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RENEWABLE ENERGY MONITORING SYSTEM FOR MICROGRIDS: A COMPREHENSIVE IOT-BASED FRAMEWORK FOR SOLAR ENERGY MANAGEMENT

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Abstract: The shift in the direction of sustainable and decentralized power generation has placed solar-based microgrids as a key solution to the growing global energy demand, as well as the environmental crisis posed by the use of fossil fuels. Nevertheless, environmental intermittency and inability to have real-time access to the electrical and thermal parameters often undermine the operational effectiveness of these microgrids. The study includes the design and implementation of a combined Renewable Energy Monitoring System with the ESP32 microcontroller and Internet of Things (IoT) protocols. The architecture proposed takes advantage of the high-precision sensing units: the ACS712 Hall-effect current sensor and the voltage attenuation circuits to obtain real-time data of the system health. The framework presents a multidimensional study of the photovoltaic (PV) performance through the incorporation of environmental sensors to measure temperature and humidity. The experimental findings, visualised with the help of a specialised web-based dashboard, prove that the system can detect suboptimal operating conditions, including overvoltage or thermal stress, with a high degree of accuracy. Intelligent control and fault isolation through the addition of an automated control layer through relay modules will provide greater resilience to microgrids. This paper will give a detailed technical description of the hardware-software synergy of the system, which is an alternative to standard SCADA-based monitoring that is scalable and cost-effective in residential and rural applications.

***Index Terms* -** Renewable Energy, Internet of Things, Solar PV, Microgrids, ESP32, Power Forecasting, Fault Detection, Energy Management System (EMS).

I. INTRODUCTION

The modern energy market of the world is at a crossroads, and it is preconditioned by a twofold challenge of growing demand and a sense of urgency for carbon neutrality. Conventional centralised power systems, which depend to a great extent on exhaustible fossil fuel deposits, are becoming more and more seen as not sufficient in the future as they contribute to greenhouse gas emissions and are vulnerable to large-scale failures. Here, solar power has become a foundation of the renewable energy shift, which has been enabled through the fast development of photovoltaic (PV) technologies and a large decrease in the costs of installations. Microgrids are a disruptive concept of energy distribution, acting as a localised, autonomous power system that combines distributed energy resources (DERs), storage systems, and controllable loads. These systems have some unique benefits, such as lower loss of transmission, better quality of power and the ability to go into an islanded mode during main grid outages, which is especially crucial in remote and rural areas, where traditional grid connectivity is constrained. Although these advantages exist, solar-based microgrids have some distinctive issues due to the variability of the solar irradiance and the vulnerability of electronic components to changes in temperature and electrical stress. Building an efficient solar microgrid demands more than energy conversion, as it demands granular monitoring of the parameters of the system in real time. In the absence of real-time data acquisition, human operators can hardly detect inefficiencies like panel shading, dust agglomeration or thermal decadence. The temporal resolution and remote accessibility needed in modern energy management is absent in traditional methods of monitoring that usually involve manual data recording or semi-automated digital instruments. Although Supervisory Control and Data Acquisition (SCADA) systems of industrial grade offer high-quality monitoring, their cost and complexity are prohibitive to small-scale microgrids. Internet of Things (IoT) and embedded systems integration has also narrowed the divide between the manual system and the high-end SCADA systems. ESP32 microcontroller, which has a dual-core processor and built-in Wi-Fi/Bluetooth stack, is a perfect edge-computing node in energy systems. By interfacing the ESP32 with Hall-effect current sensors and voltage divider networks, it is possible to create a smart monitoring node that not only collects and visualises data but also executes local control logic for fault protection. This study suggests a complete Renewable Energy Monitoring System, which is specifically meant to be used in solar microgrids. The system is concerned with high-resolution data obtainability at both electrical and environmental levels, remote monitoring through cloud-based dashboards, and automated safety systems through relay modules. Using the ADC and cores in the ESP32, the system reduces the delay between fault detection and protective response, e.g. disconnect loads in overcurrent situations. The following paragraphs describe the technical procedure, hardware setup, and performance evaluation of the suggested framework.

II. RELATED WORKS

The development of monitoring technologies in the renewable energy industry has been marked by the shift from the previous state of stationary, manual observation towards an active, interconnected system. Initial efforts in monitoring the sun used analog voltmeters and ammeters, and needed the physical inspection of the equipment, which had to be done periodically by personnel. These systems were also reactive in nature in the sense that defects could only be detected during planned maintenance, thus causing a lot of downtime and wastage of energy.

Monitoring systems in the second generation made use of 8-bit microcontrollers, including the Arduino Uno (Atmega328p), to digitalize sensor measurements and show them on local LCD displays. Although this set of systems enhanced accuracy in measurements, they had shortcomings in the form of their inability to have native networking features. In order to realise remote monitoring, developers were frequently forced to add external communication devices, such as the ESP8266 or GSM shields, which added power usage and complexity to the system.

Recent developments have centred on the combination of IoT with high-performance microcontrollers such as the ESP32 and ARM-based platforms. A study conducted by Gupta and Singh highlighted how the ESP32 can be used to offer an affordable and scalable platform to monitor solar motion in real-time and assess its performance.. Equally, the Philippine setting saw research investigating the application of the IoT in the so-called active cooling of PV panels, where the thermal conditions could be monitored, and appropriate corrective measures (e.g., turning on water pumps) could be implemented to greatly enhance the energy collection during the hottest summer days.

Another emerging area is the use of Artificial Intelligence (AI) and Machine Learning (ML) in energy monitoring. Recent Energy Management Systems (EMS) take advantage of forecasting algorithms to make predictions on the next-day output of the sun given previous irradiance and temperature measurements. Modern systems use Reinforcement Learning (RL) to do clever load sharing, in which the system automatically determines what non-critical loads to discard at times when the generation is low. This study takes these fundamental works to the next level, where high-precision sensing is combined with an automated control layer to make sure that the monitoring node becomes a robust gateway to the microgrid.

III. METHODOLOGY

The approach to be used in this project is based on a systematic engineering process, which includes multi-modal sensing, edge processing, and cloud communication as part of a single architecture.

3.1 Hardware Architecture and Sensing Unit

The system architecture is based on the ESP32 microcontroller that is the main processing and communication core. The hardware layer will consist of the following modules:

Voltage Sensing Unit:

PV panels usually produce voltages (e.g. 18V - 42V) which are way beyond the 3.3V input threshold of the ESP32 GPIO pins. Two high-precision resistors (R_1 and R_2) are used to implement a voltage divider circuit. The standard divider formula is used to calculate the output voltage V_{out}:

$$V_{out} = V_{in} \cdot \left(\frac{R_2}{R_1 + R_2}\right)$$

By selecting R_1 = 47kΩ and R_2 = 6.8kΩ the system can scale down a 24V input to approximately 3V, which is safely within the ADC range.

Current Sensing Unit:

The ACS712 sensor module is used to measure DC current from the solar panel to the load. This sensor is based on the principle of Hall-effect, according to which the magnetic field is induced by the current that passes through a copper conduction path in proportion to the magnitude of the current. At zero amperes, the sensor has an analog voltage of $V_{cc}/2$ (2.5V with a 5V supply), which was centered at $V_{cc}/2$.

The current I is derived as:

$$I = \frac{V_{analog} - V_{offset}}{Sensitivity}$$

For the 5A variant, the sensitivity is 185 mV/A.

Environmental Sensing Unit:

The DHT11 sensor will be used to measure ambient temperature and humidity, and give a digital signal to the ESP32. Also, a DS18B20 digital thermal probe can be used to measure panel surface temperature, which is essential to the computation of thermal-related efficiency drops.

Control and Alert Unit:

The ESP32 is connected to a 5V relay module using a digital GPIO pin. This module is an electronically powered switch of the load. Feedback is given through a 5mm LED and a piezo buzzer as visual and audible feedback, respectively.

3.2. Communication and Visualization Layer

The ESP32 is connected to the local access point using the built-in Wi-Fi module. The information is sent to a cloud server via the HTTP or MQTT protocol. The system is set to transmit data packets every 15 seconds to maintain a tradeoff between real-time visibility and bandwidth savings. To monitor locally, an LCD based on I2C is employed, which minimises the amount of wiring needed as it requires the use of two data lines (SDA and SCL).

3.3 Block Diagram

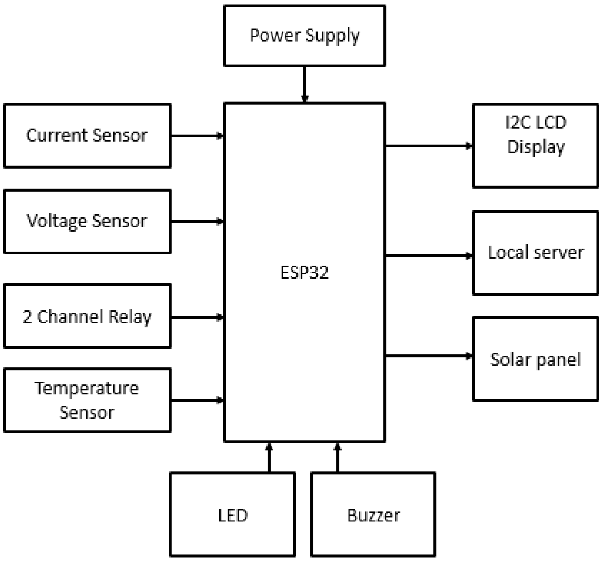


Fig 1 Block Diagram

As shown in Fig. 1, the overall system connectivity, the direction of the flow of data in the system, starting with the solar input and ending with the user dashboard. The Solar Panel is used as the source of energy, and it provides DC power to the Load via the Sensing Unit (Voltage Divider and ACS712 Current Sensor). These sensors transform physical quantities to analog signals, and these signals are handled by the ESP32 Microcontroller. Digital environmental data is also sent to the ESP32 via the DHT11/DS18B20 Sensors. According to the processed data, the ESP32 will update the I2C LCD Display to provide local monitoring and control the Relay Module to turn on the load. The Buzzer and LED are turned on in case there is a fault. At the same time, the ESP32 will be connected to the Wi-Fi Router to send the measurements to the Cloud Dashboard to be accessed remotely

IV. IMPLEMENTATION

The system implementation consists of connecting the hardware modules to a software stack written on the ESP32.

4.1. Hardware Integration

Hardware assembly is done on a standard PCB or breadboard, with high-current paths (solar panel to load) separated by low-voltage control signals to avoid electromagnetic interference (EMI). The ACS712 is connected in series to the positive line of the solar panel, with the voltage divider resistors connected in parallel to the positive and negative lines of the solar panel.

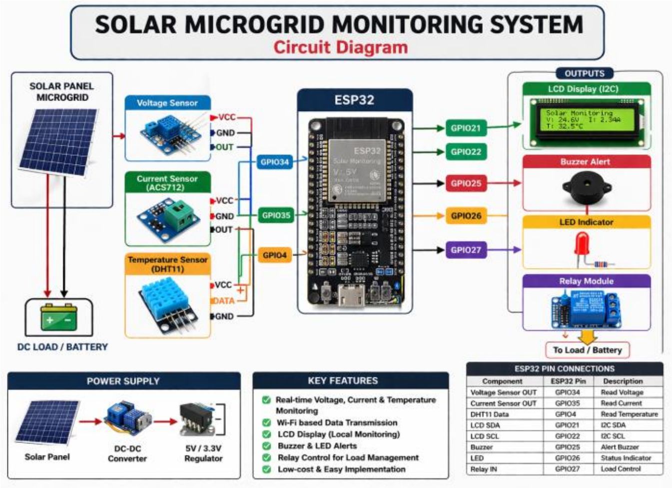
4.2 Working Principle

The system is in a continuous sensing loop. The 12-bit ADC of ESP32 averages the noises of momentary voltage and current on the analogue inputs of the voltage and current sensors by sampling the analogue inputs at 1 kHz. The calculated digital values are transformed to real Volts and Amperes through pre-calibrated linear equations. For example, the voltage sensing logic would use the ratio established by the 47kΩ/6.8kΩ divider to reconstruct the original panel voltage.

The software applies a “Threshold Logic” engine. These safety limits are stored in the non-volatile memory of the ESP32:

- Overvoltage: > 22V
- Overcurrent: > 4A
- Over temperature: > 50°C

If any sensor reading goes directly to a logic state that opens the relay, de-energizing the load. It also configures the buzzer pin to HIGH and flashes the alert LED.



- ✓ Real-time Voltage, Current & Temperature Monitoring
- ✓ Wi-Fi based Data Transmission
- ✓ LCD Display (Local Monitoring)
- ✓ Buzzer & LED Alerts
- ✓ Relay Control for Load Management
- ✓ Low-cost & Easy Implementation

ESP32 PIN CONNECTIONS

Component	ESP32 Pin	Description
Voltage Sensor OUT	GPIO34	Read Voltage
Current Sensor OUT	GPIO35	Read Current
DHT11 Data	GPIO4	Read Temperature
LCD SDA	GPIO21	I2C SDA
LCD SCL	GPIO22	I2C SCL
Buzzer	GPIO25	Alert Buzzer
LED	GPIO26	Status Indicator
Relay IN	GPIO27	Load Control

Fig 2 Circuit Diagram

As shown in Fig. 2, all components are connected according to the circuit diagram

4.3. Software Framework and Cloud Integration

The software is coded on Arduino environment in C. It has deployed WiFi.h and HTTPClient.h libraries to manage the network. The data is packaged in the form of a JSON string, which is then posted using a POST request to the cloud dashboard API endpoint.

TABLE 1 SOFTWARE TASK SCHEDULE AND FUNCTIONAL OBJECTIVES

Task	Execution Frequency	Primary Goal
Sensor Sampling	100 ms	Accurate data acquisition
Local LCD Update	500 ms	Real-time user feedback
Safety Logic Check	100 ms	Fault prevention & mitigation
Cloud Data Upload	15 seconds	Long-term logging and analysis

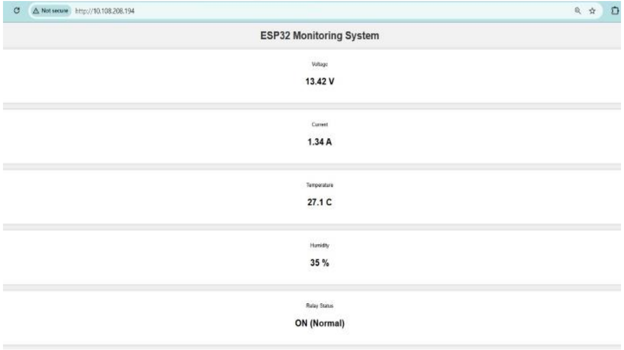
Table 1 indicates the frequency of execution of core firmware tasks. Tasks with a high priority, such as Sensor Sampling and Safety Logic Checks, are run at a minimum 100-ms interval, while tasks with a low priority, such as Cloud Data Upload, are scheduled every 15 seconds to maintain network bandwidth.

V. RESULTS AND DISCUSSION

The system that was developed was tested under various sunlight conditions and simulated load changes to measure its performance metrics, including accuracy, response time, and remote accessibility.

5.1. Performance Analysis and Output Interpretation

The monitoring interface was tested by real-time monitoring of the ESP32 web-based dashboard. The output images below represent two different operational situations.



ESP32 Monitoring System

Voltage
13.42 V

Current
1.34 A

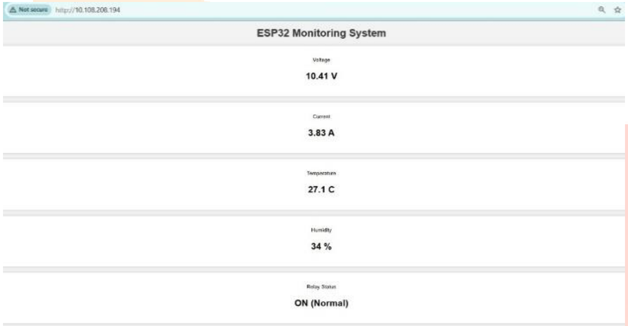
Temperature
27.1 C

Humidity
35 %

Relay Status
ON (Normal)

Fig 3 Normal Operating System

Figure 3 shows the working condition of the system at one time when it is operating optimally to generate solar power. Voltage is indicated as 13.42 V with a current reading of 1.34 A. Temperature is at 27.1 o C and Relay is ON (Normal). These readings show that the solar panel is successfully charging the system, and the load is working within safe electrical and thermal limits. The availability of these parameters visually enables users to confirm the operation of the microgrid as expected.



ESP32 Monitoring System

Voltage
10.41 V

Current
3.83 A

Temperature
27.1 C

Humidity
34 %

Relay Status
ON (Normal)

Fig 4 High Load/ Fluctuation State

Figure 4 shows a result condition with increased load or a decrease in the input voltage. The Voltage is now reduced to 10.41 V, whereas the Current is already much higher, 3.83 A, which means that the thermal stress is not critical yet. The Relay Status is still ON, indicating that the load has not exceeded the permissible threshold, but the voltage drop indicates that the system is approaching capacity or the battery is depleting. This real-time visibility plays a vital role in active energy control and avoiding the damage of sensitive loads caused by undervoltage.

5.2. Accuracy Evaluation

The sensors used in this ESP32 project were tested against a calibrated industrial-grade multimeter and clamp meter to determine their accuracy.

TABLE 2 EXPERIMENTAL VALIDATION OF SENSOR ACCURACY AND PERCENTAGE DEVIATION

Parameter	System Reading	Reference Device	Deviation (%)
Voltage (V)	13.42	13.51	0.67%
Current (A)	1.34	1.31	2.29%
Temperature (°C)	27.1	27.3	0.73%
Humidity (%)	35.0	34.2	2.34%

Table 2 shows that the result of the voltage sensing unit has great accuracy (< 1% error), and this is necessary to detect the state of charge (SoC) of the battery. The error of the current measurement is slightly higher (2.29%) because of the noise in the Hall-effect sensor and the non-linearity of the ESP32 ADC at the lower and upper limits. These were greatly enhanced when the sensor was calibrated with the help of the linear regression modelling, with the mean error between the sensor and the reference device coming to a value of approximately 0.044 units.

5.3. System Discussion

The integration of IoT technology provides a substantial improvement over traditional methods. The ability to visualize the data trends on a daily and weekly basis allows the user to detect the performance degradation due to dirt on the panels or shading by new structures. Moreover, the automated relay control makes sure that the microgrid is capable of self-recovery in case of faults without the need of human intervention, which is essential to autonomous systems in rural environments. The low power consumption (around 80mA when active) of the system is such that the monitoring infrastructure itself is not a large burden on the energy resources of the microgrid.

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