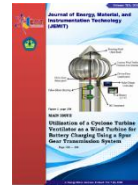




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Design and Development of an IoT-Based Monitoring and Control System for Dual Lithium-Ion Battery Charging Using Photovoltaic Energy

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Abstract

Despite the growing demand for eco-friendly electric vehicles powered by renewable solar energy, conventional battery management systems do not offer effective remote tracking nor do they efficiently handle charging path switching between dual batteries. To resolve this limitation, an Internet of Things (IoT)-based monitoring and control system was developed for dual Lithium-ion batteries (48 V 20 Ah) powered by a 100 Wp solar panel. The architecture utilizes a NodeMCU ESP32 microcontroller, a ThingSpeak platform, and a Twilio-based WhatsApp Bot for remote execution. Experimental evaluations spanning 390-minute daily cycles demonstrated that measurement errors did not exceed 3.35% (Voltage Sensor I and II achieved 97.53% and 96.65% accuracy, respectively). Furthermore, data transmission on ThingSpeak did not cause operational instability with an average latency of 10.3 seconds, while WhatsApp Bot commands took no longer than 3.72 seconds on average to activate relay responses (2.31–7.40 seconds). During charge–discharge cycles, Battery I gained +4.99 V during charging and lost -5.14 V during discharging, whereas Battery II lost -4.76 V during discharging and gained +5.40 V during charging. Overall, the designed prototype encountered no failures in tracking voltage dynamics or executing automated path switching, confirming its viability for smart renewable energy management.

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Kata kunci: Thingspeak, NodeMCU ESP32, Monitoring, Lithium Ion, Sensor, WhatsApp Bot, Panel Surya

Abstrak

Kebutuhan akan transportasi ramah lingkungan mendorong pengembangan kendaraan listrik yang terintegrasi dengan sumber energi terbarukan seperti panel surya. Namun, sistem pemantauan dan pengisian baterai secara konvensional masih memiliki keterbatasan dalam hal pemantauan jarak jauh serta efisiensi pengalihan proses pengisian antar baterai. Penelitian ini bertujuan untuk merancang dan membangun sistem pemantauan (monitoring) serta pengendalian pengisian dual baterai Lithium-ion (48 V 20 Ah) berbasis Internet of Things (IoT) dengan sumber energi panel surya 100 Wp. Sistem ini memanfaatkan mikrokontroler NodeMCU ESP32 sebagai pusat pemrosesan data dan pengontrol sakelar relay, platform ThingSpeak untuk visualisasi data secara real-time, serta WhatsApp Bot (Twilio) untuk notifikasi dan eksekusi perintah kendali jarak jauh. Pengujian sistem meliputi kalibrasi sensor tegangan DC, pengujian waktu respon komunikasi data, serta pengujian siklus pengisian (charge) dan pengosongan (discharge) dual baterai selama 390 menit (6,5 jam) per hari. Hasil kalibrasi menunjukkan bahwa Sensor Tegangan I memiliki akurasi sebesar 97,53%, error 2,47%, dan presisi 99,83%, sedangkan Sensor Tegangan II memiliki akurasi sebesar 96,65%, error 3,35%, dan presisi 100%. Waktu tunda (delay) rata-rata penerimaan data pada platform ThingSpeak adalah 10,3 detik, sedangkan waktu eksekusi perintah melalui WhatsApp Bot memerlukan rata-rata 3,72 detik dengan respon relay antara 2,31 hingga 7,40 detik. Pada pengujian charge–discharge, Baterai I mengalami kenaikan tegangan +4,99 V saat pengisian dan penurunan -5,14 V saat pengosongan, sementara Baterai II mengalami penurunan -4,76 V saat pengosongan dan kenaikan +5,40

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V saat pengisian. Secara keseluruhan, sistem yang dirancang berfungsi dengan baik dalam pemantauan tegangan dan pengendalian pengalihan jalur pengisian baterai.

1. Introduction

The number of motor vehicles in Indonesia has continued to increase in recent years. According to the latest data from Statistics Indonesia (Badan Pusat Statistik, BPS), the number of passenger cars reached 20,444,507 units in 2024, while the overall number of motor vehicles has also shown an increasing trend compared with previous years (Badan Pusat Statistik, 2025). This trend highlights the urgency of diversifying energy sources in the transportation sector through the adoption of electric vehicles (EVs). The International Energy Agency (IEA) reported that Indonesia has continued to expand its electric vehicle charging infrastructure and targets the deployment of 32,000 public charging points by 2030 (IEA, 2026).

As an environmentally friendly transportation option, electric vehicles offer several advantages, including high energy efficiency, low operating noise, and the absence of direct exhaust emissions (Efendi, 2020). Nevertheless, the adoption of EVs in Indonesia continues to face technological, economic, regulatory, and infrastructure-related challenges, particularly the limited availability of charging facilities (Lazuardy et al., 2024). The integration of photovoltaic (PV) systems with EV charging infrastructure provides a potential alternative for reducing dependence on grid electricity and fossil-fuel-based energy sources. Recent studies have indicated that standalone photovoltaic-based EV charging systems need to consider several factors, including system design, technical standards, regulatory policies, battery capacity, and charging-load characteristics (Budiarjo, 2025; Oruganti et al., 2025).

The battery is a critical component of an electric vehicle because it stores and supplies electrical energy to the propulsion system. Lithium-ion batteries are widely used in EV applications owing to their high energy density, relatively low weight, favorable charging characteristics, and longer cycle life compared with lead-acid batteries (Faruque et al., 2026). However, the performance and safety of lithium-ion batteries are strongly influenced by charging and discharging conditions, temperature, and cell aging. Overcharging may result in excessive temperature rise, internal damage, capacity degradation, and, under certain conditions, thermal runaway (Yang et al., 2026). Therefore, battery charging systems require appropriate voltage and current regulation, temperature monitoring, and control mechanisms to prevent overcharging and over-discharging conditions (Liu et al., 2026).

One approach to improving the operational continuity of electric vehicles is the use of multiple battery units managed through an energy management system. In a dual-battery configuration, the controller can regulate which battery serves as the energy source for the motor and which battery receives energy from the photovoltaic charging system. Such a configuration requires appropriate power-flow management, charging-priority strategies, and a safe mechanism for switching between energy sources (Kolech et al., 2026). Battery voltage, current, temperature, and state-of-charge (SoC) should be monitored periodically because these parameters can be used to identify abnormal operating conditions and reduce the risk of battery damage. Recent research has demonstrated that ESP32- and MQTT-based monitoring systems can wirelessly transmit battery voltage data and identify abnormal patterns in battery cells (Suddeepong et al., 2026). MQTT employs a publish-subscribe communication architecture that is well suited to resource-constrained devices because of its relatively low communication overhead. Its implementation also allows sensors, brokers, and monitoring dashboards to operate as separate components, thereby providing greater system flexibility and scalability (Babu et al., 2021; Krawiec et al., 2025).

Battery condition data can be transmitted in near real time to IoT platforms such as *ThingSpeak* for data visualization and monitoring. In addition, integration with a WhatsApp Bot can provide warning notifications (alerts) and support remote control commands (Parmar et al., 2024; Rohmawati et al., 2023). However, previous studies have generally focused on individual aspects of the system, such as battery monitoring, photovoltaic-based charging, or IoT communication. The integration of dual-battery voltage monitoring, photovoltaic charging, automatic battery-path switching, and remote control within a single IoT-based system remains an area that requires further investigation. Therefore, this study focuses on the design and development of an IoT-based monitoring and control system for dual lithium-ion battery charging using photovoltaic energy. The proposed system integrates an ESP32 microcontroller, voltage sensors, relay-based switching, *ThingSpeak* for data visualization, and a WhatsApp Bot for remote monitoring and control. The system performance is evaluated in terms of voltage-sensor accuracy and precision, communication delay, relay response time, and battery voltage variation during charging and discharging cycles.

Previous studies have extensively investigated IoT-based battery monitoring systems (Jamroen et al., 2023; Pauzi et al., 2025), as well as battery charging systems powered by solar energy (Pauzi et al., 2020). However, most existing studies have focused either on monitoring a single battery or on monitoring battery parameters without integrating a mechanism for switching the charging path between two battery units. This limitation indicates the need for an integrated system capable of monitoring and controlling multiple batteries within a photovoltaic-based charging system.

Therefore, this study aims to: (1) design and develop a voltage-monitoring system for dual lithium-ion batteries; (2) develop a relay-based switching mechanism for selecting the battery charging path; and (3) evaluate the system performance based on voltage-sensor accuracy and precision, communication delay, relay response time, and battery voltage variation during charging and discharging operations. The proposed system employs an ESP32 microcontroller, relay-based switching, *ThingSpeak* for data visualization, and a WhatsApp Bot for remote monitoring and control.

The main contribution of this study is the integration of battery monitoring, charging-path switching, and remote communication functions into a single photovoltaic-powered dual-battery system. This integration is intended to provide a practical approach for monitoring battery conditions and controlling the charging path between two lithium-ion battery units through an IoT-based platform.

2. Research Methods

2.1 Materials and Equipment

The experimental system was developed using a 100 Wp photovoltaic (PV) panel as the primary energy source and a 48 V, 20 Ah lithium-ion battery equipped with a battery management system (BMS). The main electronic and measurement components consisted of a DC voltage sensor, NodeMCU ESP32 microcontroller, relay module, solar charge controller (SCC), boost converter, I2C 16 × 2 LCD, resistors, diodes, connecting cables, and electrical connectors. A digital Deli DL4890 multimeter was used as the reference instrument for voltage measurements and sensor calibration.

For IoT-based monitoring and remote control, the system utilized the *ThingSpeak* platform for data visualization and a WhatsApp Bot integrated through the Twilio service for notification and remote control functions.

2.2 System Configuration

The overall system configuration and interconnection of the main components are illustrated in Figure 1.

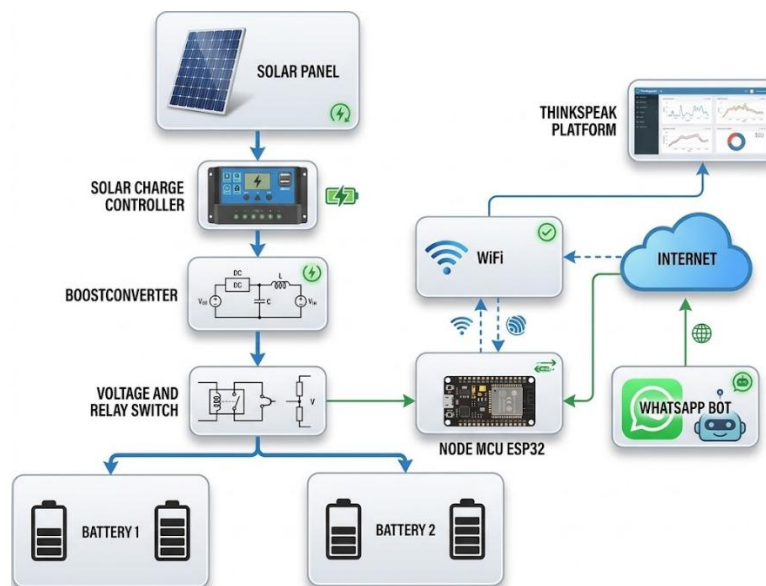


Figure 1. Schematic diagram of the multi-battery charging monitoring and control system.

As illustrated in Figure 1, the proposed system consists of two main components: the power flow path and the IoT-based monitoring and control system.

In the power flow path, the photovoltaic (PV) panel serves as the primary energy source and supplies DC electrical power to the Solar Charge Controller (SCC), which regulates the initial charging process. The output voltage from the SCC is then increased by a boost converter before being supplied to the voltage measurement and relay switching unit. This unit functions as a power-distribution switch that alternately directs the charging power to Battery 1 or Battery 2 according to the measured operating conditions.

In the control and data communication path, the NodeMCU ESP32 microcontroller acts as the central processing unit. It acquires the battery voltage measurements and controls the operation of the relay switch. The measurement data are transmitted wirelessly via a Wi-Fi network to the Internet and subsequently transferred to the *ThingSpeak* platform for cloud-based data storage and real-time graphical visualization. In addition, the system is integrated with a WhatsApp Bot connected to the Internet, which serves as a medium for system-status notifications and for receiving remote control commands from the user.

$$\%Error = \frac{Y - X_n}{Y} \times 100\% \quad (1)$$

$$\%Accurate = \left(1 - \left|\frac{Y - X_n}{Y}\right|\right) 100\% \quad (2)$$

$$\%Precisions = \left(1 - \left|\frac{Y - \bar{X}_n}{X_n}\right|\right) 100\% \quad (3)$$

2.3 Communication Testing

Communication testing was conducted to evaluate the performance of the proposed system using the *ThingSpeak* platform and WhatsApp Bot. The multi-battery charging monitoring and control system was designed to enable remote monitoring and control through an Internet of Things (IoT) framework. Several communication platforms were therefore integrated to support the implementation of these functions.

The monitoring of the multi-battery charging process was implemented using the *ThingSpeak* platform. The *ThingSpeak* interface was designed to display the battery voltage data transmitted by the ESP32, as shown in Figure 2.

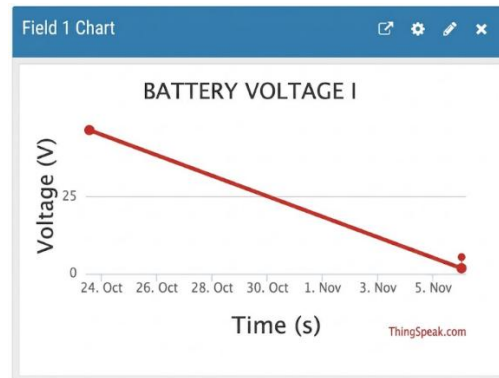


Figure 2. Monitoring interface design.

The charging control system was designed using a relay as a switching component to connect or disconnect the charging path and to transfer the charging process between Battery 1 and Battery 2. The relay enables the charging path to be selected according to the required operating condition.

For remote control of the multi-battery charging process, a WhatsApp Bot was integrated into the system through the Twilio platform. The WhatsApp Bot serves as an interface for sending control commands and receiving system-status information remotely. The design of the multi-battery charging control interface is shown in Figure 3.



Figure 3. Design of the multi-battery charging control system.

2.4 System Performance Analysis

This analysis was conducted to evaluate the overall performance of the developed system.

3. Results and Discussion

3.1 Implementation of the Monitoring and Control System

Battery charging takes place when the photovoltaic (PV) panel receives sufficient solar radiation. The complete battery-charging system is shown in Figure 5.

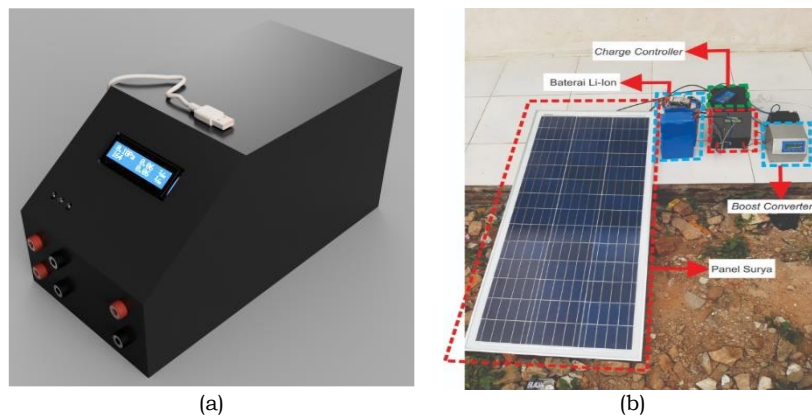


Figure 4. Complete configuration of the multi-battery charging monitoring system: (a) IoT monitoring device; (b) complete system.

Figure 4 shows the battery charging process. The photovoltaic (PV) panel is connected to the solar charge controller (SCC), and the output of the SCC is connected to the boost converter. The output of the boost converter is then connected to the monitoring and control device, which is subsequently connected to the two batteries for the charging process.

3.2 DC Voltage Sensor Calibration

The program used for the DC voltage sensor to measure the battery voltage is shown in Figure 5.

```
#define Pin 33
#define Pin2 35
float Vmodul1 = 0.0;
float Vmodul2 = 0.0;
float hasilsatu = 0.0;
float hasildua = 0.0;
float R1 = 91000.0; //91000 ohm
float R2 = 7500.0; //7500 ohm

void setup()
{
  Serial.begin(115200);
  pinMode(Pin, INPUT);
  pinMode(Pin2, INPUT);}

void loop()
{
  int value1 = analogRead(Pin);
  Vmodul1 = (value1 * 3.3) / 4095.0;
  hasilsatu = (Vmodul1 / (R2 / (R1 + R2))) + 0.9;

  int value2 = analogRead(Pin2);
  Vmodul2 = (value2 * 3.3) / 4095.0;
  hasildua = (Vmodul2 / (R2 / (R1 + R2))) + 0.9;}
```

Figure 5. ESP32 program for acquiring and displaying the voltage sensor measurements.

Figure 5 shows the program uploaded to the NodeMCU ESP32 microcontroller to acquire and display the voltage measurements obtained from the sensor. The program consists of six main parameters, namely Vmodul1, Vmodul2, hasilsatu, hasildua, R1, and R2. Pins 33 and 35 are fixed input variables corresponding to the sensor measurement channels. The values obtained from these pins are used in the calculation equations to determine Vmodul1 and Vmodul2. The parameters hasilsatu and hasildua are used to read the voltage values obtained from Vmodul1 and Vmodul2, respectively, whereas R1 and R2 represent the resistor values used in the voltage measurement circuit.

The DC voltage sensor was tested by connecting a power supply and a Deli DL4890 digital multimeter to the sensor input terminals (Vin+ and Vin-). The DC voltage sensor was connected to the NodeMCU ESP32, while the NodeMCU ESP32 was connected to a PC or laptop through a USB port. The voltage measured by the sensor was adjusted to correspond to the voltage reading of the Deli DL4890 digital multimeter. The reference voltage (V_{ref}) was supplied by the power supply, and a correction factor of 0.9 obtained from the data linearization process was incorporated into the voltage calculation.

The DC voltage sensor was tested using 20 measurement points over a voltage range of 2–21 V, with a 1 V interval between successive measurement points. The voltage measurements obtained from DC voltage sensors I and II were compared with the corresponding readings from the Deli DL4890 digital multimeter. The results are presented in Figure 6.

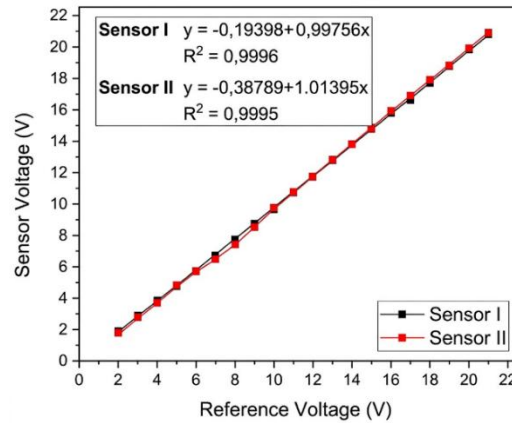


Figure 6. Voltage sensor calibration test graph.

The results of the linearity test between the DC voltage sensor measurements and the Deli DL4890 digital multimeter reference measurements are presented in Figure 6. The calibration results show a strong linear relationship between the sensor output and the reference voltage. For DC voltage sensor I, the obtained linear regression equation was ($y = -0.19398 + 0.99756x$), with a coefficient of determination (R^2) of 0.9996. Meanwhile, for DC voltage sensor II, the linear regression equation was ($y = -0.38789 + 1.01395x$), with an (R^2) value of 0.9995. These results indicate that the regression lines closely represent the measured data variations.

The average measurement error obtained from the calculations was 2.47% for DC voltage sensor I and 3.35% for DC voltage sensor II. Accordingly, the average measurement accuracy was 97.53% for DC voltage sensor I and 96.65% for DC voltage sensor II. In addition, the sensor precision was evaluated using Equation 3. The calculated average precision was 99.83% for DC voltage sensor I and 100% for DC voltage sensor II.

The obtained measurement errors indicate that the sensor performance is within an acceptable range, as the errors are below 10% (Morris, 2001; Morris and Langari, 2016). Based on the obtained error, accuracy, and precision values, both DC voltage sensors demonstrated good performance for voltage measurement under the tested conditions.

3.3 Relay Control Response Test

The relay control test was conducted by sending pre-programmed commands through *WhatsApp* using a number registered on the *Twilio* platform. The response time of the relay control system was measured to evaluate the time required for the system to receive and execute the commands. The test results are presented in Table 1.

Table 1. Relay control response time test results.

Commands	Response Time (second)
charging status	3.66
start charging	2.66
charge 1	2.63
charger 2	3.48
start monitoring	3.92
stop monitoring	7.4
stop charging	2.31

The test results indicate the presence of a communication delay that affected the response time of the relay control system. This delay occurred because the NodeMCU ESP32 functions both as the microcontroller responsible for processing the required calculations and as the communication interface for the IoT system. Consequently, the system processes the programmed tasks and commands sequentially. In addition, the response time of the control system is influenced by the data-transfer rate of the communication network (Alfannizar, 2018). Therefore, a certain amount of time is required for the system to receive, process, and execute each command.

3.4 ThingSpeak Communication Testing

The *ThingSpeak* platform was used for remote monitoring of the battery charging system. The communication test was conducted by measuring a reference voltage supplied by a power supply using the DC voltage sensor. The voltage measurement data obtained from the sensor were transmitted to the *ThingSpeak* platform through the NodeMCU ESP32. The communication delay was then determined by measuring the time required for the voltage data to be received and displayed on the *ThingSpeak* platform.

The test results are presented in Table 2.

Table 2. Data reception delay test results on the *ThingSpeak* platform.

Reference Voltage (V)	Monitoring Result Voltage (V)	Time Delay (s)
2	1.94	10,42
3	2.93	10,1
4	3.91	11
5	4.74	9,5
6	5.74	10
7	6.7	10,1
8	7.73	10,24
9	8.74	10,33
10	9.62	10,6
11	10.67	10,4
Average Time Delay		10.3

The test results showed a communication delay in the system. The average data transmission delay on the *ThingSpeak* platform was 10.3 s. Meanwhile, the relay control test resulted in a minimum delay of 2.31 s, a maximum delay of 7.40 s, and an average response time of 3.72 s. The variation in delay indicates that the system response time was not constant and was affected by the network communication process and command processing. This variation reflects fluctuations in data transmission time, although the system was still capable of supporting remote monitoring and control.

The observed communication delay was influenced by the signal strength during IoT system operation and by the capability of the *ThingSpeak* platform to receive and process transmitted data. Based on the monitoring test results, the developed system was able to transmit and display the measurement data properly and therefore could be used for remote monitoring of the battery charging system.

3.5 Charge-Discharge System Testing

The monitoring data acquisition and battery voltage measurements were performed using two batteries with identical specifications, namely a nominal voltage of 48 V and a capacity of 20,000 mAh (20 Ah). The batteries used in this study were lithium-ion (Li-ion) batteries.

For each battery, monitoring data and voltage measurements were collected under two operating conditions: charging (charge) and discharging (discharge). The charging and discharging processes were conducted to evaluate the voltage variation of each battery during operation and to assess the performance of the developed monitoring and control system under different battery operating conditions.



Figure 7. Monitoring data and battery voltage measurement results.

Data acquisition was conducted for 390 min (6.5 h). In the first test, Battery 1 was operated under the charging (charge) condition, while Battery 2 was operated under the discharging (discharge) condition. During the discharge

test, a 12 V DC motor was used as the load, supplied through a step-down converter that reduced the voltage from 48 V to 12 V. Monitoring and voltage measurements were performed at 1-min intervals.

The monitoring and measurement process was initiated by sending the command “start monitoring” through the WhatsApp application. The system responded with the message “Monitoring starts”, indicating that the monitoring process had been successfully initiated. The voltage increase and decrease recorded during the charging and discharging processes were stored on the *ThingSpeak* platform. The resulting monitoring and measurement data are presented in Figure 8(a).

For the opposite operating condition, Battery 1 was operated under the discharging condition, while Battery 2 was operated under the charging condition. This condition was initiated by sending the command “charge 2” through the WhatsApp application, which directed the charging process to Battery 2. The load was then manually transferred from Battery 2 to Battery 1 to establish a different experimental condition. The monitoring and voltage measurement results obtained during the charging and discharging processes are presented in Figure 7(b).

3.6 Battery Charging Transfer Test

The multi-battery monitoring data collected over 390 min were downloaded from the *ThingSpeak* platform in CSV format and subsequently processed and plotted to generate the graph shown in Figure 8.

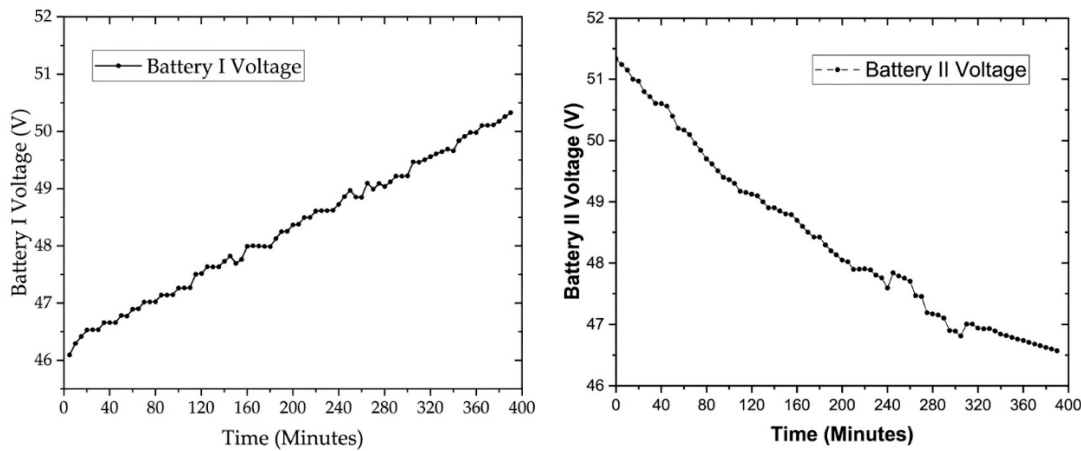


Figure 8. First dual-battery measurement graph.

The first data acquisition was conducted at 5-min intervals over a total duration of 6.5 h (390 min), with Battery 1 operating under the charging condition and Battery 2 under the discharging condition. The results show that the voltage of Battery 1 increased from 46.34 V to 51.33 V, corresponding to a voltage change rate of approximately 0.0128 V/min. Thus, Battery 1 experienced a total voltage increase of 4.99 V during the charging process.

In contrast, the voltage of Battery 2 decreased from 51.33 V to 46.57 V, corresponding to a total voltage decrease of 4.56 V and an approximate voltage decrease rate of -0.0132 V/min during the discharging process.

The second data acquisition was conducted under the opposite operating condition, in which Battery 1 was operated in the discharging condition while Battery 2 was operated in the charging condition. The measurement results for the second test are presented in Figure 9.

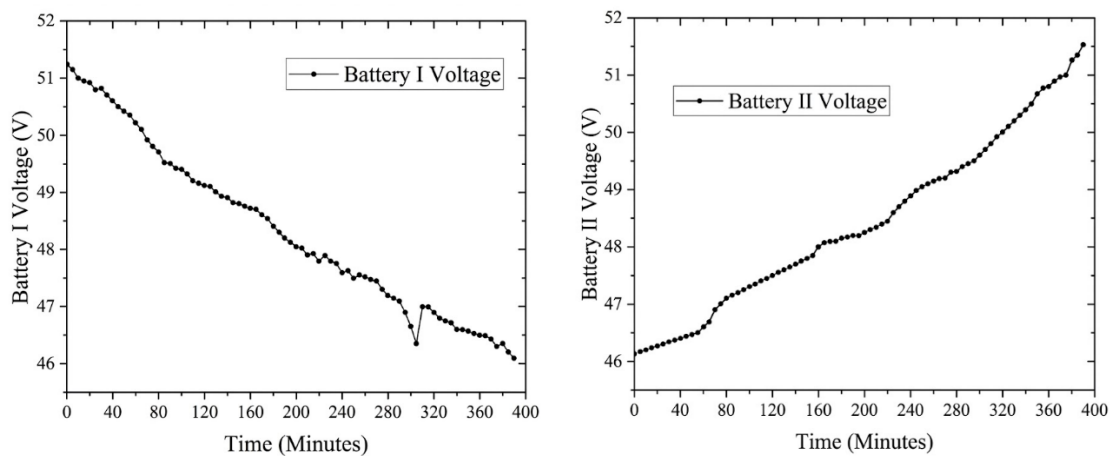


Figure 9. Second dual-battery measurement graph.

Figure 9 shows that the voltage of Battery 1 decreased from 51.24 V to 46.10 V, corresponding to a total voltage decrease of 5.14 V and an average voltage decrease rate of approximately -0.0132 V/min. In contrast, the voltage of Battery 2 increased from 46.13 V to 51.53 V, corresponding to a total voltage increase of 5.40 V and an average voltage increase rate of approximately 0.0138 V/min.

These results indicate that the voltage increase and decrease rates during the charging and discharging processes were relatively consistent between the two test conditions. The increase in battery voltage during charging was influenced by the solar energy supplied by the photovoltaic (PV) panel, with the charging voltage increased through a boost converter (Pauzi et al., 2020). Meanwhile, the decrease in battery voltage during discharging was influenced by the connected load, namely the 12 V DC motor.

The voltage variation rates during the charging and discharging processes were of a similar order of magnitude, although they were affected by the characteristics of the energy source and the connected load. These results demonstrate that the developed system was capable of monitoring the voltage variation of both batteries under alternating charging and discharging conditions.

3.7 Overall IoT System Performance

The overall performance of the developed IoT-based dual-battery monitoring and control system is summarized in Table 3.

Table 3. Overall system performance.

Components	Parameter	Results
Sensor 1	Accuracy	97.53%
Sensor 1	Precision	99.83%
Sensor 2	Accuracy	96.65%
Sensor 2	Precision	100%
ThingSpeak	Delay	10.3 s
WhatsApp Bot	Delay	3.72 s
Relay	Minimum Delay	2.31 s
Relay	Maximum Delay	7.40 s
Battery 1 charge	ΔV	+4.99 V
Battery 2 discharge	ΔV	-4.76 V
Battery 1 discharge	ΔV	-5.14 V
Battery 2 charge	ΔV	+5.40 V

The test results presented in Table 3 show that the measurement components achieved an accuracy of above 96%, while the IoT communication system exhibited a longer delay than the WhatsApp command execution time. This difference indicates that the system was faster in receiving and executing control commands than in transmitting and displaying measurement data on the monitoring platform. Therefore, *ThingSpeak* was more suitable for monitoring purposes, whereas the WhatsApp Bot functioned more effectively as a control interface.

4. Conclusion

- Based on the system design, experimental testing, and data analysis, the following conclusions can be drawn:
1. DC Voltage Sensor I measured the battery voltage with an average accuracy of 97.53%, an average measurement error of 2.47%, and an average precision of 99.83%. DC Voltage Sensor II achieved an average accuracy of 96.65%, an average measurement error of 3.35%, and an average precision of 100%. Both sensors exhibited measurement errors below the 10% tolerance level considered acceptable in this study, indicating that they were capable of supporting battery-voltage monitoring and charging-path switching under the tested conditions.
 2. The ThingSpeak platform was capable of displaying battery-voltage monitoring data with an average data-reception delay of 10.3 s. The remote-control service using the WhatsApp Bot responded to and executed user commands with an average response time of 3.72 s. The relay switch successfully responded to charging-path connection and disconnection commands, with response times ranging from 2.31 s to 7.40 s.
 3. The developed IoT-based battery monitoring and charging-path switching system powered by photovoltaic energy demonstrated its capability to operate under the tested conditions and to support continuous battery energy supply through alternating charging and discharging operations. In the first cycle, with Battery 1 charging and Battery 2 discharging for 390 min, Battery 1 exhibited a voltage increase of 4.99 V, from 46.34 V to 51.33 V, whereas Battery 2 exhibited a voltage decrease of 4.76 V, from 51.33 V to 46.57 V. In the second cycle, with Battery 1 discharging and Battery 2 charging for 390 min, Battery 1 exhibited a voltage decrease of 5.14 V, from 51.24 V to 46.10 V, whereas Battery 2 exhibited a voltage increase of 5.40 V, from 46.13 V to 51.53 V.
 4. This study has several limitations, particularly because the experimental evaluation focused on battery voltage, communication response, and switching performance. Current, power, State of Charge (SOC), battery temperature, and energy efficiency were not simultaneously analyzed. In addition, the testing duration was limited and therefore did not fully represent the long-term performance of the system. Further studies incorporating simultaneous monitoring of current, power, temperature, and SOC, together with longer-duration testing, are required to provide a more comprehensive evaluation of system performance.

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