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Application of Power Electronics and Control for Dual Battery Packs Management with Voltage Balancing and State of Charge Estimation

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Abstract

Energy storage, such as lead acid batteries, is necessary for renewable energy sources' autonomy because of their intermittent nature, which makes them more frequently used than traditional energy sources to reduce operating costs. The battery storage system has to be monitored and managed to prevent serious problems such as battery overcharging, over-discharging, overheating, battery unbalancing, thermal runaway, and fire dangers. For voltage balancing between batteries in the pack throughout the charging period and the SOC estimate, a modified lossless switching mechanism is used in this research's suggested battery management system. The OCV state of charge calculation, in the beginning, was used in conjunction with the coulomb counting approach to estimate the SOC. The results reveal that correlation factor K has an average value of 0.3 volts when VM ≥ 12 V and an average value of 0.825 when VM ≤ 12 V. The battery monitoring system revealed that voltage balancing was accomplished during the charging process in park one after 80 seconds with a SOC difference of 1.4% between Batteries 1 and 2. On the other hand, the system estimates the state of charge during the discharging process in two packs, with a maximum DOD of 10.8 V for all batteries. The project's objectives were met since the BMS estimated SOC and achieved voltage balance.

Keywords

State of Charge, Battery Management System, Lead Acid Battery

1. Introduction

There are three sections to this article. The introduction, as was previously described, is part one. The second portion explains the techniques, the third part shows the outcomes of the experiment, and the fourth part comes to a conclusion.

The growing demand for electrical power for social and commercial activities ensures that everyone has access to high-quality, reliable power, which is a key issue in many power supply and distribution systems. As a result, many electric companies are turning to renewable energy sources to make up for the shortfall in conventional power supplies [1]. The accuracy of essential parameters, as well as the appropriate functionality and diagnostics of the battery storage system, determines the effectiveness of electric renewable sources such as wind turbines and PV systems. The storage system needs to be monitored and controlled, so as to avoid critical issues such as battery overcharging, over-discharging, overheating, cell unbalancing, thermal runaway, and fire hazards [2].

Energy storage systems are essential due to the intermittent nature of renewable energy sources in order to ensure power availability during outages. Energy storage helps densely populated cities meet peak energy demands, decrease grid strain, and lower electricity costs. This would increase the efficiency and quality of renewable energy sources, as well as prevent outages during periods of extreme heat or cold, and ensure people's safety [3] [4]. Energy storage systems are divided into various groups. Compressed air, pumped hydro, solar thermal, and fuel cells are all examples of slower responses [5]. Energy sources with a medium response time, such as batteries, and energy sources with a quick response time, such as capacitor banks and secondary conductors are examples of energy storage systems [6]. Because of their versatility in use and construction, battery energy storage systems are an important approach for storing energy in any environment [7]. Sealed-Lead-Acid (SLA), Nickel-Cadmium (NiCd), Nickel-Metal-Hydride (NiMH), and Lithium-Ion (Li-Ion) are some of the battery technologies utilized in energy storage systems [8]. Due to the switching cycle, battery performance degrades with time and is now less than 5 years, although other components of the renewable energy system, such as solar panels, can last up to 25 years [9].

Due to the number of cycles in charging and discharging of batteries its efficiency to deliver the required amount of energy to meet the autonomy decreases [10]. This led to the aging of batteries and hence require their replacement or to add a bank of new batteries for efficient improvement so as to meet load demand [11]. Replacing old batteries which have the capacity to produce a certain amount of energy has economic and environmental impacts, hence, the addition of batteries to meet demand may reduce the effect [12]. It is not advisable to use batteries with varied ages and properties since it might lead to battery leakage and poor device performance. The usage of two packs, with the old batteries in Pack 1 and the new batteries in Pack 2, necessitates the monitoring and control of many parameters for voltage balance and SOC estimates. Since batteries contain hazardous substances like mercury, cadmium, and lead that are damaging to human health and the environment if improperly managed, this will help us safeguard the environment. Additionally, it's expensive to dispose of batteries [12]. Therefore, it is more cost-effective to maintain old batteries that are still functional than to recycle them [13].

This study develops a battery management system that employs modified lossless switching to achieve voltage balancing across batteries in the pack and coulomb counting to estimate the state of charge with an initial open circuit voltage. While charging, voltage balancing is accomplished, and while discharging, the system reacts to the cutoff voltage, which for lead acid batteries is 80% of the depth of discharge.

2. Literature Review

Several research efforts on energy storage systems in various parts of a battery management system have been completed so far. Some methods have been used to solve the problems of voltage unbalance and state of charge estimation, including the use of two separate sets of batteries working alternately in the same system.

In [14], Wang *et al.* proposed a study of "Sizing Optimization and Energy Management Strategy for Hybrid Energy Storage Systems Using Multi-Objective Optimization and Random Forests", in which the multi-objective grey wolf optimizer was used to obtain the Pareto front by first considering the system cost and battery life span, then the offline optimal power splitting result. Under unknown driving cycles, the suggested technique may minimize overall energy loss by 0.74% - 9.49% and battery Ah-throughput by 0.5% - 19.83%. The study developed in [15], Movassagh *et al.* use simulation analysis to provide techniques for decreasing time-cumulative and state-of-charge-proportional errors. The OCV-SOC features of high-capacity batteries under the influence of various temperatures were proposed in [16]. Temperature fluctuations have a considerable influence on the OCV-SOC characteristic curve, according to the findings. The polynomial fitting of the model is simple and uncomplicated. In the battery modeling, the exponential, polynomial, sum of sin functions and Gaussian models are all compared. The open circuit voltage approach is used in [17] to determine the level of charge in a lead acid battery. In this investigation, the OCV was used to inspect the battery during a discharging cycle as the battery voltage was increased and lowered. The coulomb counting method is used to compare the projected SOC using the OCV approach. These two methods assess a distinct value at the beginning and conclusion of a lead-acid battery's discharge cycle, according to the findings. Horkos *et al.* [18] evaluated lead-acid battery charge-discharge cycle performance for accurate SOC computation in dynamic battery operation. A constant current discharge approach was devised for a Valve-Regulated Lead-Acid (VRLA) battery. A close match was found when the State Of Charge (SOC), a performance indicator, was computed and correlated with the coulomb counting technique. Danko *et al.* [19] discuss many methodologies for assessing charge state, which may be divided into direct measurement methods, book-keeping methods, adaptive methods, and hybrid methods. Direct measurement methods are good for basic applications since they need less computing power, but they are inaccurate in specific SOC ranges. The OCV method is straightforward to use, but because a battery cannot be drained to determine SOC, traction batteries can only be examined when the vehicle is stationary. Adaptive estimating approaches have strong accuracy throughout the whole SOC range, but model-based methods have accuracy that is reliant on the complexity and precision of the battery model.

Kim *et al.* [20] developed an individual cell voltage equalizer for series connected Li-Ion battery strings using selective two current paths. Instead of a specialized charge equalizer for each cell with a power rating design guide, a central equalization converter is shared by all battery cells through the cell selection switch in this work. For lithium iron phosphate batteries, an active battery equalization system is proposed. To improve the inconsistency of series-connected lithium iron phosphate batteries, Wang *et al.* [21] developed a battery-equalization system. An equalization circuit with a bidirectional fly-back transformer and a segmented hybrid control technique based on cell voltage and State Of Charge (SOC) constructed. To balance voltage inside the cell pack and determine the SOC, charging voltage curves based on lithium-ion battery pack equalization were utilized. The genuine battery module experiment was carried out in [22]. The capacity was enhanced by 13.03 percent, while the greatest absolute errors of Open-Circuit Voltage (OCV) and State Of Charge (SOC) were 21.9 mV and 1.86 percent, respectively. In [23], the authors used an active charge balancing method to provide online state of charge estimate for a lithium-ion battery pack in this work. Through four switched DC/DC Buck-Boost converters, the capacity of each cell is computed using the SOC function predicted using the Back Propagation Neural Network (BPNN) method. The simulation results show that the developed BMS can effectively synchronize cell equalisation by reducing SOC estimation error (RMSE of 1.20%). Rospawan and Simatupang [24] develop a microcontroller-based lead-acid battery balancing system for use in electric vehicles. The NUCLEO F767ZI microcontroller replaces the LTC3305's functionalities, allowing the balancing process, battery voltage, drawn current to or from the auxiliary battery and surrounding temperature to be properly monitored.

A lossless cell balancing-based battery with software configuration was created. A switching matrix allows for regulated access to each battery cell while allowing for a resting interval to lessen the strain on the batteries and extend battery life. By reducing DOD from 80% to 60%, SHS life goes up by 1.5 years and approximately 4.7 tonnes of e-waste can be avoided [25]. According to the findings, the system is appropriate for mission-critical applications and has a battery life extension of over 20% [26].

A control system based on a Programmable Logic Controller (PLC) for increasing the life of old and new batteries in a pack developed in [27]. Instead of turning off the storage system entirely, this solution allows the autonomy of the current storage system to be adjusted as its capacity declines over time. On the other hand, Katche *et al.* [8] presented a microcontroller-based control system. Using a PIC16F877A microcontroller as the main controller instead of a Programmable Logic Controller (PLC), a system that allows the alternate use of two battery packs (or dual battery sets), referred to as battery Pack 1 and battery Pack 2.

An overview of different applications of power electrons, voltage balance methods, SOC estimation in energy storage, and battery storage management has been presented as conducted by different researchers and noted that the battery management system for two packs with an estimation of SOC and voltage balance as key gaps for this study. The lossless switching voltage balance and OCV with the Coulomb counting SOC estimation method have filled this void.

3. Methodology

This article's goal is to create a battery management system that will enable the alternating usage of two battery packs while balancing voltage across the pack's batteries and monitoring the battery's state of charge. Since just one pack of batteries will be supplying the load at any one time and two distinct packs of batteries will be utilized for storage in the same circuit, the BMS will lengthen the life of the batteries by minimizing the number of charging and discharging frequencies. The old battery set can still be used in conjunction with the new one, increasing overall storage system capacity and reducing the frequency with which batteries must be changed, thus lowering costs. As a result, this BMS will also lower the replacement cost of a standalone system. Decreasing the pace of chemical waste and the production of new battery sets will help benefit the environment. When the batteries in the pack are balanced in terms of voltage, this system will transition from one set of batteries to another. The BMS will charge a low pack while balancing voltage using a lossless switching technique. To ensure the required amount of power from sources to the batteries is given during the charging time, the system will be combined with a charge controller.

3.1. Block Diagram

The block diagram for schematic and circuit design implementations is shown in **Figure 1**. It comprises a switching unit with four relays and four power MOSFETs for switching between two operational packs, standby mode, and charging mode. Additionally, switching has occurred during isolation and series connection. The sensor circuit generates Direct Current (DC) signals that indicate the current, voltage, and temperature of the batteries. The sensor output control signal from the microcontroller is 12 V DC for the battery and 24 V DC for the

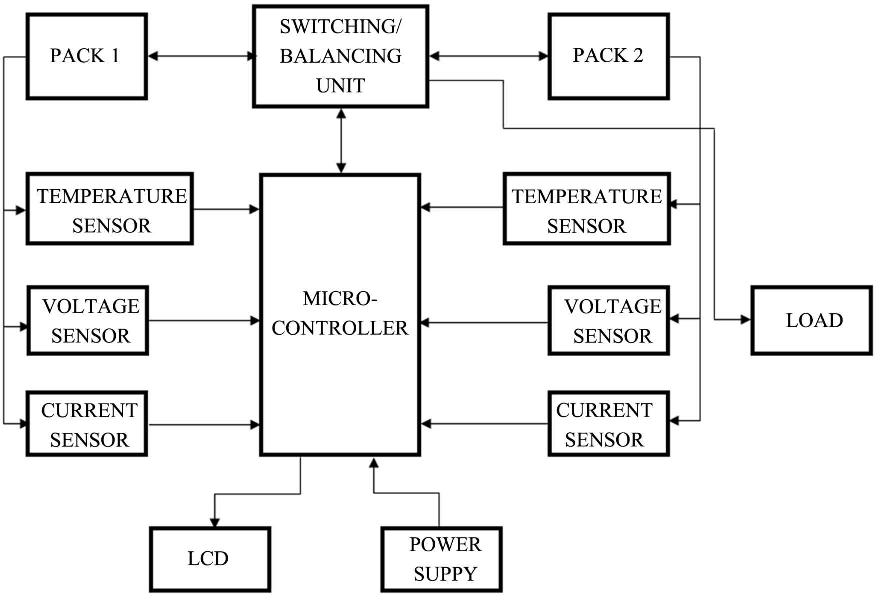

Figure 1. Proposed battery management system block diagram.

pack. Only the charge regulator handles the fully charged and depleted states, which are critical in this sub-battery monitoring system. Depending on the level of voltage handled by the charge regulator, the sensing unit will allow the charging or discharging condition of batteries to move from an empty battery set to one with greater energy. Each battery in a pack is represented by the pack's status, and the display unit also reveals the activity a BMS is taking. Each battery pack in the storage unit with two batteries contains two batteries that supply the load when high voltage is sensed, driving the load alternately. For improved SOC estimates, each battery's current, voltage, and temperature inside a pack are monitored and controlled by a sensor device. Power MOSFETS are used to equalize battery voltage during charging and before authorization for use.

The flow chart of **Figure 2** shows the performance of the system in a coherent manner. P1 and P2 have been used to mean battery Pack 1 and Pack 2 respectively.

3.2. SOC Estimation

In this study, an Arduino Mega-based platform was used to develop the coulomb counting method. The software was developed, which determine the battery temperature, current, Voltage and initial SOC.

3.2.1. Open Circuit Voltage

The open circuit voltage estimation done at the beginning when batteries are connected to the BMS

$$\mathrm{SOC} = \beta_1 \times (V_t - V_m) + \beta_2 \tag{1}$$

where SOC = State of Charge, β_1= Multiplier Constant, V_m = Minimum Battery Voltage, V_t = Maximum Battery Voltage and β_2 = Correction Factor.

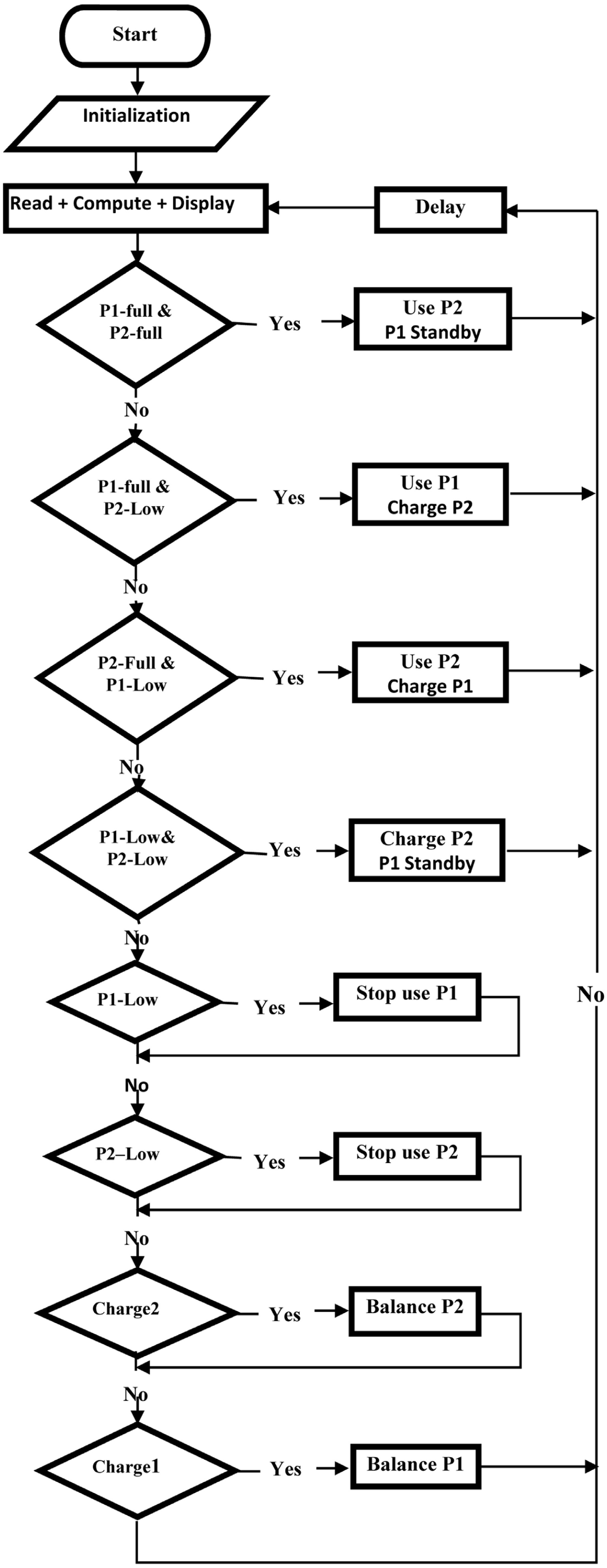

Figure 2. Flow-chart proposed battery management system.

As a result, a battery's OCV (V_{OC}) may be represented as Equation (2) [28], where V_L is the measured voltage when loads are coupled to the battery and K is a value obtained from $V_{oc} - V_L$ after the battery has rested

$$V_{OC} = V_L \pm K \tag{2}$$

3.2.2. Coulomb Counting

The coulomb counting approach for assessing the state of charge measures the discharge current of a battery and integrates it over time to calculate the SOC [29]. Using previously determined SOC values, SOC(t − 1), acquired from the Open Circuit Voltage approach, the Coulomb counting method is used to estimate the SOC(t), which is calculated from the discharging current, $I(t)$.

$$\text{SOC}(t) = \text{SOC}(t-1) + \frac{I(t)}{Q_n}\Delta t \tag{3}$$

where SOC(t) is the SOC in the present time, SOC(t − 1) is the SOC in the previous time step, $I(t)$ is the battery current in the present time, Δt is the duration of each time step, Q_n is the rated capacity of battery in Ah.

3.2.3. Battery Balance

Battery balancing is a technique in which voltage levels of every individual Battery connected in series to form a **battery pack** is maintained to be equal to achieve the maximum efficiency of the battery pack. Variations in voltage levels induce battery unbalancing, which can result in Thermal Runaway, Battery Degradation, or Incomplete Pack Charging. An active voltage balancing between the batteries in the pack was designed to reduce these impacts.

3.3. Lossless Switching Balance Method

Lossless balancing is a method that reduces losses by reducing the hardware components and providing more software control to makes the system simpler and easier to design. This method uses a matrix switching circuit which provides the capability to add or remove a battery from a pack during charging and discharging (**Figure 3**).

A path to software-controlled batteries is now open according to the updated switching matrix, which enables control of each battery separately. Utilizing current and voltage sensors allowed the hardware to run according to the SOC of each battery and the pack. A battery may be charged concurrently with balancing voltage and state of charge estimation due to the measured current, voltage, and state of charge estimation, and a battery with a high voltage can be taken out of the charge using switch arrangements (**Figure 4**).

3.4. Design Prototype for the Proposed Circuit

Experimental arrangements for correlation factor K determination and BMS testing were achieved, as shown in **Figure 5** and **Figure 6**, respectively. The circuit was developed in Proteus software, and a Printed Circuit Board (PCB) was created on which the components were mounted, as shown in **Figure 7**.

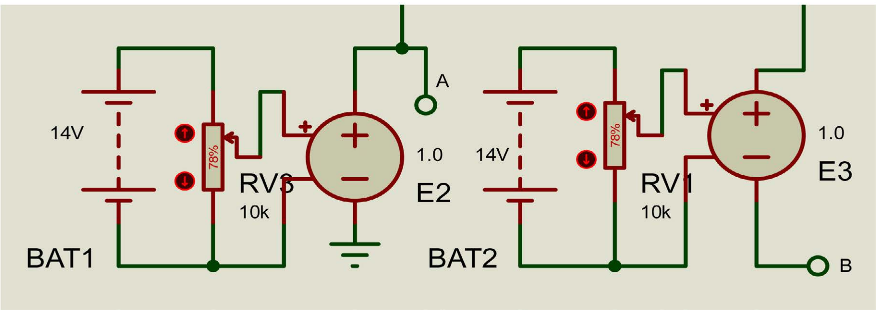

Figure 3. Typical voltage and current profile for a constant current discharge.

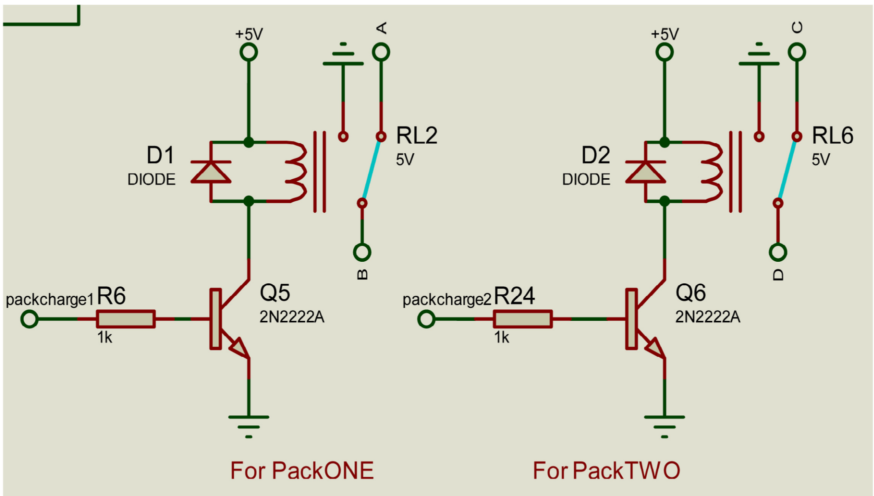

Figure 4. Relay switch for isolation mode and series connection mode.

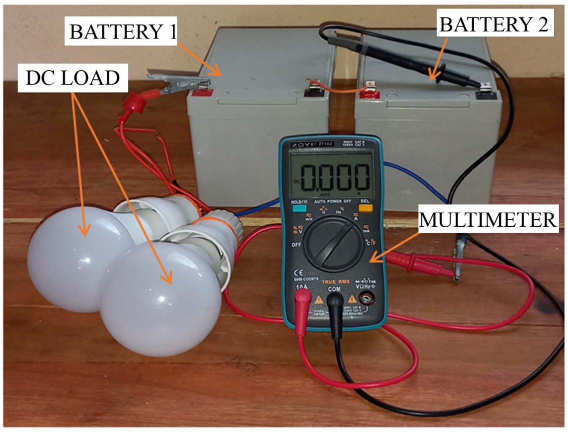

Figure 5. A complete experimental arrangement for K determination.

4. Results and Discussion

Balancing results and state of charge estimate outcomes make up the two primary sections of this study's findings. Two techniques, including open circuit and coulomb counting state of charge estimate, have been used to obtain the SOC estimation findings. Additionally, the lossless switching technique was created to balance the voltage within the pack.

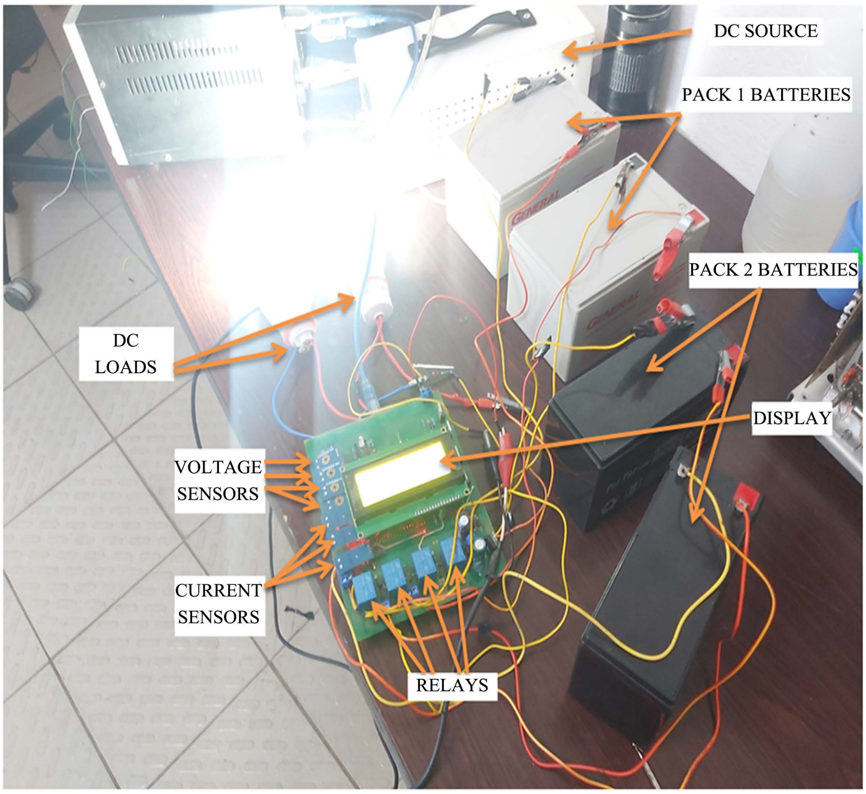

Figure 6. Experimental set up for BMS testing.

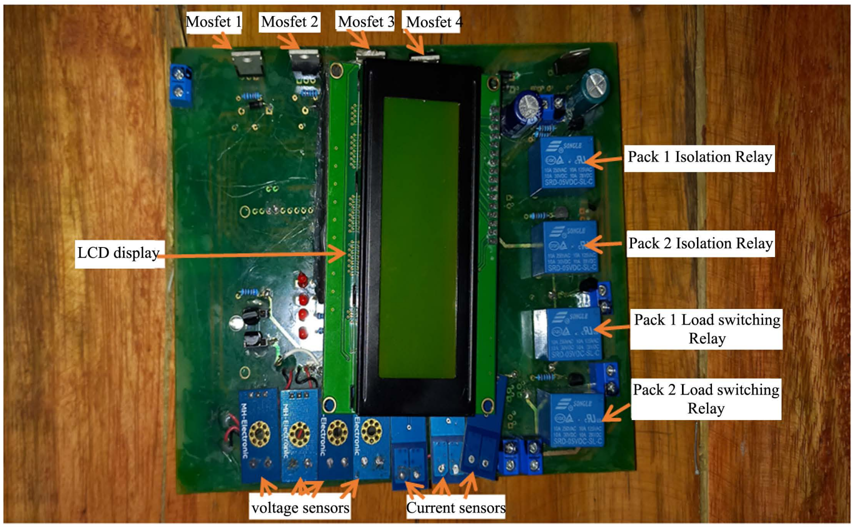

Figure 7. Printed Circuit Board (PCB) with fixed component.

The system can estimate the SOC of charge between batteries in the pack and balance the voltage between them, as well as alternate pack usage by loading when fully charged. As from **Table 1**, when Pack 1 was balanced, relay 3 closed for Pack 1 to be used while Pack 2 was charging for balancing. As Pack 1 reached the maximum DOD while Pack 2 was balanced, the system allowed Pack 2 to be used by the load with a relay switching time of 3 milliseconds.

Table 1. Lookup table for determination of K and OCV SOC.

		Battery Voltage after 10 Min Resting Time			Battery Voltage with 24 Watt Load		
Current (A)	Time min	B1 (V)	B2 (V)	Pack (V)	B1 (V)	B2 (V)	Pack (V)
0	0	13	12.9	25.9	12.7	12.6	25.3
0.8	60	12.9	12.9	25.8	12.6	12.6	25.2
0.78	120	12.9	12.8	25.7	12.6	12.5	25.1
0.79	180	12.8	12.7	25.5	12.5	12.4	24.9
0.82	240	12.7	12.7	2.4	12.4	12.4	24.8
0.84	300	12.6	12.6	25.2	12.3	12.3	24.6
0.85	360	12.5	12.5	25	12.2	12.2	24.4
0.81	420	12.4	12.4	24.8	12.1	12	24.1
0.77	480	12.3	12.2	24.5	12	11.9	23.9
0.73	540	12.3	12.1	24.3	11.9	11.8	23.7
0.68	600	12.1	11.9	24	11.3	11.2	22.5
0.62	640	12	11.8	23.8	11.2	11	22.2
0.56	700	11.9	11.7	23.4	10.6	10.6	21.2

4.1. Correlation Factor K Determination

Using the experimental data obtained from the EUR1212 Valve Regulated Lead Acid battery for Pack 1 and the identification and SOC estimation techniques, we evaluated the efficiency and accuracy of the BMS performance. The load was attached to two series batteries to determine the correction factor K.

A table displaying the data is followed by graphs that provide an analysis. For each $V_M > 12$ V, the conditional correlation between K and V_M has a negative gradient. With an average K-value of 0.3 volt for $V_M > 12$ volts, the K-value is comparatively constant (see Figure 8).

4.2. BMS Testing Results

The battery management system is linked to four batteries, presenting Pack 1 and Pack 2, a load of 24 W, and a charging DC source, and the switching logic was seen to be maintained as shown in the flow chart. Figure 2 depicts the results of testing with resistive static DC loads. Because Battery 1 SOC was smaller than Battery 2 SOC when the BMS was attached to the batteries, all relays and MOSFETs were in standby mode. Relay 1 and MOSFET 1 were activated to isolate and charge Battery 1. MOSFETs 2 and 3 were both switched on simultaneously. When Pack 2 was fully charged, relay 4 activated to connect the Pack to the load, while MOSFETs 3 and 4 and relay 2 turned off to disengage the batteries from charging and link Pack 2 batteries in series. The charging and discharging procedures are permitted during this test under regulated conditions

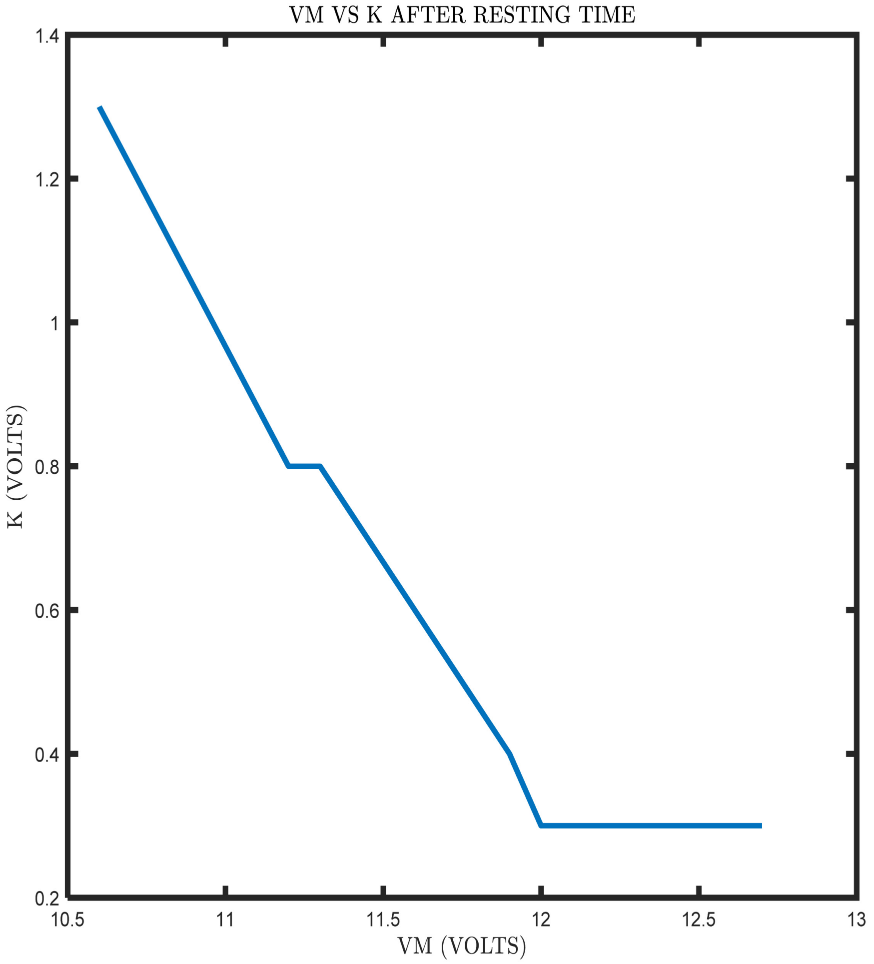

Figure 8. Correlation between measured voltage V_M under loaded condition and correction parameter K.

with current ratings of 3.6 A and 1.30 A, respectively. The SOC is determined by applying Equation (3), while the results pertaining to these variables are directly plotted from the lessons of the appropriate sensors.

4.3. Balancing Test Results

The lossless switching mode created by the voltage equalisation approach is particularly efficient and effective. A balancing system that also made sure that all the batteries had an equal SOC before being used by the load enabled two batteries to be charged to a maximum voltage of 13.0 V in isolation. During charging, the balancing procedure in Pack 1 achieves a 1.4% SOC difference between batteries 1 and 2 for 80 seconds (Table 2).

The balancing time with respect to the state of charge has been attained, as indicated in Figure 9. From 46.6 percent SOC in Pack 1, Battery 1 takes 80 seconds to achieve 48.6 percent SOC in Battery 2. As in Figure 10, the results demonstrate the algorithm's success. As demonstrated on the graph, a linear relationship exists between SOC and time.

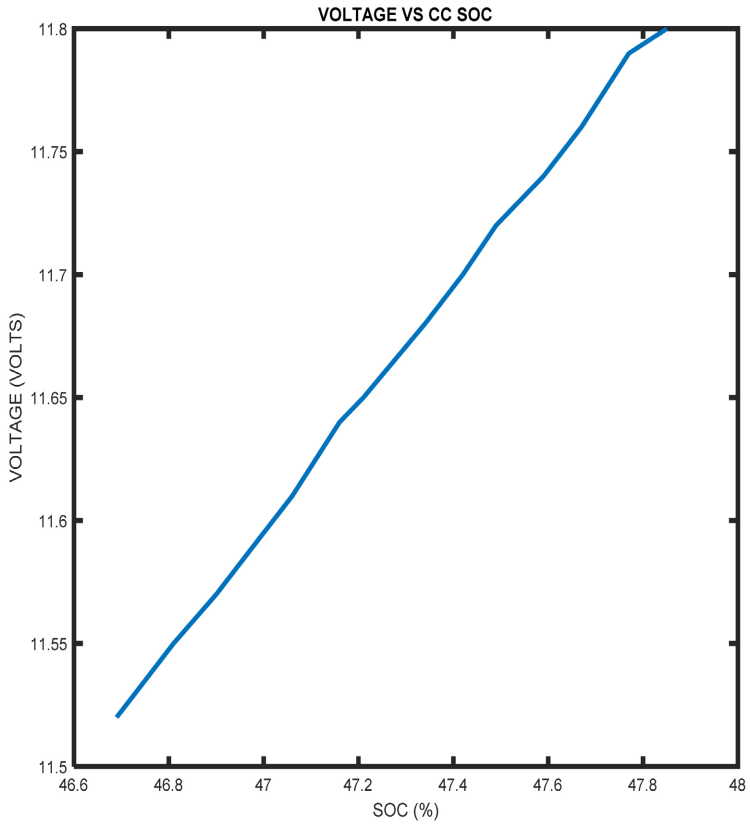

Figure 9. The SOC with voltage during balancing Pack 1 using BMS.

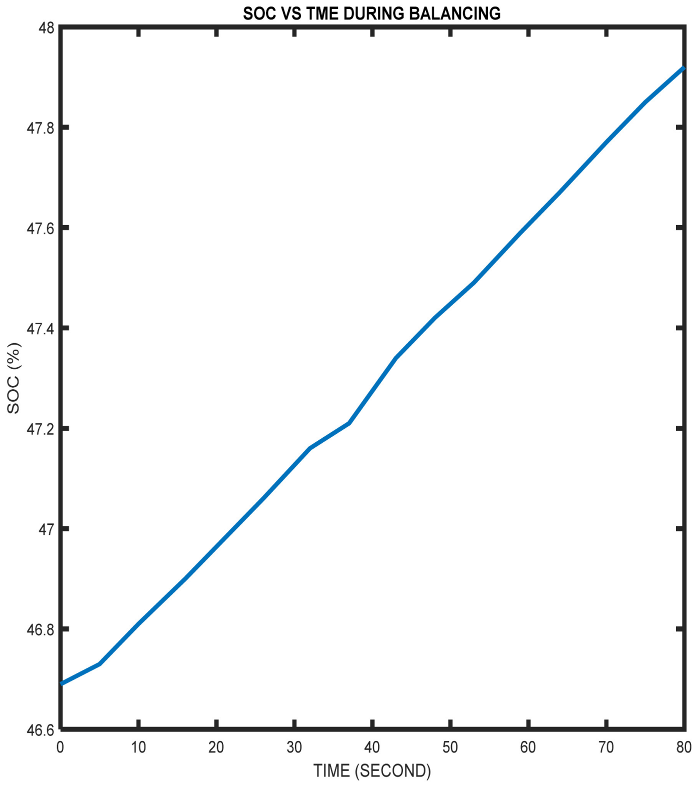

Figure 10. The SOC with time during balancing Pack 1 using BMS.

Table 2. State of charge with voltage during balancing time.

SOC (%)	Voltage (V)	Time (S)
46.69	11.52	0
46.73	11.53	5
46.81	11.55	10
46.9	11.57	16
46.98	11.59	21
47.06	11.61	26
47.16	11.64	32
47.21	11.65	37
47.34	11.68	43
47.42	11.7	48
47.49	11.72	53
47.59	11.74	59
47.67	11.76	64
47.77	11.79	70
47.85	11.8	75
47.92	11.84	80

4.4. Discharge Test with BMS

The battery was discharged using a BMS with identical values of the load current intensity. Because of the load consumption over a specific period, the current is observed to alter as the state of charge decreases. The voltage seems to be constant at 13.1 V up to 12.22 V and 12.29 V for Battery 1 and Battery 2, respectively before the system is connected to the load. The current appears to be constant at 1.3 A on average.

$$\mathrm{SOC}(\%) = 43.466V_{B1} - 484.12 \tag{4}$$

Figure 11 and Figure 12 depict the experimental results and demonstrate how the BMS may be programmed to cut off power to the load when Battery 1 hits 10.82 V and Battery 2 reaches 11.7 V. The fact that the cut-off voltage is 10.8 V for every battery in the pack demonstrates the precision of balancing throughout the discharging phase. The relay module was able to attain a 3 milliseconds stand-by mode switching time.

The discharging tests for the battery pack in Figure 13 illustrate that the SOC and voltage have a linear relationship with a positive gradient since the R-square value is approximately 1.

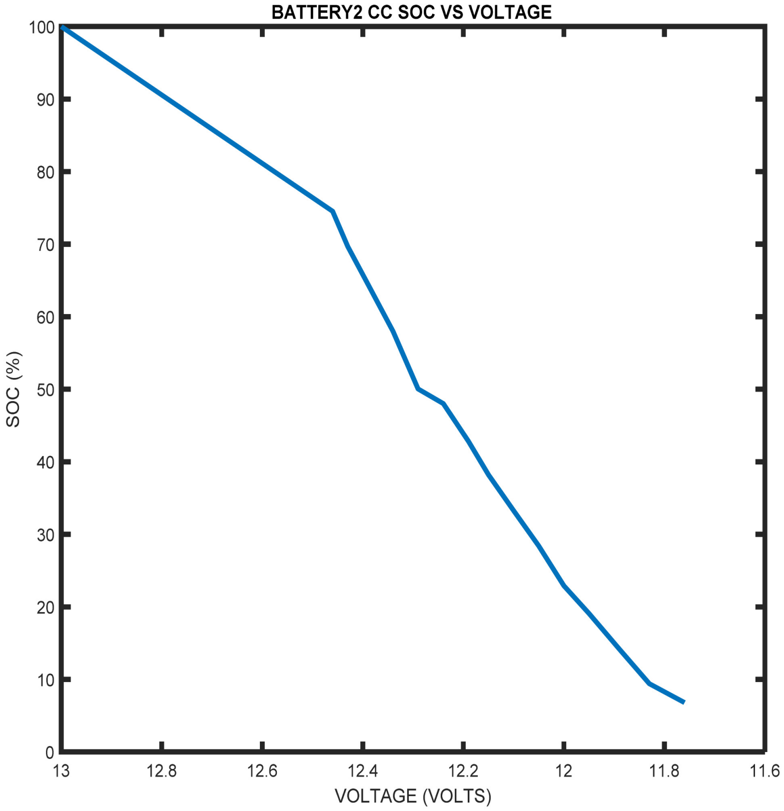

Figure 11. The graph of Battery 2 during discharging using BMS.

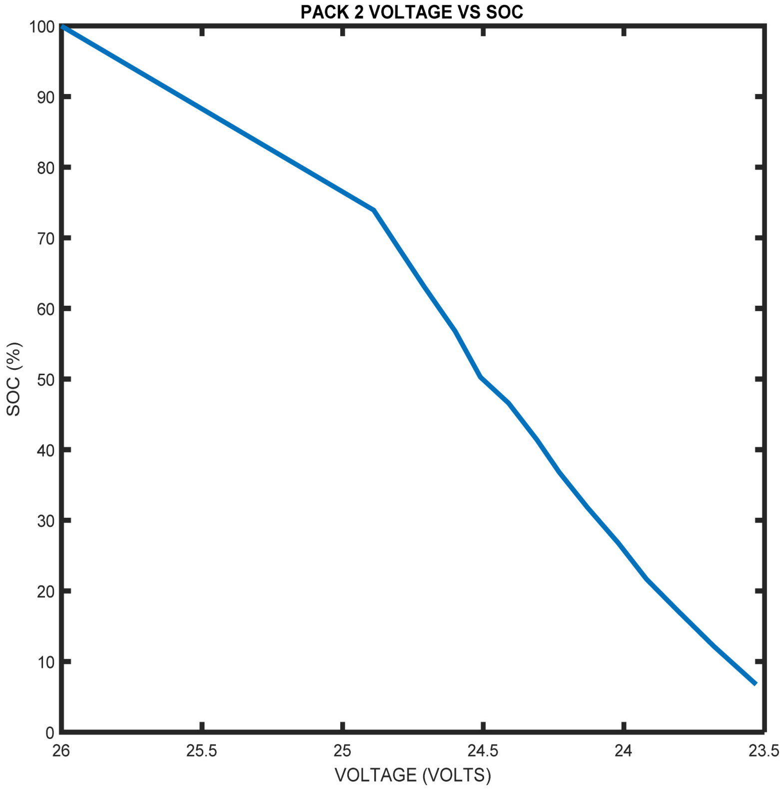

Figure 12. The graph of pack during discharging using BMS.

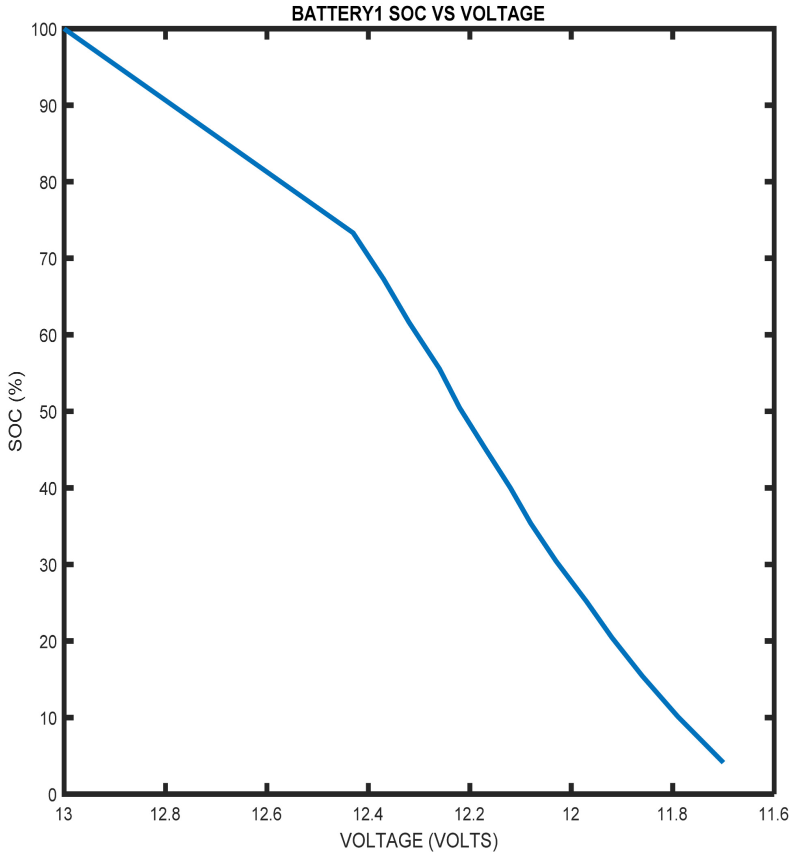

Figure 13. The graph of Battery 1 during discharging using BMS.

5. Conclusion

Through testing, the effectiveness of the recommended BMS was compared with some design-based SOC and voltage balancing. Readings for the proposed battery management system's voltage, current, state of charge, and temperature are all within acceptable bounds. By using the coulomb counting for the SOC estimate and the lossless switching approach during voltage balance, the project's goals were satisfied. With a state of charge differential of 1.4% between the 46.6 percent SOC of Battery 1 in Pack 1 and the 48.6 percent SOC of Battery 2, it took 80 seconds to complete the balancing process. Furthermore, the experimental results demonstrate how the BMS may be programmed to cut off power to the load when Battery 1 hits 10.82 V and Battery 2 reaches 11.7 V. The fact that the cut-off voltage is 10.8 V for every battery in the pack demonstrates the precision of balancing throughout the discharging phase. The findings indicate that the system cannot determine the age of batteries used in a pack, which is an area for future research.

6. Recommendations

Energy storage management has grown in importance as a means of increasing battery life and reducing replacement costs as a result of the rising usage of renewable energy. For future improvements in system accuracy and performance, further research is needed, particularly in switching voltage and current sensing units.

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Conflicts of Interest

The authors declare that there are no conflicts of interests.

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