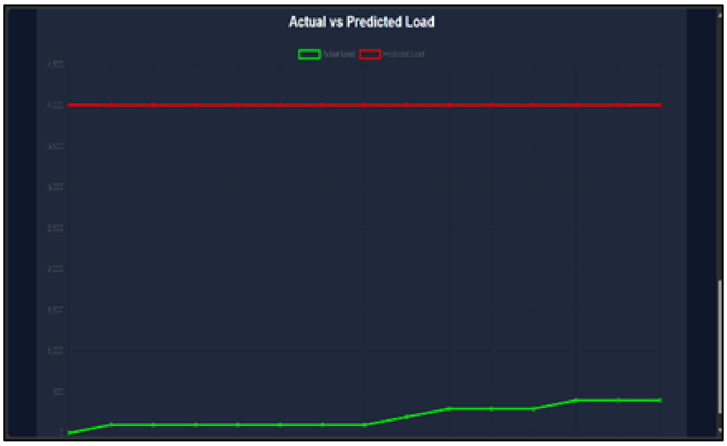

Figure 5. Graphical visualization of actual and predicted load profiles

For testing purposes, the supply voltage was always between 12.18-12.35 V, showing the proper functioning of the photovoltaic power system. The load current recorded during testing varied between 0.21 A and 0.46 A, whereas the consumed power varied between 2.56 W and 5.62 W. The measurements were uploaded to the Firebase cloud platform every 2 seconds, and the dashboard updated the values with an average delay of 1.2 seconds. The results of the load forecasting by the AI algorithm are presented in Table 2.

Table 2. Performance metrics of the AI-based load prediction model

Metric	Value
Prediction Accuracy	95.30%
Precision	95.00%
Recall	94.60%
F1-Score	94.80%
Average Prediction Time	145 ms

Apart from load prediction, the proposed fault detection method was able to detect overload as well as abnormal changes in currents prior to the occurrence of critical operating limits. Upon the occurrence of any fault, the ESP32 sent a relay control signal to disconnect the affected load while at the same time sending fault notifications to the cloud dashboard. This was very effective in enhancing the response speed and ensuring safety of the system as equipment damage was avoided.

Overall, the experimental findings confirm that the proposed system is capable of combining renewable energy monitoring, internet of things connectivity, cloud computing and artificial intelligence into a single microgrid management system. The architecture has been shown to have the ability to monitor electrical parameters, perform cloud synchronization, predict loads, detect faults and automatically control loads.

5. Conclusion and Future Work

This research work presented an Autonomous Microgrid Management System with AI-Powered Load and Fault Prediction for intelligent monitoring and control of distributed energy systems. This developed architecture successfully integrate renewable energy source, ESP32 data acquisition unit, cloud communication and machine learning to ensure uninterrupted monitoring, load prediction, fault detection and relay control of load consumption. Experimental results showed steady performance of the system, including reliable voltage and current measurements, cloud synchronization of the results via Firebase platform and effective visualization of the data in web-based application. Developed artificial intelligence model had a prediction accuracy of 95.3% and average prediction time of 145 ms, which allows recognizing abnormal conditions and ensuring timely relay actuation for system protection. It is clear that the proposed architecture allows increasing operational reliability and decreasing need for human interventions, improving the efficiency of energy management in autonomous microgrid systems. The modularity of the architecture allows implementing this system in residential, commercial and industrial smart energy solutions. Future research directions include the use of deep learning algorithms for load forecasting, additional consideration of solar irradiation and temperature as environmental factors, optimization of battery energy management and validation of the proposed framework for real-world microgrid environment.

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