RESSTECH

Vol. 3, No. 01, pp. 37-51, 2026
RESEARCH ON INSTRUMENTATION
https://rin.resstech.org/

ESP32-Based Battery Management System with Passive Balancing and Smartphone Monitoring

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ARTICLE INFO

Article history:
Received June 12, 2026
Revised June 20, 2026
Accepted June 30, 2026
Available online June 30, 2026

Keywords*:*
Battery Management System (BMS)
Passive Balancing
Lithium-Ion Battery
ESP32
DC Voltage Divider Sensor

ABSTRACT

A Battery Management System (BMS) is an electronic system designed to protect batteries from potentially harmful operating conditions. However, conventional BMSs still have limitations in cell balancing, protection, voltage monitoring, and State of Charge (SOC) estimation, which may reduce battery performance and increase the risk of battery damage. This study aims to design and implement an ESP32-based BMS equipped with voltage and SOC monitoring, overcharge and undervoltage protection, and passive balancing, enabling real-time battery monitoring through a smartphone application. The proposed system was developed using an ESP32 microcontroller and DC voltage divider sensors to measure the voltage of series-connected battery cells. The measured data were processed using the Arduino IDE and displayed on the Blynk application, including battery voltage, SOC, and protection status indicators. System performance was evaluated through sensor characterization, voltage measurement accuracy and precision testing, and assessments of passive balancing and monitoring functions. The experimental results showed that the proposed system achieved a relative voltage measurement error ranging from 0.149% to 0.302%, with an average accuracy of 99.8% and precision of up to 99.8%. Furthermore, the passive balancing function successfully equalized the cell voltages to approximately 4.00 V-4.02 V, resulting in a battery pack voltage of 12.03 V and an SOC of 100% after 105 minutes of charging. These result indicate that the proposed BMS operated effectively according to its intended functions and provided reliable voltage monitoring, protection, and passive balancing. Therefore, the developed BMS has the potential to support safer and more effective battery utilization.

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1. INTRODUCTION

A battery is an electrochemical device capable of storing energy and converting it into electrical energy through electrochemical reactions [1]. The use of battery technology has increased significantly due to the growing demand for energy storage in electronic devices, such as portable electronics, electric vehicles, and uninterruptible power supply (UPS) systems, enabling them to operate independently [2]. However, batteries are susceptible to overcharging during operation. This condition can accelerate battery degradation, damage electronic devices, and impair overall system performance.

In addition, discharging a battery below its recommended operating limit (undervoltage) can degrade battery performance and lead to system failures, as reported in an industrial application at PT MRT Jakarta [3]. Furthermore, voltage imbalance during the charging process reduces battery capacity and accelerates performance degradation. These conditions indicate that the absence of an adequate Battery Management

System (BMS) increases the risk of battery damage and shortens its service life. Consequently, the battery is unable to supply electrical power to the load efficiently [4].

Several previous studies have attempted to address these issues through the development of Battery Management Systems (BMS). In [5] developed a BMS with an overcharge protection function; however, the system did not include digital voltage monitoring. In [6] proposed a battery voltage balancing system, but it lacked overcharge protection. In [7] designed a BMS with undervoltage protection; however, inaccuracies were observed in the State of Charge (SOC) estimation. Furthermore, in [8] developed a BMS incorporating protection functions based on AND and NOR logic gates, but the system did not include a balancing function.

To overcome these limitations, this study proposes an ESP32-based BMS that employs relays as switching devices to disconnect the battery during overcharge and undervoltage conditions, thereby ensuring safe battery operation. The proposed system employs a passive balancing module to equalize the voltages of individual battery cells during the charging process. Battery voltage is monitored using DC voltage divider sensors, and the measured data are displayed on a smartphone through the Blynk application, enabling real-time monitoring of critical battery parameters. Furthermore, the microcontroller-based system is cost-effective, easy to program, and adaptable for digital battery monitoring applications.

Through these features, the proposed BMS enhances battery performance, extends battery service life, and improves the safety and reliability of battery-powered electronic devices and systems by ensuring that the battery operates within its recommended operating conditions [9]. Therefore, the proposed system offers a practical solution for supporting the safe, reliable, and sustainable operation of battery-powered applications across various fields.

2. MATERIAL AND METHODS

This research was conducted at the Electronics and Instrumentation Laboratory, Department of Physics. The study commenced in February 2026 and was carried out in several stages, including system design, prototype development, performance evaluation, and final documentation. This study employed an engineering research approach involving the development of a system based on theoretical understanding and engineering principles. The research procedure consisted of idea formulation, system design, prototype fabrication, and performance evaluation.

The variables in this study were classified into three categories. The independent variable was the battery operating voltage applied to the BMS. The dependent variables included the measured battery voltage, State of Charge (SOC), protection status, and passive balancing performance. The controlled variables consisted of the electronic components, battery specifications, power supply, and experimental conditions that were kept constant throughout the study.

The hardware system consisted of DC voltage divider sensors as the primary input for measuring the cumulative voltages of the series-connected battery cells. The voltage of each individual cell was then determined from the measured values using voltage difference calculations. An ESP32 microcontroller served as the central processing unit, while relays provided overcharge and undervoltage protection by disconnecting the battery pack when the predefined voltage limits were reached. A passive balancing module was employed to equalize the voltages of individual battery cells during the charging process. A smartphone running the Blynk application was used to display the voltage of each battery cell and the overall State of Charge (SOC) of the battery pack. The specifications of the battery used in this study are presented in Table 1.

Table 1. Specifications of the battery

Battery Specification	Value
Battery type	Li-ion 18650
Nominal cell voltage	3.70 V
Discharge cut-off voltage	2.75 V/cell
Charging voltage	4.20 V$\pm$0.05/cell
Charging method	CC-CV
Cycle life	500 cycle
Specific energy	150 Wh/kg

Mass	2.15 kg

The battery used in this study was a Li-ion 18650 cell with a nominal voltage of 3.70 V per cell. According to the manufacturer's datasheet, the discharge cut-off voltage is 2.75 V per cell, while the charging voltage is 4.20$\pm$0.05 V per cell. For the three-cell series configuration used in this study, the datasheet-based discharge cut-off voltage is 8.25 V, calculated from 2.75 V per cell multiplied by three cells. The battery was charged using the constant-current constant-voltage (CC-CV).

The system was designed by first developing a block diagram that illustrates the relationship among the main system components, as shown in Figure 1. The cumulative voltages of the three series-connected battery cells were measured using DC voltage divider sensors, while the voltage of each individual cell was calculated by the ESP32 microcontroller. When the battery pack voltage decreased to the predefined minimum threshold, the ESP32 deactivated Relay 2 to disconnect the load, thereby providing undervoltage protection. Subsequently, the microcontroller activated Relay 1 to initiate the battery charging process [10].

During the charging process, the voltages of the battery cells were equalized by the passive balancing module until all cells reached relatively uniform voltage levels. When the total battery pack voltage reached the predefined maximum charging threshold, the ESP32 microcontroller deactivated Relay 1 to disconnect the charger, thereby providing overcharge protection. The proposed BMS also enabled users to monitor the voltage of each battery cell and the battery pack SOC in real time through a smartphone using the Blynk application.

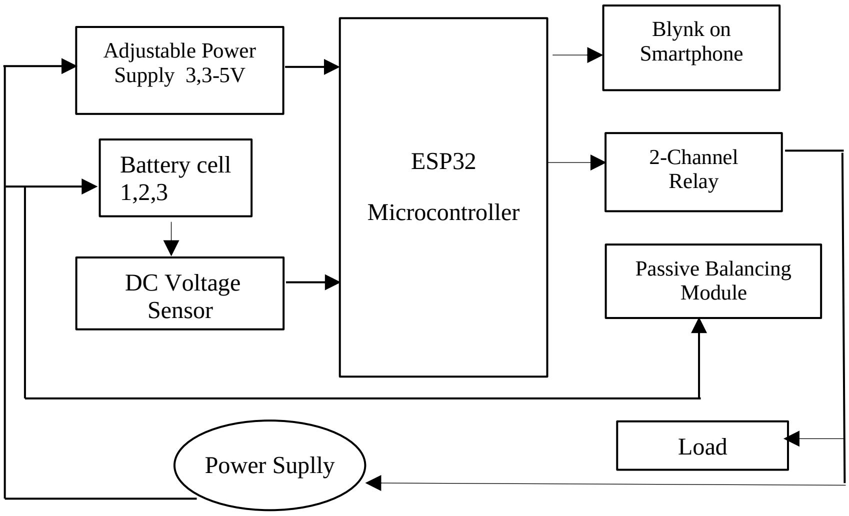

Figure 1. Diagram Blok

The physical design of the proposed BMS was developed as a compact prototype, as shown in Figure 2. The prototype measured 20 cm × 10 cm × 7 cm. Each battery cell was connected to a DC voltage divider sensor, while the ESP32 microcontroller and other supporting electronic components were neatly integrated within the instrument enclosure.

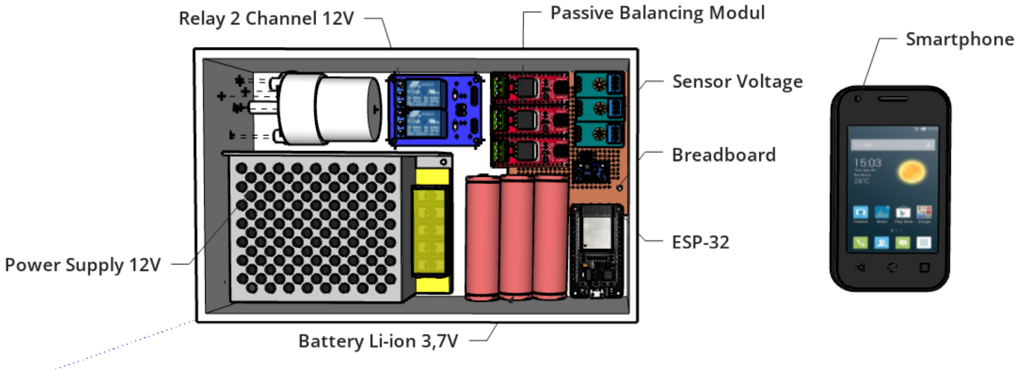

Figure 2. The Physical Design

The software was developed using the Arduino IDE with the C++ programming language. The system algorithm included component initialization, battery voltage measurement, overcharge and undervoltage protection, passive balancing during the charging process, and real-time monitoring of battery voltage, State of Charge (SOC), and protection status through the Blynk application on a smartphone. The program flowchart is illustrated in Figure 3.

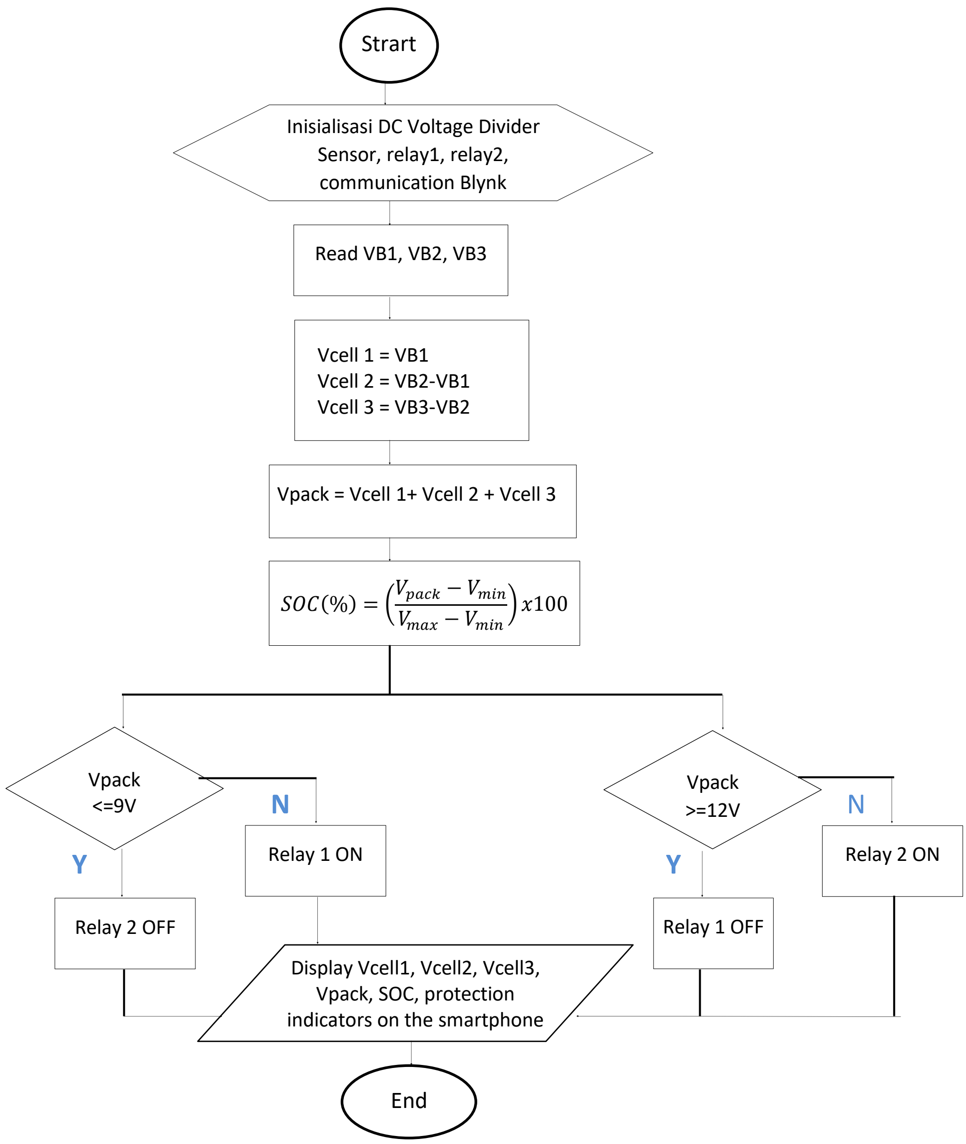

Figure 3. Battery Management System Program

After the system was fully assembled, a series of experiments was conducted to evaluate its performance. Data were collected by measuring the battery voltage using DC voltage divider sensors at various voltage levels. The voltage measurements were performed using a DC voltage divider circuit, whose output voltage is determined according to the voltage divider principle, as expressed in Equation (1).

$$V_{out} = V_{in} x \frac{R_2}{R_1 + R_2} \quad (1)$$

The DC voltage divider sensors measure voltage with respect to the common ground (GND), where the ground potential is defined as 0 V. In a series-connected battery pack, the intermediate and upper battery terminals do not share the same ground reference because they are not directly connected to the common ground [11]. Therefore, the voltage of each individual battery cell was determined using the voltage difference method, as expressed in Equation (2).

$$\begin{gathered}\mathrm{V_{cell1}} = \mathrm{B1} \\ \mathrm{V_{cell2}} = \mathrm{B2} - \mathrm{B1} \\ \mathrm{V_{cell3}} = \mathrm{B3} - \mathrm{B2}\end{gathered} \tag{2}$$

Here, V_{cell1}, V_{cell2}, and V_{cell3} represent the voltages of battery cells 1, 2, and 3, respectively. B1, B2 and B3 denote the measured voltages at measurement points 1, 2, and 3, respectively [12]. The total battery pack voltage for the series-connected cells was calculated using Equation (3).

$$\mathrm{V_{total}} = \mathrm{V_{cell1}} + \mathrm{V_{cell2}} + \mathrm{V_{cell3}}$$

$$\Sigma \mathrm{V} = 0 \tag{3}$$

The voltage relationship in Equation (3) is consistent with Kirchhoff's Voltage Law (KVL), which states that the algebraic sum of all voltages around a closed electrical circuit is equal to zero [13]. The measured voltage signals were digitized by the ESP32 microcontroller and analyzed to evaluate the sensor response to variations in the input voltage. The measurement accuracy was assessed by comparing the sensor readings with the reference voltage supplied by a regulated DC power supply, and measured using a digital multimeter.

Precision was evaluated by repeatedly measuring the same voltage and analyzing the consistency of the measured values. The performance of the proposed BMS was assessed by evaluating the passive balancing function for voltage equalization and the protection functions to verify the system's ability to disconnect the battery pack when the predefined voltage limits were reached. The battery State of Charge (SOC) was estimated from the total battery pack voltage using Equation (4).

$$\mathrm{SOC}\ (\%) = \left(\frac{\mathrm{V_{total}} - \mathrm{V_{min}}}{\mathrm{V_{max}} - \mathrm{V_{min}}}\right) \mathrm{x}100 \tag{4}$$

The collected data were analyzed using error, accuracy, and precision metrics. The voltage measurement error was calculated using Equation (5).

$$\%\mathrm{error} = \left|\frac{\mathrm{Y_n} - \mathrm{X_n}}{\mathrm{Y_n}}\right| \mathrm{x}100\% \tag{5}$$

Here $\mathrm{Y_n}$ is the reference battery voltage measured using a digital multimeter, and $\mathrm{X_n}$ is the battery voltage measured by the proposed BMS. The measurement accuracy was calculated using Equation (6).

$$\mathrm{Akurasi} = 1 - \left|\frac{\mathrm{Y_n} - \mathrm{X_n}}{\mathrm{Y_n}}\right| \tag{6}$$

Measurement precision was determined using the standard deviation, as given in Equation (7).

$$\mathrm{Presisi}(\%) = 100\% - \left(\frac{\mathrm{SD}}{\bar{\mathrm{X}}} \mathrm{x}100\right) \tag{7}$$

In addition, a feasibility evaluation was conducted to assess the usability, operational efficiency, and reliability of the proposed BMS. The evaluation included the battery charging time, verification of the protection functions, assessment of component safety during operation, and validation of the voltage measurement performance of the BMS. The performance of the proposed system was then compared with that of the battery pack operated without the BMS.

3. RESULTS AND DISCUSSION

This study successfully developed an ESP32-based Battery Management System (BMS) prototype integrating protection, passive balancing, and voltage monitoring functions. A series of experiments was conducted to evaluate the system design and performance, including battery charging without and with the proposed BMS, sensor characterization, voltage measurement accuracy, and measurement precision.

3.1 System Design Specifications

The design specifications of the proposed BMS were determined through a series of performance evaluations, including sensor characterization, voltage measurement accuracy, and measurement precision. These evaluations were conducted to verify that the developed system not only operated effectively but also demonstrated a high level of measurement reliability and performance.

The DC voltage divider sensor was calibrated by applying different input voltage levels using a regulated DC power supply. The input voltage was varied from 1.50 V to 3.33 V, while the corresponding reference voltage was measured using a digital multimeter. The ADC readings obtained from the ESP32 were recorded for each reference voltage level to evaluate the sensor response and establish the calibration relationship.

The sensor output was an analog voltage signal that was acquired by the ESP32 microcontroller through its analog-to-digital converter (ADC). The calibration results showed a linear relationship between the ADC output and the reference voltage, indicating that the sensor responded consistently to changes in the input voltage and was suitable for battery voltage measurement. The relationship between the ADC output and the measured voltage is presented in Figure 4.

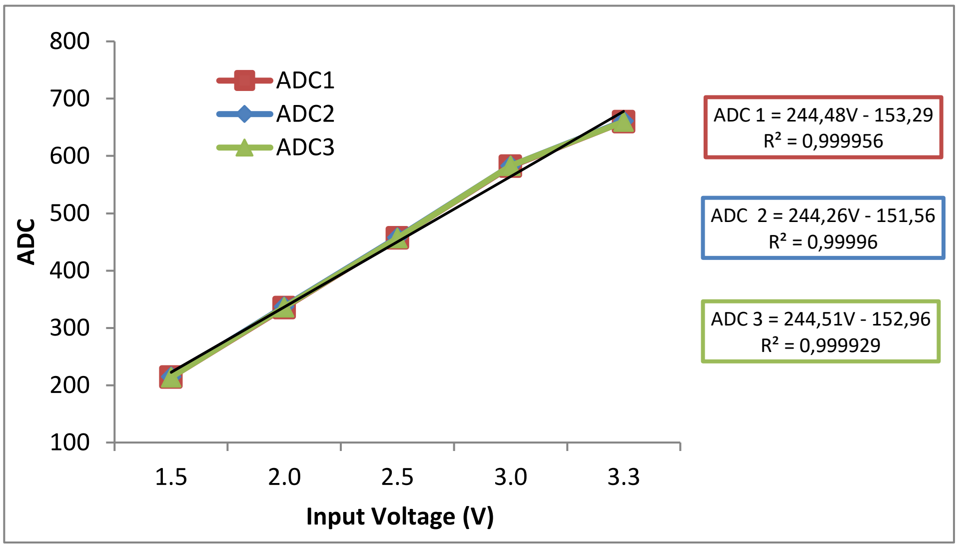

Figure 4. Relationship Between the Input and Output Voltages of the DC Voltage Divider Sensor

To evaluate voltage measurement accuracy, the voltage measured by the proposed BMS was compared with the reference voltage measured using a digital multimeter. The BMS measurements (Xn) and the multimeter reference measurements (Yn) were analyzed to determine the percentage error. The comparison results, presented in Figure 5 show that the voltage measurement error remained below 2% for most measurements, demonstrating that the proposed BMS provides accurate and reliable voltage monitoring. The numerical data used for this analysis are presented in Tables 2–4**.**

Table 2 Accuracy of Sensor 1 Voltage Measurements

NO	Input Voltage (V)	Reference Voltage (V)	Sensor 1 Voltage (V)	Relative Error (%)	Accuracy	Accuracy (%)
1	1,00	1,00	1,00	0,00	1,00	100
2	1,25	1,25	1,24	0,80	0,992	99,2
3	1,50	1,50	1,50	0,00	1,00	100
4	1,75	1,75	1,75	0,00	1,00	100
5	2,00	2,00	2,00	0,00	1,00	100
6	2,25	2,25	2,25	0,00	1,00	100
7	2,50	2,50	2,50	0,00	1,00	100
8	2,75	2,75	2,76	0,36	0,996	99,6
9	3,00	3,00	3,01	0,33	0,996	99,6
10	3,33	3,33	3,33	0,00	1,00	100

Average	0,149 %	0,998	99,8 %

Table 3 Accuracy of Sensor 2 Voltage Measurements

NO	Input Voltage (V)	Reference Voltage (V)	Sensor 2 Voltage (V)	Relative Error (%)	Accuracy	Accuracy (%)
1	1,00	1,00	0,99	1,00	0,99	99
2	1,25	1,25	1,24	0,80	0,992	99,2
3	1,50	1,50	1,50	0,00	1,00	100
4	1,75	1,75	1,75	0,00	1,00	100
5	2,00	2,00	2,00	0,00	1,00	100
6	2,25	2,25	2,25	0,00	1,00	100
7	2,50	2,50	2,50	0,00	1,00	100
8	2,75	2,75	2,76	0,36	0,996	99,6
9	3,00	3,00	3,01	0,33	0,996	99,6
10	3,33	3,33	3,33	0,00	1,00	100
		Average		0,249 %	0,997	99,7 %

Table 4 Accuracy of Sensor 3 Voltage Measurements

NO	Input Voltage (V)	Reference Voltage (V)	Sensor 3 Voltage (V)	Relative Error (%)	Accuracy	Accuracy (%)
1	1,00	1,00	1,00	0,00	1,00	100
2	1,25	1,25	1,25	0,00	1,00	100
3	1,50	1,50	1,50	0,00	1,00	100
4	1,75	1,75	1,75	0,00	1,00	100
5	2,00	2,00	2,01	0,50	0,995	99,5
6	2,25	2,25	2,26	0,44	0,995	99,5
7	2,50	2,50	2,51	0,40	0,996	99,6
8	2,75	2,75	2,77	0,72	0,992	99,2
9	3,00	3,00	3,02	0,66	0,993	99,3
10	3,33	3,33	3,34	0,30	0,996	99,6
		Average		0,302 %	0,996	99,6 %

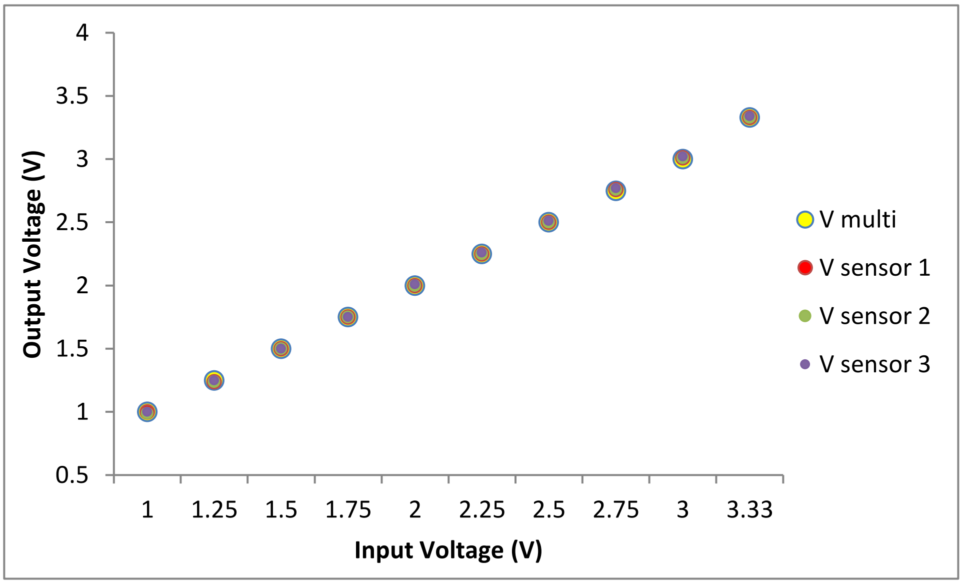

Figure 5. Voltage Measurement Accuracy

Although the voltage measurement error presented in Tables 1–3 remained below 2% several technical factors may have contributed to these discrepancies. First, the sensitivity of the DC voltage divider sensor may have influenced its response to variations in battery voltage, resulting in slight differences in the measured signal received by the microcontroller. Second, the analog output signal from the sensor was converted into digital data by the analog-to-digital converter (ADC) of the ESP32 microcontroller. Although the ESP32 ADC provides adequate resolution for voltage measurement, small quantization errors may occur during the analog-to-digital conversion process, leading to minor deviations in the measured voltage values.

In addition to accuracy, the precision of the voltage measurements was evaluated to determine the stability of the proposed BMS. The precision test was performed by repeatedly measuring the same input voltage of 3.33 V ten times. The measured voltage values were recorded and analyzed by calculating the mean value and standard deviation. The small variation observed among the repeated measurements indicates that the proposed BMS produced consistent voltage readings under identical input conditions. These results demonstrate the good repeatability and stability of the measurement system. The detailed results are presented in Tables 5–7**.**

Table 5 Precision Data of Sensor 1 Voltage Measurements

Trial	**Reference Voltage (V)**	**Sensor 1 Voltage (V)**	**Relative Error (%)**	**Precision**	**Precision (%)**
1	3,33	3,33	0,00	1,00	100
2	3,33	3,34	0,29	0,997	99,7
3	3,33	3,34	0,29	0,997	99,7
4	3,33	3,33	0,00	1,00	100
5	3,33	3,33	0,00	1,00	100
6	3,33	3,34	0,29	0,997	99,7
7	3,33	3,33	0,00	1,00	100
8	3,33	3,34	0,29	0,997	99,7
9	3,33	3,33	0,00	1,00	100
10	3,33	3,32	0,30	0,996	99,6
Average		3,333	0,146 %	0,998	99,8 %

Table 6 Precision Data of Sensor 2 Voltage Measurements

Trial	**Reference Voltage (V)**	**Sensor 2 Voltage (V)**	**Relative Error (%)**	**Precision**	**Precision (%)**
1	3,33	3,33	0,00	1,00	100
2	3,33	3,33	0,00	1,00	100
3	3,33	3,33	0,00	1,00	100
4	3,33	3,33	0,00	1,00	100
5	3,33	3,32	0,30	0,996	99,6
6	3,33	3,32	0,30	0,996	99,6
7	3,33	3,32	0,30	0,996	99,6
8	3,33	3,33	0,00	1,00	100
9	3,33	3,33	0,00	1,00	100
10	3,33	3,32	0,30	0,996	99,6
Average		3,326	0,12 %	0,998	99,8 %

Table 7 Precision Data of Sensor 3 Voltage Measurements

Trial	**Reference Voltage (V)**	**Sensor 3 Voltage (V)**	**Relative Error (%)**	**Precision**	**Precision (%)**

1	3,33	3,34	0,29	0,997	99,7
2	3,33	3,33	0,00	1,00	100
3	3,33	3,34	0,29	0,997	99,7
4	3,33	3,33	0,00	1,00	100
5	3,33	3,34	0,29	0,997	99,7
6	3,33	3,33	0,00	1,00	100
7	3,33	3,34	0,29	0,997	99,7
8	3,33	3,34	0,29	0,997	99,7
9	3,33	3,32	0,30	0,996	99,6
10	3,33	3,33	0,00	1,00	100
Averange		3,334	0,175 %	0,998	99,8 %

3.2 System Performance Specifications

The proposed BMS consists of three main stages: input, processing, and output. The input stage employs DC voltage divider sensors to measure the battery voltage. The sensor signals are transmitted to the analog input pins of the ESP32 microcontroller, where they are converted into digital data by the built-in analog-to-digital converter (ADC) and processed according to the system algorithm to determine the battery voltage and operating status. The processed data are then transmitted to the Blynk application on a smartphone for real-time monitoring [14]. The complete electronic system is shown in Figure 6.

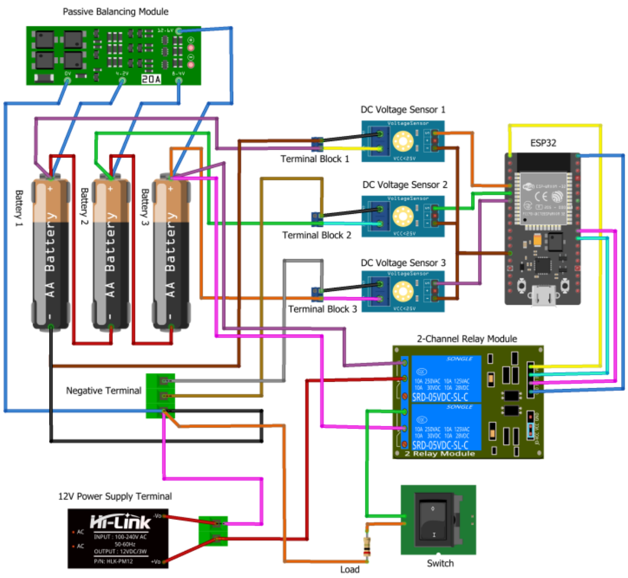

Figure 6. Complete Electronic System

To evaluate the performance of the proposed system, the battery voltage was monitored during charging under two conditions: without the BMS and with the proposed BMS. The passive balancing process was observed throughout the charging cycle. The measured data were plotted as voltage-versus-time graphs using Microsoft Excel for further analysis. These graphs illustrate the differences in battery charging performance between the two operating conditions. The charging data obtained without the BMS are presented in Table 8, while the corresponding charging curve is shown in Figure 7**.**

Table 8 Battery Charging Data Without a Battery Management

Time (minutes)	**Multimeter Voltage (V)**				**SOC (%)**	**Sensor Voltage (V)**				**SOC (%)**
	Vcell 1	**Vcell 2**	**Vcell 3**	**Vtotal**		**Vcell 1**	**Vcell 2**	**Vcell 3**	**Vtotal**	
0	3,588	3,809	3,430	10,820	60%	3,588	3,811	3,430	10,800	60%

15	3,778	3,847	3,723	11,340	77%	3,779	3,841	3,720	11,300	77%
30	3,809	3,884	3,802	11,490	83%	3,806	3,883	3,805	11,500	83%
45	3,821	3,899	3,810	11,530	83%	3,819	3,899	3,808	11,500	83%
60	3,833	3,912	3,820	11,570	87%	3,832	3,911	3,819	11,600	87%
75	3,844	3,919	3,831	11,590	87%	3,844	3,921	3,830	11,600	87%
90	3,857	3,928	3,842	11,630	87%	3,855	3,927	3,841	11,600	87%
105	3,870	3,935	3,856	11,660	90%	3,869	3,932	3,857	11,700	90%
120	3,878	3,941	3,866	11,680	90%	3,878	3,943	3,868	11,700	90%
135	3,884	3,945	3,874	11,700	90%	3,884	3,945	3,871	11,700	90%
150	3,892	3,953	3,884	11,730	90%	3,893	3,953	3,884	11,700	90%
165	3,897	3,957	3,887	11,740	90%	3,897	3,957	3,887	11,700	90%
180	3,905	3,963	3,894	11,760	93%	3,905	3,963	3,894	11,800	93%
195	3,907	3,964	3,897	11,768	93%	3,907	3,964	3,896	11,800	93%
210	3,912	3,969	3,901	11,771	93%	3,913	3,968	3,901	11,800	93%
225	3,914	3,972	3,907	11,793	93%	3,914	3,972	3,907	11,800	93%
240	3,919	3,977	3,912	11,800	93%	3,919	3,977	3,912	11,800	93%
255	3,924	3,982	3,916	11,820	93%	3,924	3,982	3,916	11,800	93%
270	3,929	3,989	3,924	11,840	93%	3,929	3,989	3,925	11,800	93%
285	3,930	3,990	3,928	11,840	93%	3,930	3,990	3,928	11,800	93%
300	3,934	3,995	3,930	11,860	97%	3,934	3,995	3,930	11,900	97%
315	3,936	3,998	3,933	11,860	97%	3,936	3,998	3,933	11,900	97%
330	3,939	4,000	3,935	11,870	97%	3,939	4,000	3,935	11,900	97%

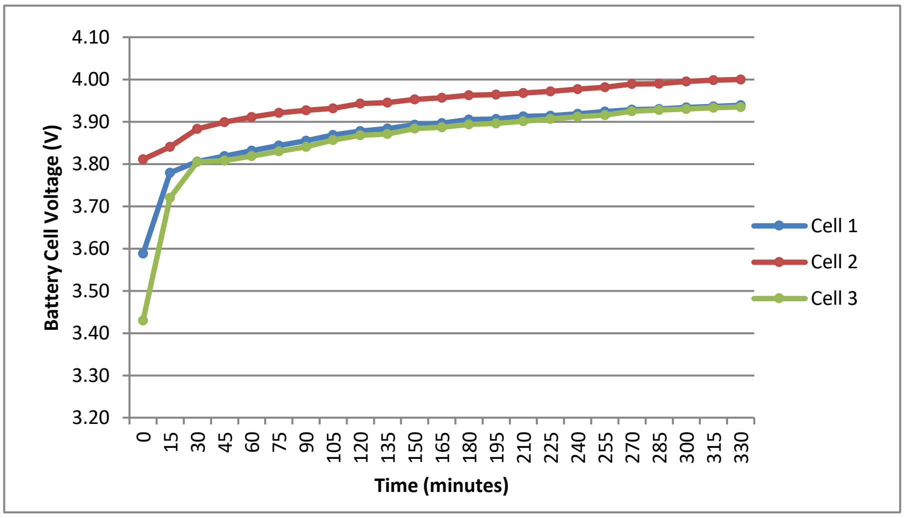

Figure 7. Battery Charging Curve Without a BMS

The battery charging process without the BMS exhibited voltage imbalance among the series-connected battery cells throughout the charging process. Charging started at a total battery pack voltage of 10.8 V, corresponding to an estimated SOC of 60%**.** This total voltage represents the sum of the voltages of the three series-connected battery cells [13]. At this stage, the cell voltages were not evenly distributed. The voltage differences were 0.221 V between Cell 1 and Cell 2, 0.379 V between Cell 2 and Cell 3, and 0.158 V between Cell 1 and Cell 3, indicating a significant voltage imbalance among the cells. The SOC represents the overall charge condition of the battery pack and indicates the change in battery's state of charge during the charging process, as shown in Figure 8**.**

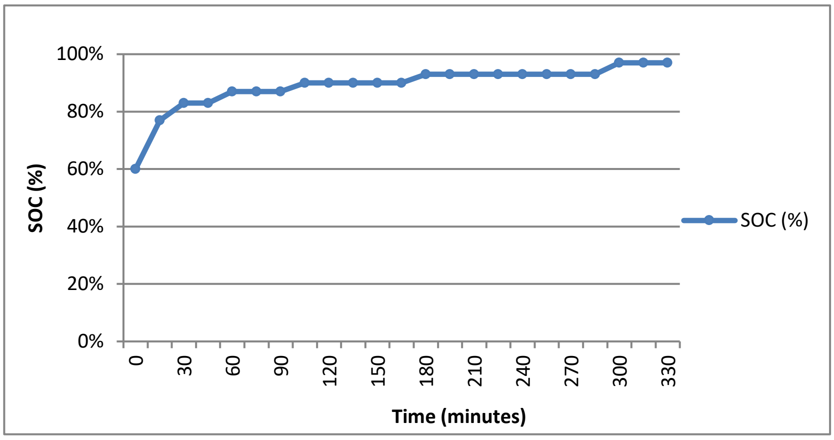

Figure 8. SOC During Battery Charging Without a BMS

The charging curve shows that the battery SOC increased gradually from 60% to 97%. However, the battery pack had not yet reached a balanced charging condition, as the voltages of the individual cells remained unequal. To demonstrate the effect of the proposed BMS, the battery charging performance with the BMS was also evaluated and compared with the charging process conducted without the BMS. The charging data obtained using the proposed BMS are presented in Table 9, while the corresponding charging curve is shown in Figure 9.

Table 9 Battery Charging Data with the Proposed Battery Management System (BMS)

Time (minutes)	Multimeter Voltage (V)				SOC (%)	BMS Voltage (V)				SOC (%)
	Vcell 1	Vcell 2	Vcell 3	Vtotal		Vcell 1	Vcell 2	Vcell 3	Vtotal	
0	3,631	3,64	3,617	10,9	63%	3,625	3,625	3,542	10,8	60%
15	3,837	3,842	3,828	11,5	83%	3,833	3,837	3,824	11,5	83%
30	3,889	3,892	3,884	11,7	90%	3,885	3,893	3,868	11,7	90%
45	3,915	3,919	3,912	11,7	90%	3,916	3,907	3,908	11,7	90%
60	3,941	3,945	3,937	11,8	93%	3,943	3,938	3,937	11,8	93%
75	3,969	3,971	3,96	11,9	97%	3,973	3,964	3,968	11,9	97%
90	3,998	4,003	3,986	12,0	100%	3,991	4,001	3,988	12,0	100%
105	4,014	4,017	4,004	12,0	100%	4,000	4,006	3,988	12,0	100%

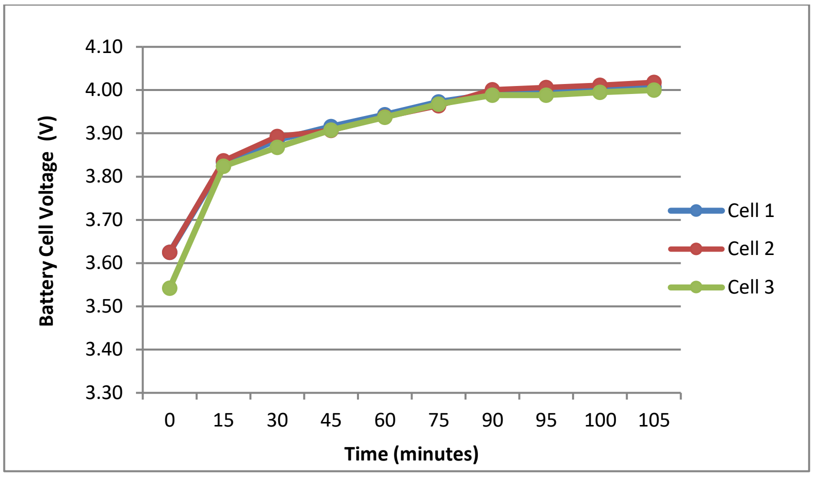

Figure 9. Battery Charging Curve with the BMS

Charging with the proposed BMS minimized the voltage differences among the battery cells. When the voltage of one cell became higher than that of the others, the BMS detected the imbalance and activated the passive balancing module to equalize the cell voltages [15]. At the end of the charging process, the voltages of the three cells reached relatively uniform values ranging from 4.00 V to 4.02 V, resulting in a total battery pack voltage of 12.03 V. This result is consistent with the characteristics of a series-connected battery pack, where the total voltage is equal to the sum of the individual cell voltages [16]. At this point, the battery pack reached an SOC of 100%, as shown in Figure 10.

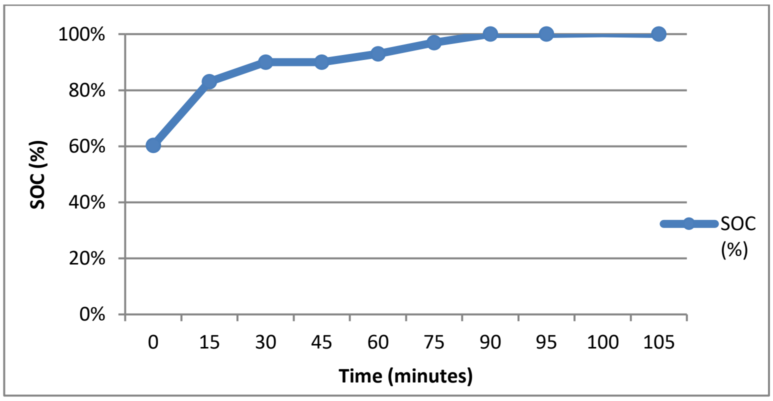

Figure 10. SOC During Battery Charging with the BMS

During the BMS charging test, the voltages of all three battery cells reached approximately 4.0 V after 105 minutes, indicating that the passive balancing process successfully equalized the voltage distribution among the cells. Once each cell reached its fully charged condition, corresponding to a battery pack State of Charge (SOC) of 100% and a total pack voltage of approximately 12 V, the overcharge protection function was activated. The ESP32 microcontroller deactivated Relay 1, disconnecting the charger to prevent further charging and avoid overvoltage. This behavior is also illustrated by the SOC-versus-time curve shown in Figure 10.

Furthermore, the undervoltage protection function was implemented by disconnecting the load through Relay 2 when the battery pack voltage reached the predefined undervoltage protection threshold. During the experiment, the protection function was activated at a measured battery pack voltage of 10.90 V, with individual cell voltages of 3.631 V, 3.640 V, and 3.617 V, respectively. The measured cut-off voltage was higher than the datasheet-based discharge cut-off voltage of 8.25 V for the three-cell series configuration, which was calculated from the specified minimum discharge voltage of 2.75 V per cell. This indicates that the proposed BMS disconnected the load before the battery pack approached the manufacturer's minimum discharge limit, thereby providing a safety margin against excessive discharge. The implementation of undervoltage protection is consistent with the function of a BMS in preventing excessive battery discharge and protecting the battery from unsafe operating conditions [12].

The proposed BMS was successfully fabricated as a physical prototype using a protective enclosure with overall dimensions of 20 cm x 10 cm x 7 cm. The prototype integrates the Li-ion battery pack, passive balancing module, ESP32 microcontroller, relay module, DC voltage divider sensors, and adapter within the enclosure. Each battery cell was connected to a DC voltage divider sensor using jumper wires to provide the voltage measurement signals required by the ESP32. The fabricated prototype and its smartphone monitoring interface are presented in Figure 11.

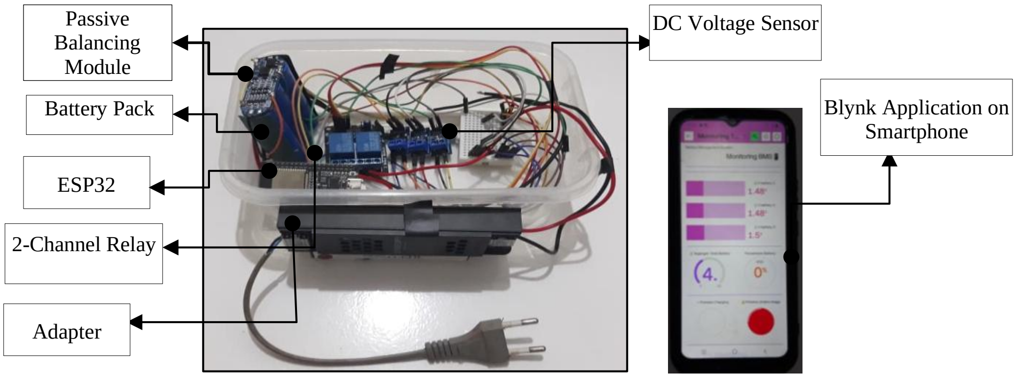

Figure 11. Mechanical Design of the BMS

The battery voltage measured by the sensors was displayed on a smartphone through the Blynk application, enabling real-time monitoring of the battery pack. The smartphone interface is shown in Figure 12.

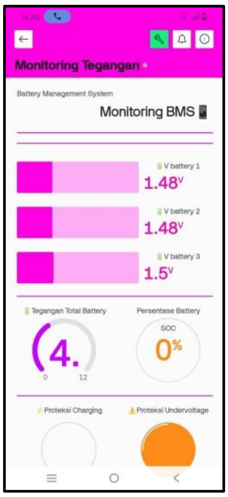

Figure 12. Battery Monitoring Interface on the Smartphone

As shown in Figure 12, the smartphone interface displays the voltage of each battery cell together with the battery State of Charge (SOC) expressed as a percentage. The upper section of the interface presents the individual cell voltages (Vcell1, Vcell2, and Vcell3). The middle section displays the total battery pack voltage (Vtotal) and the battery SOC (%), where the SOC value is updated according to the measured total battery pack voltage. The lower section contains two status indicators: the left indicator represents the overcharge protection status, while the right indicator represents the undervoltage protection status. When either protection function is activated, the corresponding indicator changes to orange.

4. CONCLUSION

This study successfully developed an ESP32-based Battery Management System (BMS) integrating protection, passive balancing, and voltage monitoring functions. The performance evaluation demonstrated that the proposed system effectively performed the intended protection and monitoring function while providing accurate voltage measurements. The voltage measurement error ranged from 0.149% to 0.302%

over the tested voltage range of 1.50–3.33 V. Precision testing based on repeated measurements produced mean voltage values ranging from 3.326 V to 3.334 V, compared with a reference voltage of 3.33 V, indicating stable and consistent measurement performance. The passive balancing function successfully equalized the voltage of the three battery cells during the charging process, with the battery pack reaching approximately 12 V and an SOC of 100%. The proposed BMS was evaluated using a three-cell series-connected Li-ion battery pack, with SOC estimated from the total battery pack voltage. Therefore, the current system is primarily applicable to a three-cell battery configuration and the SOC estimation is based on pack voltage.These limitations provide opportunities for further development of the system. Future research may focus on evaluating the BMS under various charging and load conditions, improving the SOC estimation method, and extending the system to support a larger number of battery cells. Futher development may also include evaluating the balancing performance under different cell imbalance conditions to assess its effectiveness under a wider range of operating conditions.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to the Department of Physics and the Electronics and Instrumentation Laboratory at Universitas Negeri Padang for providing the research facilities that greatly supported the data collection process.

DECLARATIONS

Authorship contribution

Raisa Analista: Conceptualization, methodology, formal analysis, software and writing.
Yohandri: Validation, Writing-review and editing.

Competing Interest

The authors declare that they have no conflict of interest regarding this study.

Funding statement

This research received no external funding.

Ethical Clearance

This study did not involve human participants; therefore, informed consent was not applicable.

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