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An Efficient IoT Based Solar Photovoltaic System with Sun-Tracking and Power Monitoring Capabilities

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A B S T R A C T

Conventional methods of mounting solar panels, facing true north in the southern hemisphere and true south in the northern hemisphere, lead to the underutilization of available solar energy resources [1]. This is because solar panels can only convert most of the incident light energy to electrical energy when the light rays strike the panel surface perpendicularly. When the angle of incidence is not perpendicular, a significant percentage of the incident light is lost and not converted to electrical energy [2]. To address this issue, a sun-tracking mechanism was proposed to ensure that light rays from the sun always strike the solar panel surface perpendicularly throughout the day. This solution involves enabling the solar arrays to rotate along two axes: the azimuth axis and the zenith axis, ensuring the panels are always directly facing the sun. The system comprises a microcontroller connected to light-dependent resistor sensors to track light movement and two servo motors to rotate the panels accordingly. Additionally, the project includes an Internet of Things (IoT) powered remote monitoring web application. This application monitors and tracks the system's performance by displaying real-time trends of the system's parameters and historical trends through periodic data logging via power monitoring circuitry. The developed system can track the sun from dawn to dusk and maintain a communication channel with an IoT server for real-time monitoring, thus maximizing power harvest from the sun. Life-size systems can be developed using this prototype, depending on the size of the panels and specific system requirements.

Keywords: Internet Of Things (IoT), Solar photovoltaic, Solar tracking, Power monitoring, Web application

1. Introduction to the Solar PV System

Sustainable energy production is becoming a crucial part of our daily lives as it aligns with the goal of a greener, smarter, and more sustainable future. With increasing electricity demand, many thermal power stations have been established, leading to significant carbon emissions and environmental damage. Therefore, there is a need to transition to clean renewable energy sources to power homes, offices, and industries [3]. Examples of such renewable energy sources include solar energy, wind energy, and hydroelectric energy. Extensive research has been conducted to maximize and optimize power harvest from these renewable sources [4] and ensure their smart utilization.

The project presented in this paper focuses on three major sectors: optimizing the energy harvested by solar panels, monitoring the power production of the solar system, and enabling virtual remote monitoring of the entire system through the IoT initiative. Most of the solar energy reaching the Earth's surface arrives in straight lines [5]. A solar panel or array captures more energy when it is directly facing the sun, perpendicular to the incident light. To maximize energy capture, this project involves learning the sun's movement throughout the day and ensuring that the PV panels always face the sun. The project includes a feedback control system employing light-dependent resistors (LDRs) to detect the sun's movement and a controller that sends output signals to servo motors to adjust the PV panels' orientation accordingly. The IoT-based solar power monitoring and control system can measure and monitor the system's performance in real-time, logging data to a cloud database. This enables users to have an overview of the system's behaviour, keep track of performance parameters, and display them remotely on their mobile phone or personal computer.

The entire system integrates a microcontroller that receives input signals from voltage sensors, current sensors, and LDRs, performs necessary calculations, sends output signals to the servo motors, and uploads the system's data to the cloud for remote access. The project employs an IoT architecture consisting of three layers. The first layer contains peripherals responsible for sensing and actuating actions, and the controller processes input data from the sensors to produce the required output signals for the actuators and the cloud database to be displayed on the graphical user interface (GUI). The second layer is the network layer, enabling data and control signal transmission between the lower and upper layers. The final upper layer is the application layer, responsible for the GUI and cloud platform for remote access.

2. IoT-based System Design

The overall system is divided into three individual modules that are designed separately before being combined into one major system. This modular design allows precise work on each module without interfering with the others, making troubleshooting relatively easy. Figure 1 shows the basic structure of the entire system.

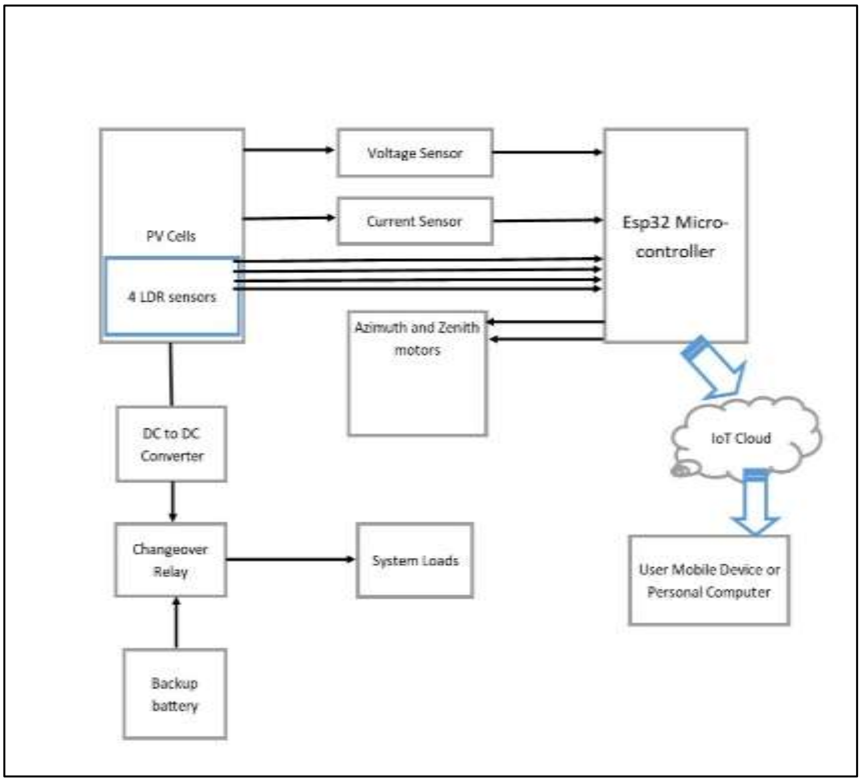

Fig. 1 Whole System Structure

2.1 Sun Tracking System Design

Module 1 in Figure 2 shows the design of both the azimuth axis circuit and the zenith axis circuit, which are crucial for enabling the dual-axis rotation of the solar panels to track the sun's movement accurately.

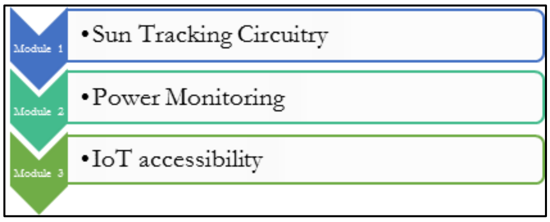

Fig. 2 Layered view of the system design.

The feedback loop for positioning the motors is shown in Figure 3. This loop ensures that the motors adjust the solar panels' orientation based on the detected light intensity differences.

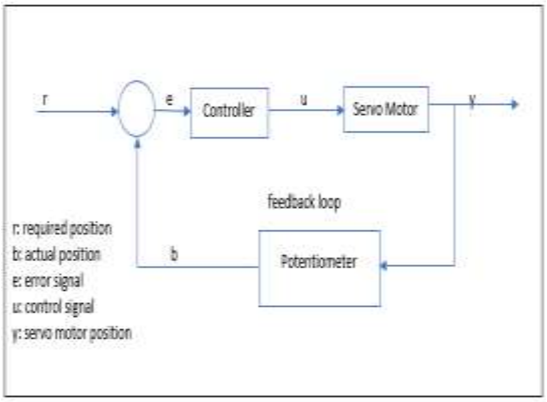

Fig. 3 Servo motor feedback loop

Figure 4 illustrates the circuit for a one-axis tracker. In this circuit, two light-dependent resistors (LDRs) are placed on opposite sides of the panel to detect differences in light intensity. When there is a difference, the system adjusts the panel's position to equalize the light intensity on both LDRs, ensuring the panel faces the sun directly.

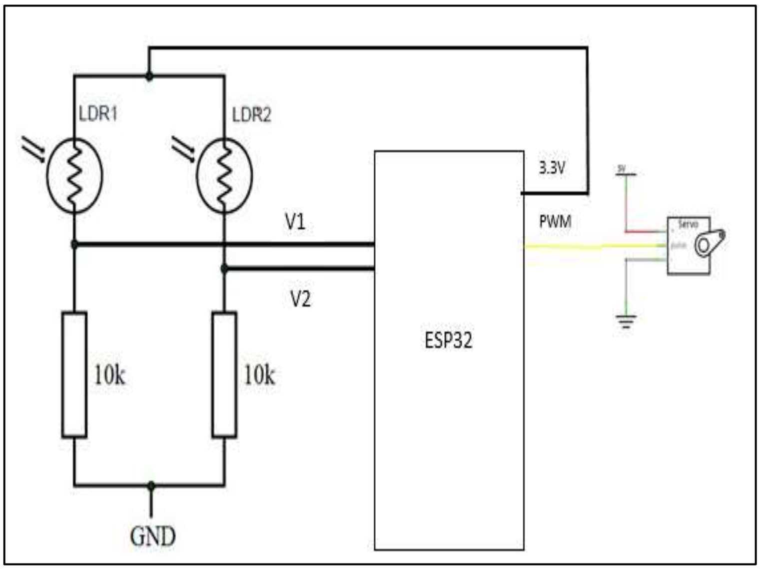

Fig. 4 Single axis control circuit

The voltages V_1 and V_2 from the LDRs are given as follows:

$$V1 = \frac{R}{R+R_{LDR}} V_{Ref} \qquad (1)$$

Where $V1 = Output\ voltage, R_{LDR} = LDR\ resistance, V_{Ref} = 3.3V$

The same expression applies for V_2. The output voltages will vary depending on the light intensity on each LDR. When one LDR receives more light, its resistance decreases, resulting in a change in the output voltage. The microcontroller compares these voltages and adjusts the servo motors to rotate the solar panel until the voltages are balanced, indicating the panel is directly facing the sun. The LDR properties, which influence the voltage output based on light intensity, are shown in Figure 5. These properties are essential for understanding how the system responds to varying light conditions and ensures accurate sun tracking throughout the day.

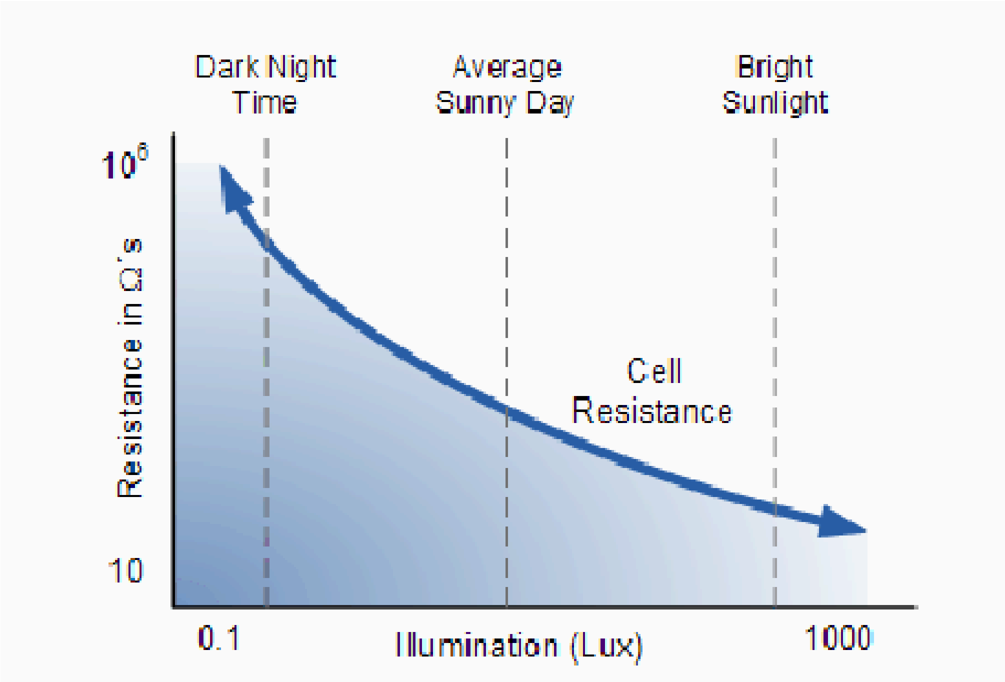

Fig. 5 LDR properties

Resistor Value Calculations

The objective is to maximize the swing between the maximum and minimum voltage that the LDR circuit inputs to the microcontroller. This swing determines the range of light intensity that the analog-to-digital converter (ADC) can process, ensuring accurate readings under various lighting conditions. The first step is to determine the maximum and minimum resistances of the LDRs within the illumination range that the solar panel will operate under. The following table shows the assumptions used in this project:

Table 1 - LDR Approximate Values

Light Intensity	**Resistance**
Bright Sunlight (approximately 10000 lux)	100Ω
Dark Night (approximately 0.1 lux)	1MΩ

Next, we model the change in the circuit output voltage (ΔV) for the different extreme values of the LDR resistance using the following equations:

$$\Delta V = V_{max} - V_{min} \quad (2)$$

$$\Delta V = \left(\frac{R}{R_{min}+R} - \frac{R}{R_{max}+R}\right)V \quad (3)$$

$$\Delta V = \left(\frac{R(R_{max}+R)-R(R_{min}+R)}{(R_{min}+R)(R_{max}+R)}\right)V \quad (4)$$

$$\Delta V = \left(\frac{R(R_{max}-R_{min})}{(R_{min}+R)(R_{max}+R)}\right)V \quad (5)$$

The next step is to determine the maximum value of the function ΔV by evaluating its derivative function and equating it to zero as shown below.

$$\frac{\partial}{\partial R}\Delta \text{V} = 0 \quad (6)$$

The equation simplifies to:

$$R_{min}R_{max} - R^2 = 0 \quad (7)$$

Therefore:

$$R = \sqrt{(R_{min}R_{max})} \quad (8)$$

The flowchart in Figure 6 illustrates the algorithm used to implement this task, showing the steps taken to calculate and optimize the resistor values for maximizing the voltage swing. By accurately determining the resistor values, we ensure the LDR circuit provides a wide and sensitive range of voltage inputs to the microcontroller, enabling precise sun tracking under varying light conditions.

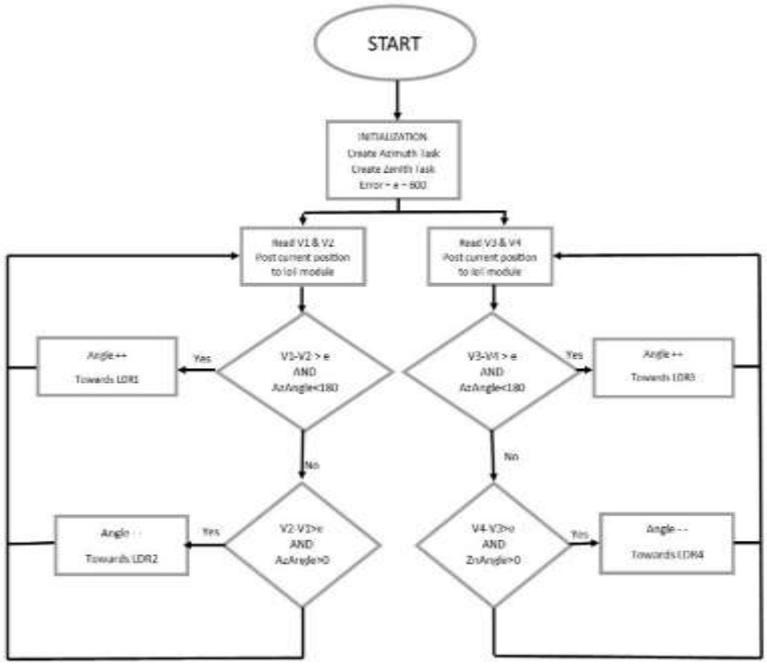

Fig. 6 Sun Tracking Algorithm

2.2 Power Monitoring Module Design

This module is dedicated to designing a power monitoring circuit for the system, focusing on monitoring the voltage and current readings from the PV array to determine power production at any given time. Its primary goal is to evaluate the performance of the solar system and record system parameters for remote monitoring. The module plays a crucial role in providing system parameters for real-time data logging, calculating, and storing the maximum voltage, minimum voltage, average power production, and total energy production (kWh) of the system. Subsequently, it transfers these parameters to the IoT module, which is responsible for pushing the data to the server database for access through the web application.

2.2.1 Power Monitoring Basic Structure

Figure 7 illustrates the basic structure of the power monitoring module implementation. The system utilizes the Acs712 current sensor to measure the current in the circuit and the voltage sensor to measure the voltage of the solar panel array at any given time. The solar array powers the system loads when sunlight is available. If the ESP32 detects that the solar array voltage is too low, it switches the changeover relay from solar input to backup battery input. The step-down DC-DC converter is then used to convert the varying input DC to a stable 5V DC for the connected loads, ensuring uninterrupted power supply even under challenging conditions.

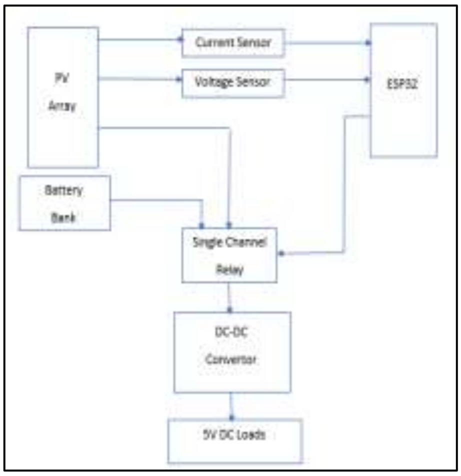

Fig. 7 Power Monitoring Structure

2.2 2 System Data Logging

The Power Monitoring Module is responsible for providing the IoT module with data logging parameters periodically so that the data can be stored in the database for historical details of the performance of the system. Figure 8 shows the flowchart of the system that implements real-time trending power monitoring and data logging by making measurements and pushing the data it has collected to the IoT module which is responsible for posting the data to the system's cloud database.

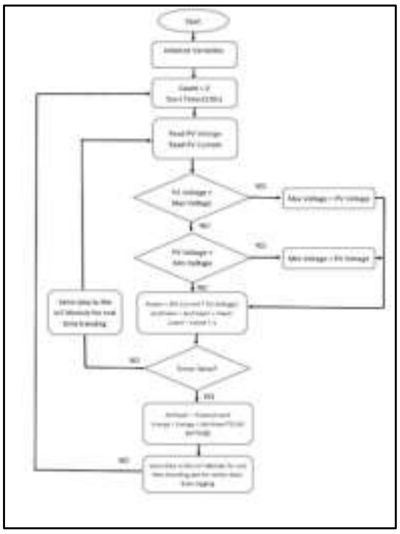

Fig. 8 Power Monitoring Algorithm

2.3 IoT Monitoring Module Design

The IoT monitoring module serves as the application layer, managing the graphical user interface (GUI) and the cloud platform for remote access. It enables communication with the IoT cloud, providing remote access to the system. This module includes the design of a web application for remote system access. The implementation utilizes the station (STA) mode of the ESP32 microcontroller. Figure 9 depicts the basic communication structure of the IoT monitoring module.

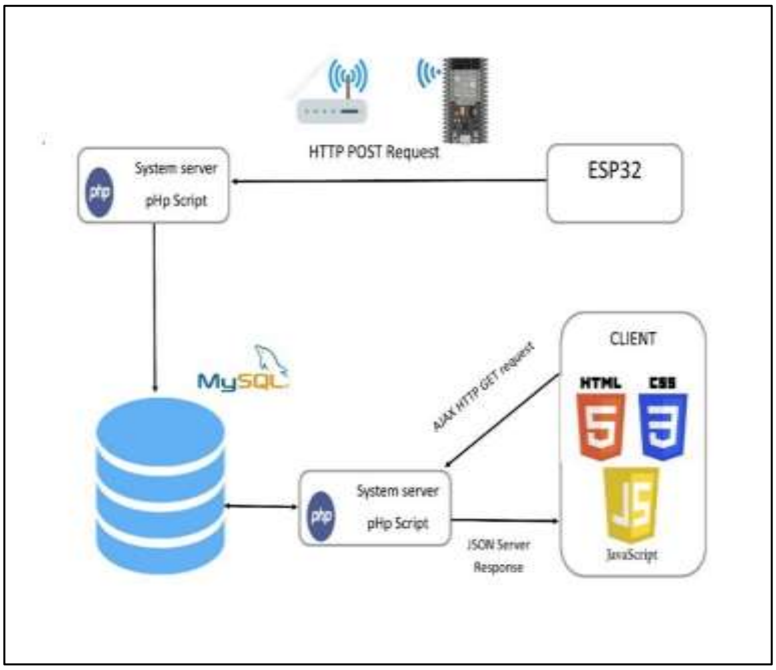

Fig. 9 Web Server Communication Structure

2.3.1 Web Application Data Logging

The web application's client's side starts with user authentication. This provides security to ensure that only authorized personnel have access to the system. There are two methods by which the data can be sent from the client to the server, and these are the HTTP POST method and the HTTP GET method. Figure 10 shows the flowchart algorithm that is implemented during the authentication procedure.

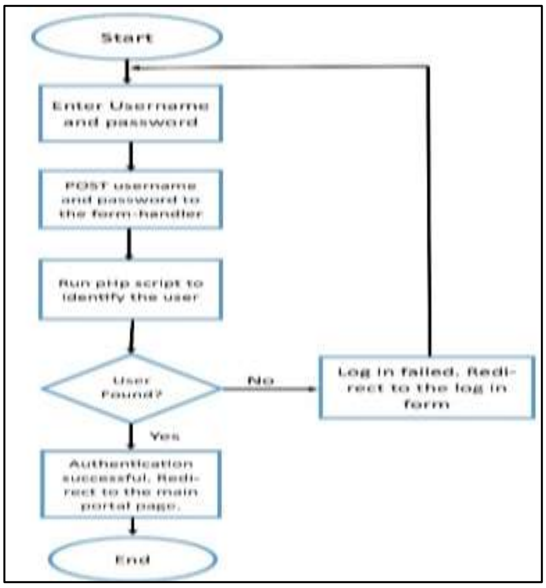

Fig. 10 User Authentication Algorithm

2.3.2 Main Page Design

After logging in, the user is redirected to the monitoring portal, which serves as the main page for displaying real-time system information. This page provides details on the system's performance, power production patterns, and the movement of the panels throughout the day by showing their updated positions. To ensure the main portal displays current information about the system, it must continuously interact with the web server. This interaction involves making requests to the server and receiving updated data, which is then displayed on the graphical user interface (GUI). To achieve continuous interaction without refreshing the entire web page, the system uses Asynchronous JavaScript and XML (AJAX). AJAX enables the system to send and receive information from the server without reloading the page. It sends HTTP requests that prompt the server to execute PHP scripts, accessing updated information from the MySQL database. The process is summarized in the flowchart shown in Figure 11 below.

Fig. 11 Main Page Periodic Data Fetching Algorithm

2.3.3 ESP32-to-Server Real-time Data Communication

This section describes how the ESP32 continuously updates the system server with new data. Initially, the ESP32 is configured to operate in Station Mode (STA), where it connects to the WLAN router using the provided Service Set Identifier (SSID) and authentication password. Once connected, the ESP32 needs the HTTP address of the server it will interact with. While running, the system measures parameters such as PV voltage, PV current, PV power production, and azimuth and zenith angles. It then creates an HTTP client object and posts the data to the server. The server responds by running a PHP script that verifies the API key to ensure it only accepts data from the ESP32. Once verified, the PHP script accepts the data and updates the data table in the MySQL database. The flowchart in Figure 12 illustrates the algorithm implemented for this task, showing the steps involved in the ESP32-to-server real-time data communication process.

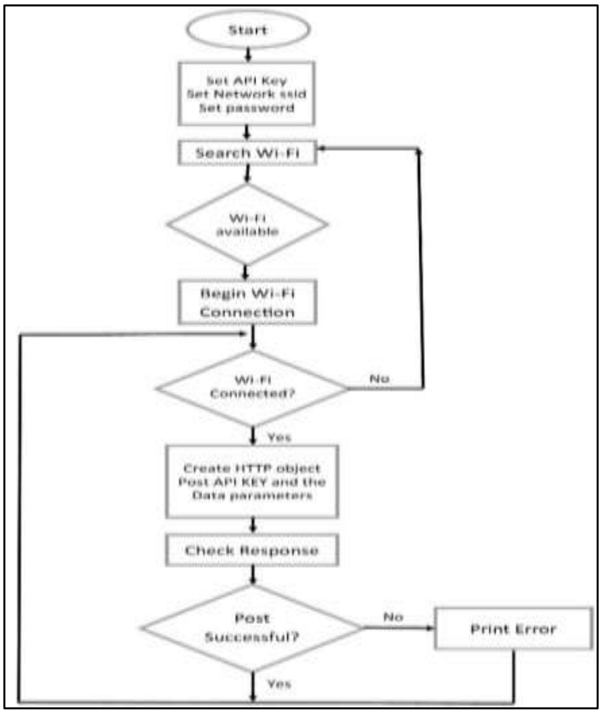

Fig. 12 ESP32-To-Server Real-Time Data Communication

2.3.4 Cloud-Based Data logging

The web application includes a page for users to view data logged by the solar system into the MySQL database. The system records data periodically, encapsulates it into a JSON file, and posts it to the cloud database when online. Figure 13 illustrates the overall data logging sequence.

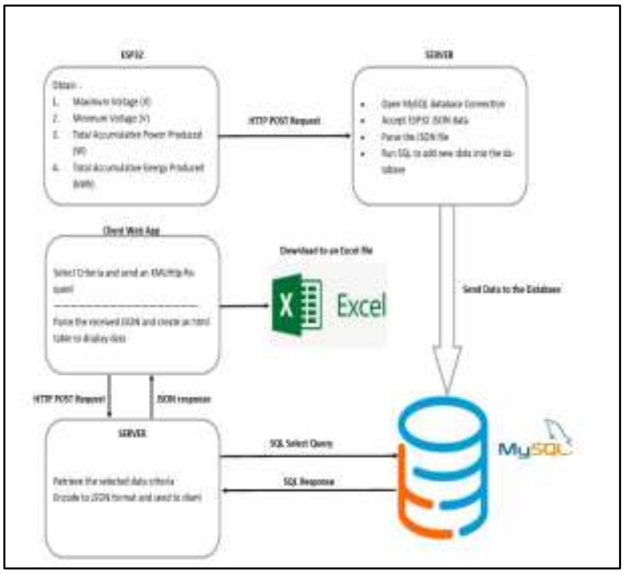

Fig. 13 Cloud-based Data logging structure

The flowchart in Figure 14 shows the algorithm to be implemented by the ESP32 to log data into the system's database.

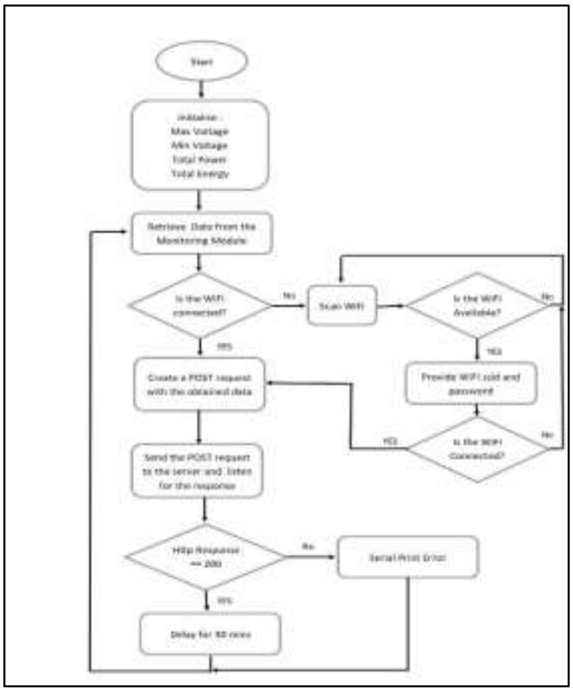

Fig. 14 ESP32 data logging flowchart

The flowchart in Figure 15 illustrates the algorithm implemented on the data logging page of the web app. Users can choose to view either all the data or data from a specific date. If the user clicks "View All," JavaScript invokes a function that creates an XMLHTTP request with no additional data appended. This request is sent to the backend PHP data logging server. When the server receives this request, it recognizes that the user has requested all the data without any selection criteria. Consequently, the PHP script executes an SQL "SELECT ALL" query to retrieve the entire table from the database.

If the user selects a specific date from the calendar dropdown, JavaScript captures the selected date and appends it to an XMLHTTP request, which is then sent to the backend server.

Fig. 15 Data Logging Portal Flowchart

When the PHP server receives this request, it notes the date sent from the frontend application and uses it as a selection criterion for querying the database. In response to both types of requests (all data or specific date), the PHP server encapsulates the SQL query results into a JSON file and sends it back to the frontend application.

4. Results and Discussion

4.1 Circuit Setup Results

This section presents the circuit components comprising the entire system as designed.

4.1.1 Sun tracking circuit results

Figure 16 illustrates the sun tracking circuit, highlighting several key components. The positioning of the solar panel is designed to maximize sun exposure, with light-dependent resistors (LDRs) on the panel's surface detecting the sun's movement throughout the day to ensure optimal alignment. The resistors forming the LDR circuit are essential for detecting changes in light intensity. Figure 17 provides additional details about the setup. It shows six connecting wires from the bracket to the ESP32 controller, which consist of Vcc, Ground, V1 (LDR 1), V2 (LDR 2), V3 (LDR 3), and V4 (LDR 4). These wires facilitate communication and power supply. The position of the zenith servo motor, which controls the panel's movement along the zenith axis, allows for vertical adjustments, while the azimuth servo motor controls rotation along the azimuth axis, enabling horizontal adjustments. These components work together to ensure the solar panel remains optimally aligned with the sun throughout the day, maximizing energy capture.

Fig. 16 Panel Bracket showing sensors

Fig. 17 Panel Bracket showing wiring

4.1.2 Power Monitoring Circuit Results

Figure 18 illustrates the power monitoring circuit, which includes several key components. A voltage sensor measures the voltage of the solar array, while an ACS712 current sensor measures the current flowing through the circuit. A changeover single-channel relay automatically switches between the solar array power supply and the backup battery power supply, ensuring a continuous power supply. Additionally, a DC-DC buck converter steps down the DC voltage to suit 5V DC loads.

Fig. 17 Power Monitoring Circuit view

4.1.3 Web Application Results

The web application includes a login page for user authentication, a monitoring portal for displaying and tracking the system's performance, and a data logging portal for showing historical trends of the system.

4.1.4 Login Page

The login page allows users to enter their credentials to access the system. After clicking the sign-in button, the system verifies the credentials to ensure only authenticated users gain entry. Figure 19 depicts the login page of the remote operating web application. After successful verification, authenticated users are directed to the solar system monitoring portal. This portal provides users with various information including the system's status (online or offline), solar array voltage, PV current, power production, azimuth angle of the solar array, zenith angle of the solar array, and an option to view the historical records page.

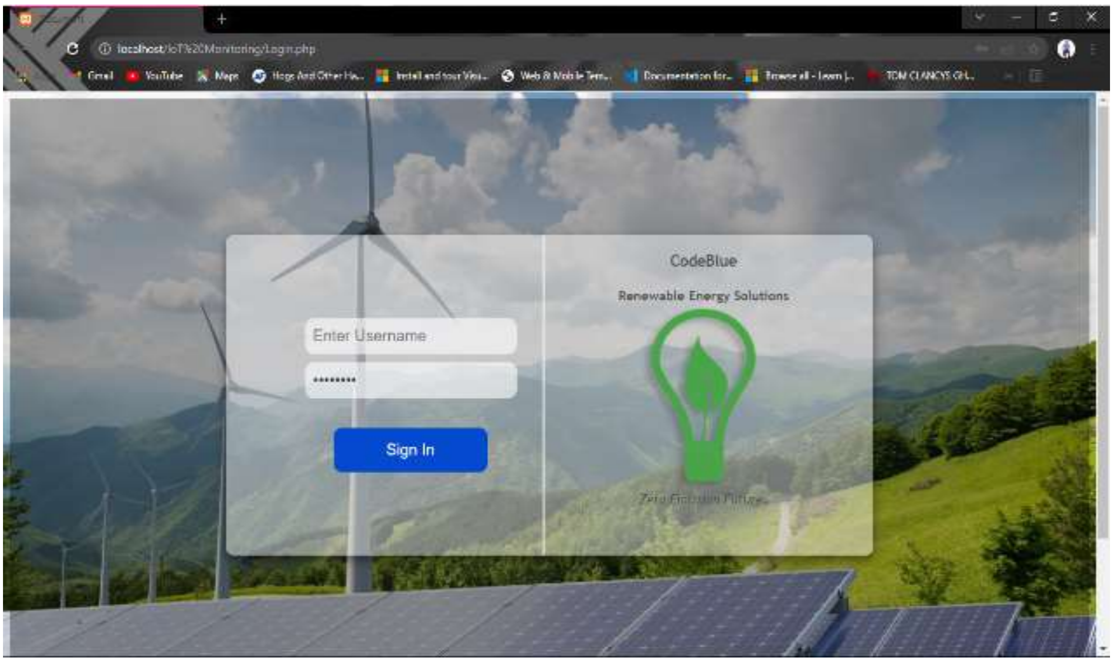

Figure 20 - Monitoring Portal Page test1 displays a screenshot of the system during the testing phase. The image indicates that the system is online, operating on solar power with a PV voltage of 6V and a current of 0.48A. The graph provides a real-time plot of the system's power production. Additionally, the page displays the current values of the azimuth angle from true north and the zenith angle from the earth's horizon.

Fig. 18 Monitoring Portal Page test1

Figure 21 shows a screenshot of the monitoring portal when the ESP32 has lost its connection to the internet. The user will be notified that there is no longer communication between the ESP32 and the system's server.

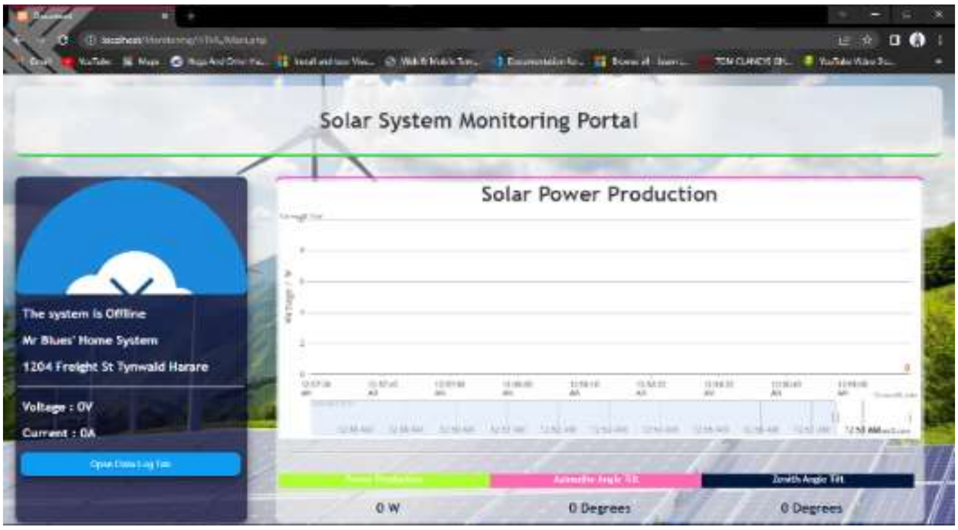

Fig. 19 Monitoring Portal without internet connection

4.1.4 Data Logging Portal

The data logging portal, shown in Figure 22, serves as the page responsible for presenting historical data regarding the system's performance, offering valuable insights for technical decision-making. One of its key features is an HTML table that displays recorded data, providing a comprehensive view of past system performance metrics. Additionally, the portal offers users the option to view all recorded information from the cloud database, enabling a thorough analysis of system data. Users can also select a specific date, triggering the server to run a query and fetch data for the chosen date. This feature allows for detailed examination of system performance on specific days, aiding in pinpointing trends or anomalies. Moreover, the portal includes an option to clear system entries, facilitating the management of recorded data. This feature is particularly useful for maintaining an organized and up-to-date database. Furthermore, the portal offers an export to Excel option, allowing users to download data from the table for offline use and storage. This feature enhances the accessibility and usability of the recorded data, enabling users to analyze it in their preferred format.

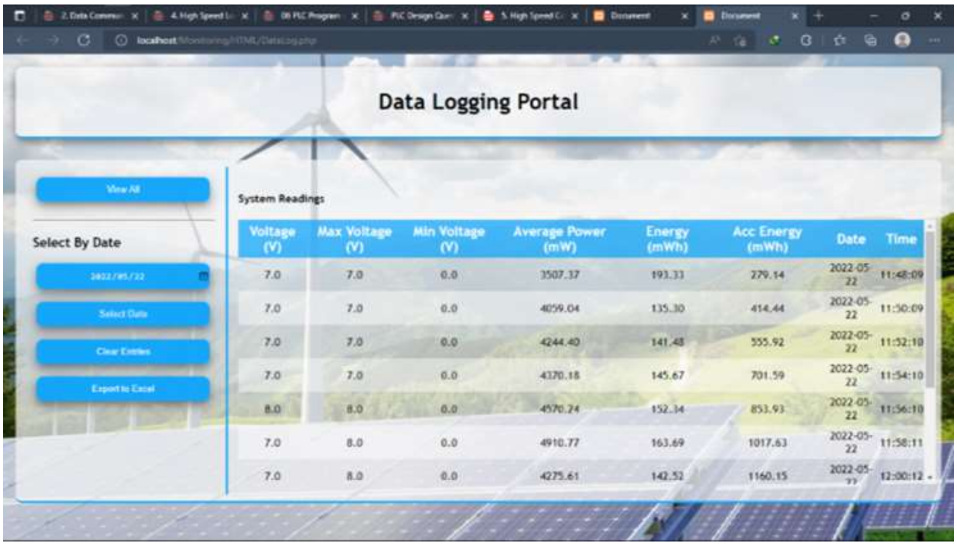

Fig. 22 Data Logging Results Table

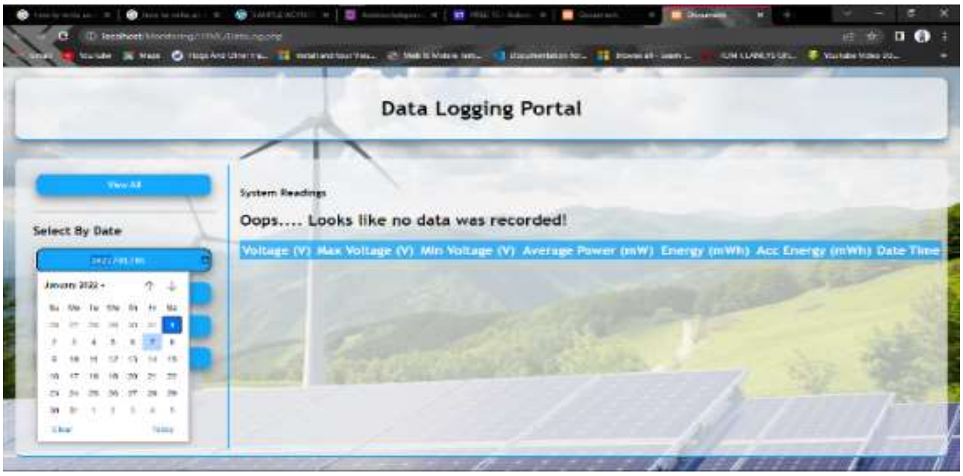

Figure 23 shows the notification for the user when the date selected has no data recorded.

The following snippet in *Figure 24* shows a sample of data that was downloaded from the Data Logging Portal to an excel file for offline usage.

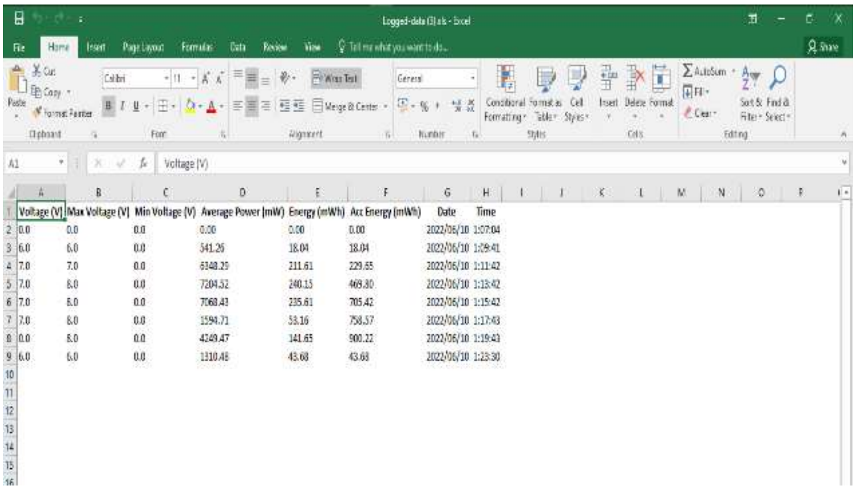

Fig. 24 Excel Export

5. Summary of Findings

The system's design and implementation across its three main modules have revealed several key insights. Sun Tracking Circuitry: The use of two opposite LDR circuits for each axis allows for the detection of differences in light intensity. This setup enables the system to detect when the sun's rays are not perpendicular to the solar arrays. When such differences are noted, the microcontroller sends output commands to the servo motors. These commands adjust the solar panels until all LDR circuits receive the same light intensity, indicating that the light is arriving perpendicular to the panels. Power Monitoring Circuitry: The system's ability to monitor PV voltage and current provides crucial insights into the solar system's power production. The PV voltage sensor's output directly influences the signal sent to the relay changeover, facilitating the system's seamless switch between PV and backup battery power sources as needed. IoT Monitoring: The ESP32's automatic connection to a known Wi-Fi network streamlines its setup process. Once connected, the ESP32 establishes two distinct HTTP POST instances. One instance enables real-time communication with the server, while the other facilitates periodic data logging into the online database. The web application developed for the system offers users a comprehensive platform for monitoring and managing the system's performance. Through this application, users can remotely monitor the system's performance in real-time. Additionally, the web application provides access to historical trends of the solar system through the online data logging portal.

6. Conclusion

The developed system demonstrates a robust capability to track the sun's movement, monitor essential parameters of the solar system, and communicate effectively with an online monitoring web application. The system's ability to track the sun ensures optimal alignment of the solar panels throughout the day, maximizing energy capture. Additionally, the system's power monitoring capability enables real-time monitoring of crucial parameters such as PV voltage and current, providing valuable insights into the system's performance. Furthermore, the system's IoT capabilities allow for seamless communication with the online monitoring web application, providing users with remote access to real-time system data. The system's ability to perform periodic data logging ensures that historical data is captured and stored, enabling detailed performance analysis over time. The inclusion of an export-to-Excel feature enhances the system's usability by allowing users to extract data for further analysis and reporting. Overall, the designed system offers a comprehensive solution for monitoring and managing solar system performance, demonstrating its effectiveness in providing valuable insights and facilitating informed decision-making for system optimization and maintenance.

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