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Design of battery state of charge monitoring and control system using coulomb counting method based

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ABSTRACT

Lead-acid batteries are commonly used in photovoltaic systems to store solar energy for continuous use. However, lead-acid batteries have a relatively short lifespan due to frequent over-charging and over-discharging. A battery management system (BMS) is essential for accurately predicting the battery state of charge (SoC) value in order to extend the battery lifespan. In this research, a BMS is developed using the coulomb counting method to estimate the SoC value of a lead-acid battery. The coulomb counting algorithm provides a reliable estimation of the battery's SoC value by calculating the incoming and outgoing currents. The BMS also uses two normally closed relays to prevent overcharging and over-discharging. The first relay turns on when the SoC reaches 100% full charge and turns off when the SoC decreases to 70%. The second relay turns on when the SoC reaches 20%. The BMS was tested using Blynk, a cloud-based internet of things (IoT) platform. The results showed that the BMS successfully provided monitoring and reliable control of the lead-acid battery, with a low margin of error. This demonstrates that the developed BMS can be practically implemented in photovoltaic (PV)-battery systems to extend the battery lifespan and improve the overall performance of the system.

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1. INTRODUCTION

Solar energy is the most widely developed and reliable renewable energy source [1]. The performance of photovoltaic (PV) systems in generating electrical energy is highly dependent on solar radiation and temperature [2]. To address this intermittency and enable continuous utilization of generated power, PV systems are typically coupled with energy storage systems (ESS). Batteries are the most common type of ESS used in PV systems [3]. Despite their limitations, batteries remain a crucial component of PV systems. The widespread adoption of PV systems is dependent on the development of new battery technologies that can address the limitations of current batteries [4]. Researchers are actively developing new battery technologies, such as flow batteries, which have the potential to provide large-scale energy storage with a long lifespan. However, these technologies are still in their early stages of development and are not yet commercially available [5]. The specific limitations of a battery will depend on its type and characteristics [6]. For example, lead-acid batteries are relatively inexpensive and have a high energy density, but they have a short lifespan and a low power output. Lithium-ion batteries are more expensive than lead-acid batteries, but they have a longer lifespan and a higher power output [7]–[9].

The commonly used battery in renewable energy applications is the lead-acid battery. Lead-acid batteries are widely utilized for photovoltaic systems due to their relatively low cost and deep discharging capabilities. However, these batteries have a drawback, their lifespan becomes shorter when subjected to overcharging and overdischarging [10], [11].

To address this issue, a battery management system (BMS) is required to accurately predict the state of charge (SoC) value of the battery. SoC is defined as the ratio of the total energy capacity that can be extracted from a battery to its overall battery capacity [12]. SoC indicates the available energy as a percentage of the battery's capacity value. The SoC value ranges from 0 to 1, with 0 representing an empty battery and 1 indicating a fully charged battery. The SoC value can also be expressed as a percentage, ranging from 0% to 100% [13].

From the various discussions provided, a BMS is required to accurately estimate the SoC value of a battery. The selection of an appropriate method is also necessary to support the calculation of an accurate SoC value. By achieving precise SoC calculations, it is anticipated that this information can serve as a reference for battery operation, ensuring safe operating conditions and enhancing the performance of existing systems [14]–[16].

A battery's SOC cannot be measured directly and must be calculated using an estimator. Omiloli *et al.* [17] performed SoC estimation on lithium-ion batteries using an extended kalman filter (EKF), which is improved for estimation tasks due to its nonlinear implementation and adaptability to noise. The result of this method reduces the maximum error to 2.05%, which indicates the quality of the estimator. However, this study has the disadvantage of being unable to counteract the influence of significant disturbances and unknown noise signals. Furthermore, Souaihia *et al.* [18] conducted SoC estimation on lead-acid batteries using an adaptive EKF. This article claims that EKF is proven more effective and accurate with the combination of EKF using the highest polynomial function and the third-order model having better performance in limiting errors. The drawback to this method is the difficulty in limiting the performance of the Kalman filtering algorithm due to nonlinearity in the system. Therefore, this study will use the coulomb counting method for SoC estimation in lead-acid batteries to overcome the weakness of the EKF.

There are two SoC estimation methods that will be employed in this research: coulomb counting (CC) and open circuit voltage (OCV) methods [19]–[21]. The CC method, also referred to as ampere hour counting, is used to estimate SoC by establishing a linear relationship between SoC and OCV [22]. In this method, the estimated SoC value of the battery can be calculated by measuring the electric charge (coulombs) entering or leaving the battery. Electric current is generated by the movement of electric charge per unit of time (in seconds). Therefore, the process of calculating the coulomb count in the battery involves integrating the amount of current entering and exiting per unit of time. The advantage of this method is its ease of implementation. However, its limitation lies in the accuracy of sensor measurements. When performing coulomb calculations, precise accuracy is required in the initial SoC estimation, necessitating knowledge of the battery's OCV value [23]. Based on the aforementioned explanations, the author is interested in conducting research using the CC method to estimate the solar PV battery remaining capacity which can be monitored via the internet of things (IoT). The goal is to establish control measures for disconnecting the battery during instances of overcharging or overdischarging, thereby extending the battery's lifespan.

2. METHOD

2.1. Materials

BMS uses ESP32 as an SoC microcontroller equipped with WiFi 802.11 b/g/n, Bluetooth version 4.2, and various other peripherals. Equipped with 2 ACS712 current sensors that will measure the incoming and outgoing current from the battery, a voltage sensor to measure battery voltage, which is needed to estimate the SoC and maintain the health status of the batteries used as a whole. Installed 2 NC switch relays for cut off 1 to the source, and cut off 2 to the battery which is useful for connecting the battery circuit with load or battery with charging. solar charge controller (SCC) is used to keep the solar system stable and ensure that the battery is charged safely and efficiently.

2.2. Methods

SoC indicates the percentage of battery capacity remaining at a given time. The method employed to determine the SoC of a battery is called the CC method. This method calculates the electric charge (coulombs) entering or exiting the battery. This is done by measuring the current flowing to and from the battery and multiplying that current by the same period of time. The result of this calculation is referred to as "coulombs" which signifies the total amount of energy generated or utilized by the battery [22].

For SoC estimation with this method, the total amount of electric charge entering the battery during charging and the total amount of electric charge leaving during discharge is measured. By knowing the total cost in and out, this method can calculate the amount of electric charge still available in the current battery and convert that amount to a percentage of the current battery capacity. In general, the CC method is (1) and (2):

$$I = \frac{dQ}{dt} \rightarrow Q = \int_{t_0}^{t} I dt \tag{1}$$

$$SoC(t) = SoC(t_0) \pm \frac{\eta}{C_\eta} \int_{t_0}^{t} I dt \tag{2}$$

where:
Q = Electric charge
$SoC(t_0)$ = Initial SoC before the charging/discharging process
$SoC(t)$ = Current SoC
η = Charging efficiency
C_η = Maximum battery capacity
I = Input current or output current

In this research, data collection is conducted twice: during the discharge and charging processes. The data types collected include the flowing current value, battery voltage, and SoC value of the battery. The process flow of battery charging and discharging can be observed in Figure 1. Figure 1(a) is battery dishcarge process and Figure 1(b) is battery charge process. The process of discharging and charging the battery aims to calculate the amount of electric charge that comes out of the battery. From the results of this experiment, we get the maximum value and minimum value of the electric charge, so we can estimate the SoC value in percentage value. For the safety control system, relays are used to limit overcharging and overdischarging.

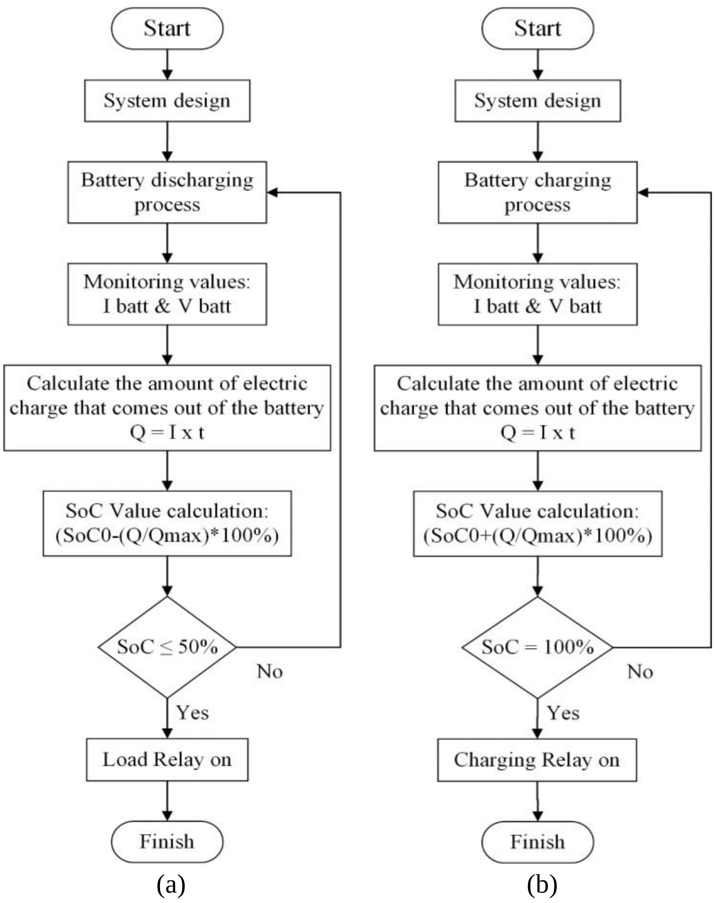

Figure 1. Process flow of battery charging; (a) battery discharge process and (b) battery charging process

The battery used in this study is a Kijo VRLA battery, model JDG12-100, with a voltage of 12 V and a capacity of 100 Ah. The battery's SoC values are determined during both the discharge and charge processes. Before determining the SoC value using the coulomb counting method, calibration is carried out on the current and voltage sensors. This calibration step is crucial to obtain accurate current and voltage values during the discharge and charging processes, as current and voltage are essential parameters for determining the SoC value of the battery. Subsequently, further testing is conducted to determine the SoC value of the battery using the OCV method as a reference. This is done to provide additional data, including the relationship between the open circuit voltage value of the battery (Voc) and the battery's SoC, and to use this data as a reference for determining the initial SoC using the CC method. The solar PV battery discharge process used the following data specifications:

Total time : 5 hours
Load : 100 W
Discharge current : 9.91 A (average)
Data collection interval : 30 seconds
Total charge utilized : 50.02 Ah
Discharge relay trigger : 50%
Initial discharge voltage : 12.65 V
Initial SoC : 100%

During the charging process, the initial SoC value is taken from the last data point in the battery discharge process, which is 50%. Then, the charging process is performed using photovoltaic input with the following specifications:

Total time : 8.75 hours
Average charge current : 5.72 A
Data collection interval : 30 seconds
Total charge during charging : 50 Ah
Charging relay trigger : 100%
Initial charge voltage : 12.52 V
Initial SoC : 50%

The block diagram of the entire system can be seen in Figure 2. The system designed in this research employs an ESP32 as the data processor for the sensors. The sensors utilized include voltage and current sensors, which are used to acquire the SoC value. With in this system, there are two relays that will be used to halt the charging from the photovoltaic source to the battery and to stop the discharge from the battery to the load. These relays are automatically controlled by the ESP32 based on the SoC value. The data from this system can be monitored through an IoT platform called Blynk.

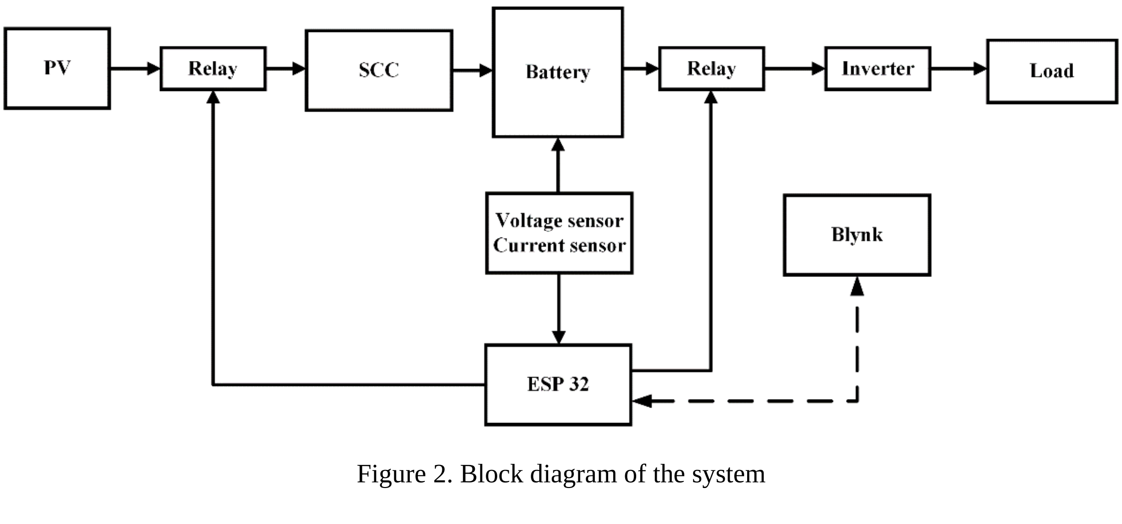

Figure 2. Block diagram of the system

3. RESULTS AND DISCUSSION

3.1. Current sensor test

The current sensor is a crucial component in this design to determine the SoC value, as this method heavily relies on the accuracy of the measured current. The current sensor utilized in this research is the ACS712 with a maximum current rating of 20 A. Testing is conducted by comparing the measurement results of the ACS712 current sensor with a calibrated current measuring instrument (Fluke Multimeter).

The following are the test results of the ACS712 current sensor compared to the multimeter readings for different current test values in Table 1. From the results of the ACS712 current sensor testing, the current measurements obtained from the ACS712 sensor closely match the values from the Fluke Multimeter, with an error value of 1.30%. With this error level, the ACS712 current sensor remains suitable for accurately measuring current [24].

Table 1. Current sensor test

ACS712 (A)	Multimeter fluke (A)	Error (%)
9.05	8.9	1.69
6.74	6.7	0.60
8.84	8.7	1.61
Average		1.30

3.2. Voltage sensor test

The voltage sensor plays a crucial role in detecting battery voltage values, as it is not advisable to use the battery below the cut off voltage or SoC below 20%. This voltage sensor will measure the battery voltage during charging and discharging. Voltage sensor test is conducted by comparing the voltage readings from the voltage sensor with a calibrated voltage measuring instrument (Fluke Multimeter) that uses a power supply as the test voltage source.The following are the test results of the voltage sensor compared to the multimeter readings for different voltage test values in Table 2. The testing results also indicate that the voltage readings obtained from the voltage sensor closely align with the voltage values measured by the Fluke Multimeter. The average error value is 0.28%, indicating that the voltage sensor in this SoC monitoring system demonstrates accuracy and is suitable for use [25].

Table 2. Voltage sensor test

Voltage sensor (V)	Multimeter Fluke (A)	Error (%)
9.97	10.01	0.40
10.98	11.01	0.27
11.98	12.00	0.17
Average		0.28

3.3. Battery discharge process

In determining the battery SoC using the CC method, obtaining an accurate initial SoC value is crucial. Therefore, the battery will charge to its maximum voltage before discharge. In this case, the value is based on the datasheet of the VRLA 12 V 100 Ah battery. When the battery reaches its maximum voltage, its SoC is assumed to be 100%. The battery discharge process is in Figure 3.

Figure 3. Battery discharge process

In the monitoring system, the ESP32 also sends sensor reading data to Blynk, allowing remote monitoring of current values, voltage values, SoC values, and relay indicators through the web. In Figure 4 depicts the graph illustrating battery voltage's impact on time during the discharge process. The discharge graph depicts an initial voltage of 12.65 V, followed by a relatively modest decrease. By the end of the discharge process, the voltage reaches 11.73 V. Based on the obtained data, the final voltage value differs by approximately 0.3 V from the battery datasheet. This variance could be attributed to the battery's age and extended usage, causing the SoC readings to deviate from the datasheet. In Figure 5 illustrates a graph depicting the SoC value versus time during the discharge process caused by the use of an electrical load from the electrical energy stored in the battery.

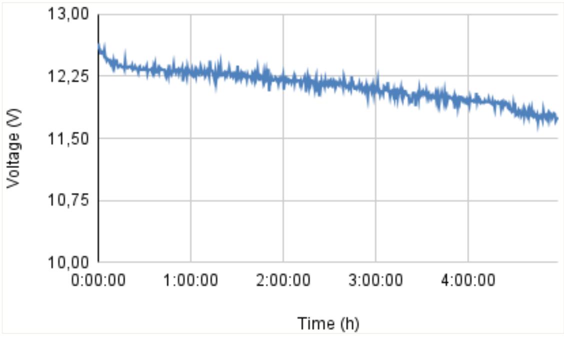

Figure 4. The graph of voltage-time during discharge

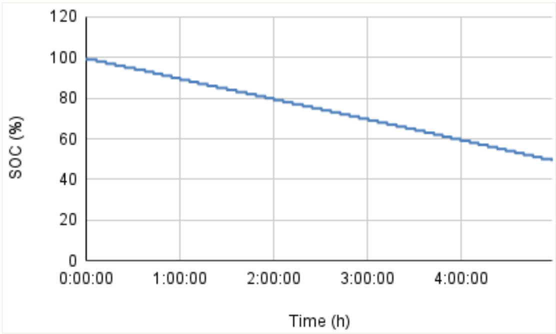

Figure 5. The graph of SoC-time

The graph reveals that the relationship between SoC values and time during the discharge cycle is directly proportional the longer the battery is used, the more charge is utilised. Consequently, this leads to a reduction in the battery's SoC value. Figure 6 displays the graph depicting the relationship between voltage and SoC values during the discharge process.

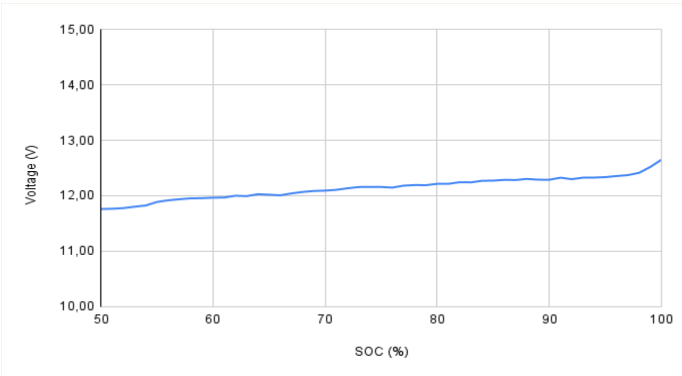

Figure 6. The graph of SoC-voltage during discharge

This graph illustrates the relationship between voltage and SoC values during the discharge process. At a SoC value of 50%, the voltage is measured at 11.73 V. According to the datasheet, a SoC of 50% corresponds to a voltage of 12 V. However, the data obtained when the voltage is at 12 V indicates a SoC of 60%. As a result, there is a difference of approximately 0.3 V between the obtained data and the datasheet. This variance can be attributed to the battery's age and extended usage, leading to a divergence between the actual SoC readings and the values stated in the datasheet.

3.4. Battery charge process

After the discharge process, the subsequent step involves charging the battery using photovoltaic energy, connected to a SCC, to regulate the charging current within the maximum standard charge current specified in the battery's datasheet. In the monitoring system, the ESP32 continues transmitting sensor reading data to Blynk, enabling remote monitoring of current, voltage, SoC values, and relay indicators through the web. During the charging process, the initial SoC value is derived from the last recorded data in the battery discharge process, which is 50%. The battery charging process is in Figure 7. In Figure 8 illustrates the graph depicting the relationship between battery voltage and time during the charging process.

Figure 7. Battery charge process

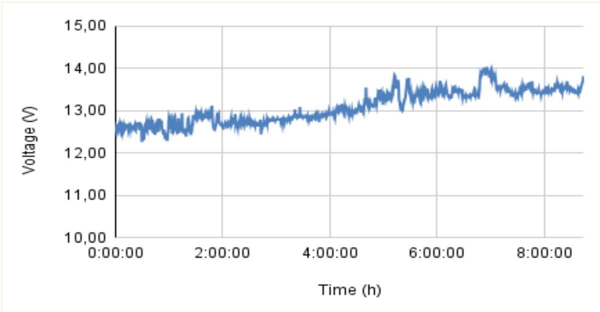

Figure 8. The graph of voltage-time during charging process

The above graph shows that the battery voltage during the charging process produces higher values than the discharge process. Another observation is a significant voltage increase between 6 hours and 47 minutes to 7 hours and 20 minutes. This occurrence is influenced by the incoming current reaching the maximum cutoff limit set by the SCC.

At the end of the charging process, the voltage reaches 13.82 V, whereas the datasheet indicates a voltage of 14.1 V at the end of charging. This difference is due to the unstable charging current from the photovoltaic source, causing the voltage data to deviate from the battery datasheet. Figure 9 shows the graph of battery SoC values against time during the charging process.

From the graph, it can be observed that the relationship between battery SoC values and charging time is directly proportional. The longer the battery charging process takes, the higher the SoC value increases until it reaches 100%. However, the SoC against time graph appears to have some non-linearity due to the inconsistent charging current. Figure 10 represents the graph of voltage values against SoC during the charging process.

Based on the above graph, the voltage values exhibit unstable fluctuations. When the SoC values are between 92-95%, there is a significant increase in voltage. The incoming current adds charge to the battery, increasing battery voltage. Conversely, outgoing current reduces the battery's charge, causing the voltage to decrease. The unstable increase in voltage is due to the incoming current reaching the maximum cutoff limit set by the SCC.

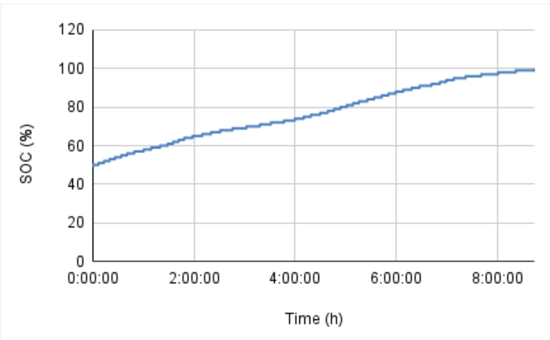

Figure 9. The graph of SoC-time during charging process

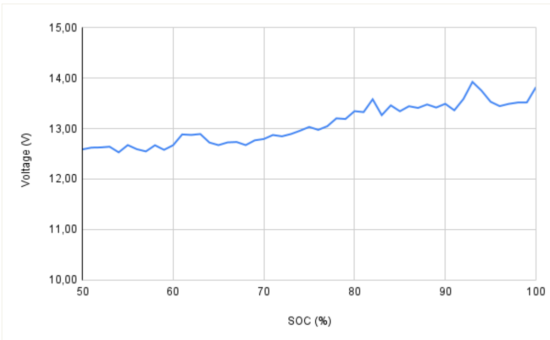

Figure 10. The graph of voltage-SoC during the charging process

3.5. Battery management system

After the battery discharging and charging processes, the estimated SoC values obtained through the coulomb counting method are sufficiently accurate. Thus, these estimated SoC values in the BMS system can be used to control the battery charging and discharging processes. The system is designed such that when the battery discharge is ≤ 50%, a relay is activated to interrupt the flow of electricity from the battery to the load, preventing over-discharging. Similarly, when the battery charging reaches 100%, a relay interrupts the flow of electricity from the PV to the battery to prevent over-charging. This system is implemented through IoT using the Blynk platform, as depicted in Figure 11.

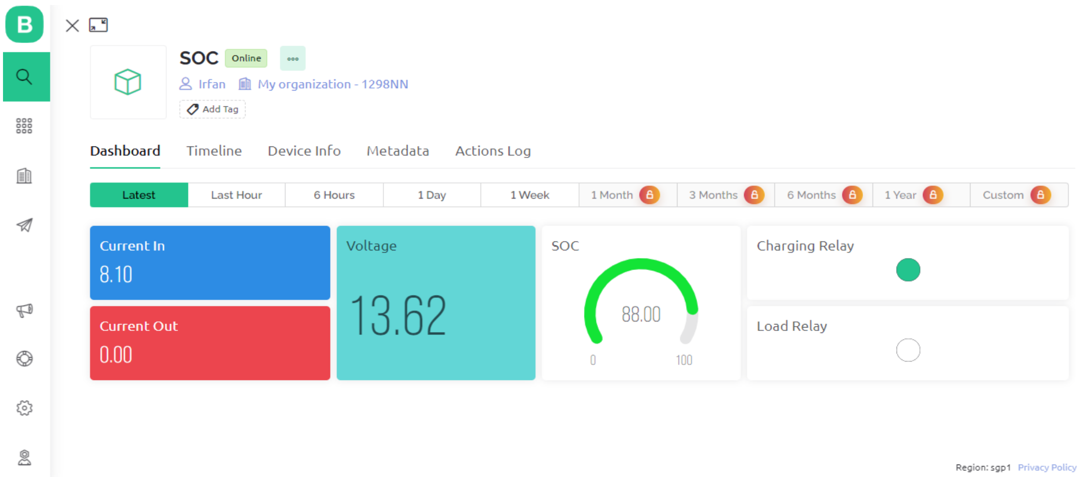

Figure 11. User interface of the battery monitoring system via Blynk platform

The BMS system in this design can be remotely monitored through Blynk. The presented information includes incoming and outgoing current values, battery voltage, battery SoC, and relays for preventing over-charging and over-discharging. This remote monitoring capability allows users to keep track of the battery's performance and take necessary actions to ensure its proper operation.

4. CONCLUSION

The coulomb counting method utilized in this system can accurately estimate the charged battery capacity with adequate precision. The coulomb counting algorithm reliably estimates the battery's SoC value by calculating the incoming and outgoing currents. The maximum voltage is set at 14 V, equivalent to 100% SoC, and the minimum voltage is set at 11.6 V, equivalent to 20% SoC. The BMS uses two normally closed relays as part of system management. The first relay turns on when the SoC reaches 100% full charge with 14 V voltage and turns off when the SoC decreases to 70%. This relay is used to prevent overcharging. The second relay turns on when the SoC reaches 20%, where the voltage drops to 11.6 V. In performance testing, the system successfully provides monitoring and reliable control through Blynk, with a low margin of error. The system can be practically implemented in PV-battery systems, yielding satisfactory outcomes for controlling over-charging, over-discharging, and extending the battery's lifespan.

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