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FINAL REPORT

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Abstract

The battery system is affected by several factors, including cell imbalance. Without a balancing system, battery capacity and life quickly decrease over time. This will cause the entire battery system to fail. Thus, cell balancing has an important role in preserving battery life and performance. This report is presented various cell balancing methodologies and particularly, a comparison of passive cell balancing in detail. The cell balancer modelling of passive cell balancing technique with three serially connected cells is presented based on MATLAB/Simulink. Since three passive cell balancing circuits are compared and the algorithm and the switch have different efficiencies such as time and error values, the algorithm and the switch thus affect the efficiency of the passive cell balancing circuit. In addition, a study on cooling systems and coolants is proposed to reduce the efficiency of BMS, which is the limitation of passive cell balancing.

Introduction

Global warming has become a challenge as carbon dioxide increases around the world (Florides and Christodoulides, 2009). Thus, one of the various ways to solve global warming is the arrival of electric vehicles. Existing internal combustion engine vehicles emit carbon dioxide (Hausberger, 2011). However, electric vehicles can contribute to reducing carbon dioxide emissions (Dong et al., 2019). In electric vehicles, batteries are essential, but lithium-ion batteries have high energy efficiency and power density, so they can be designed to be light and small, therefore, they are considered as suitable batteries for electric vehicles (Chen et al., 2012; Hu et al., 2017). However, as lithium-ion batteries have a large capacity and are connected in series sequentially, they have limitations in terms of cost, stability, and reliability (Lu et al., 2013). In addition, lithium-ion batteries have risks such as over-charge and over-discharge, overvoltage, low voltage, and cell voltage imbalance (Hemavathi, 2020; Wen, 2009). A battery management system has been introduced to prevent these risks.

The battery management system (BMS) is a system for improving energy efficiency and extending life by optimally managing batteries. There are many functions of BMS software but the one of the most important parts is battery equalisation (balancing) because one of the factors that quickly reduce the capacity and life of the battery is the imbalance between cells (Lu et al., 2013; Cheng et al., 2011). The types of cell balancing are largely divided into active balancing and passive balancing. First, there are two methods of passive balancing: the Fixed Shunting Register and the Switched Shunting Register (Kıvrak et al., 2019). The fixed shunting registers are not suitable for lithium-ion batteries but for nickel and lead acid batteries (Moore and Schneider, 2001). In the case of the switched shunting register, this method requires a controller for controlling a circuit by connecting resistors in parallel with each series connection cell through a controlled switch/relay to adjust each cell voltage (Hemavathi, 2020). Second, active balancing uses storage elements such as capacitors or inductors that transfer energy from high to low charge cells until all cells are balanced. It can also be used for charging and discharging operations (Daowd et al., 2011).

Generally, since a battery management system is expensive, making it inexpensive and efficient is one of the main challenges. Therefore, it is possible to choose between passive balancing and active balancing focusing on the price aspect. The biggest advantage of passive balance is price (Daowd et al., 2011; Hemavathi, 2020; Omariba, Zhang and Sun, 2019; Uzair, Abbas and Hosain, 2021). It is much cheaper than active balancing because it is simple and does not require many parts. In addition, it is easier to control and implement than active balancing based on a circuit design. Therefore, although passive balancing is less efficient because energy and thermodynamically lost than active balancing, it can be an appropriate method for modelling cell balancing circuits.

The aim of this report is to model an efficient BMS circuit by comparing three passive cell balancing circuits and applying the more efficient circuit to the BMS circuit. In addition, when comparing the efficiency of the three passive balancing circuits, this report explores whether the algorithm and the switch affect the efficiency.

Methods

Passive cell balancing is a method that consumes a fully charged high voltage capacity with resistance so that the remaining cells can continue to charge (Samaddar, Senthil Kumar and Jayapragash, 2021). In addition, during passive cell balancing, the first discharged cell is controlled to stop discharging without over-discharging, and the over-charged state is consumed as the resistance when one cell is over-charged. For the voltage of all cells to be the same, the capacity of all cells must be the same as the weakest cell. As a simple example, Figure 1 shows that it is assumed that there are three cells, A, B and C, in which the State of Charge (SoC) is 30%, 50%, and 70%, respectively, before balancing the cells. In the case of passive cell balancing, energy is dissipated from the cell with a high SoC, and all cells reach the same level of SoC as the lowest cell, resulting in cell C (30%).

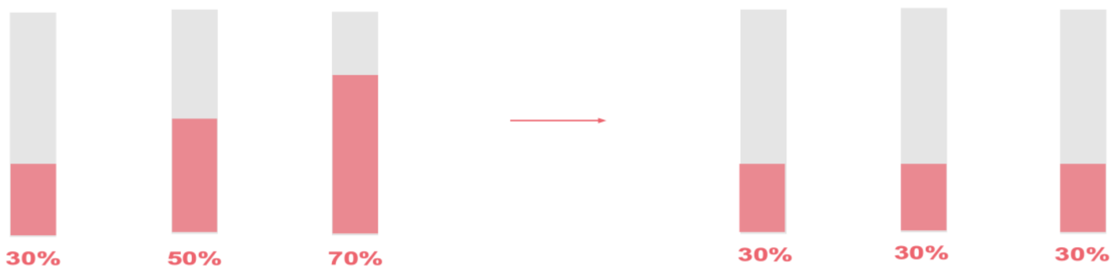


Figure 1. Diagram of example methodology of passive cell balancing

This report compares passive cell balancing techniques using MATLAB/Simulink. The comparison target is three different passive cell balancing circuits, and the circuits are Scheme 1, Scheme 2 and Scheme 3. Although the overall configuration of the circuits is similar, the only differences are the type of switches and algorithm, which are therefore considered very significant within the circuit. All setting values such as SoC of battery, nominal voltage, rated capacity, and battery response time are the same.

Figure 2, 3 and 4 show passive cell balancing circuit diagrams. They consist of three lithium-ion battery cells connected in series. These lithium-ion batteries are connected to a switch connected to the load resistance. The load resistance value is measured as 3 Ω. The switch is different for each circuit, and the switch in Scheme 1 is MOSFET, Scheme 2 is IGBT, and Scheme 3 is Ideal Switch. The initial charge state of lithium-ion battery needs to be verified for passive cell balancing, so several batteries have different charge state. That is, the SoC of each cell is different. One cell's SoC is set at 15, another cell is set at 35, and the other cell is set at 50. In addition, the battery's nominal voltage is set to 3.7 V, the rated capacity is set to 2.6 Ah, and the battery response time is set to 30 s.

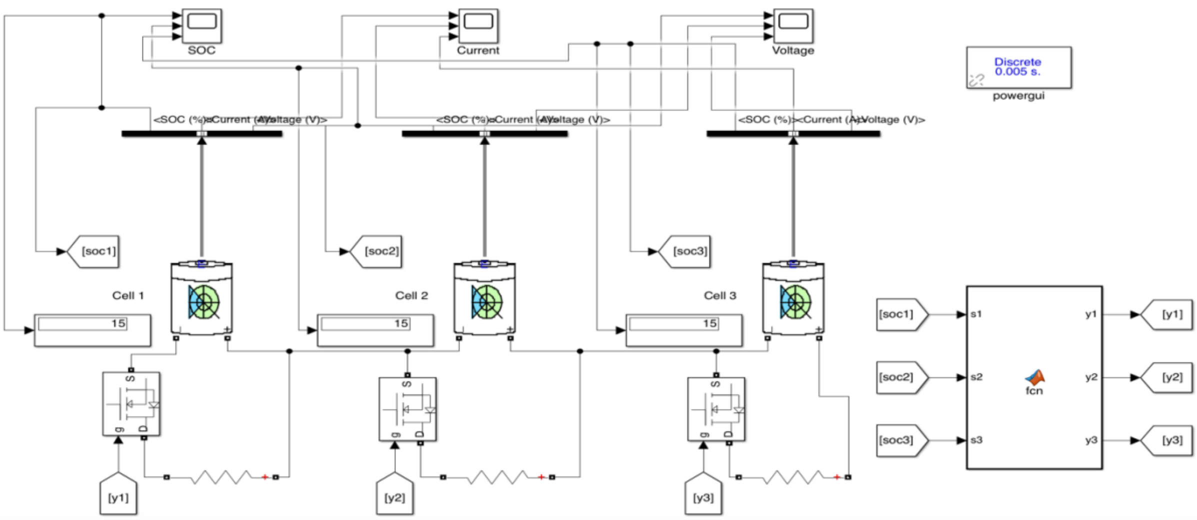


Figure 2. Diagram of Scheme 1’s passive cell balancing circuit

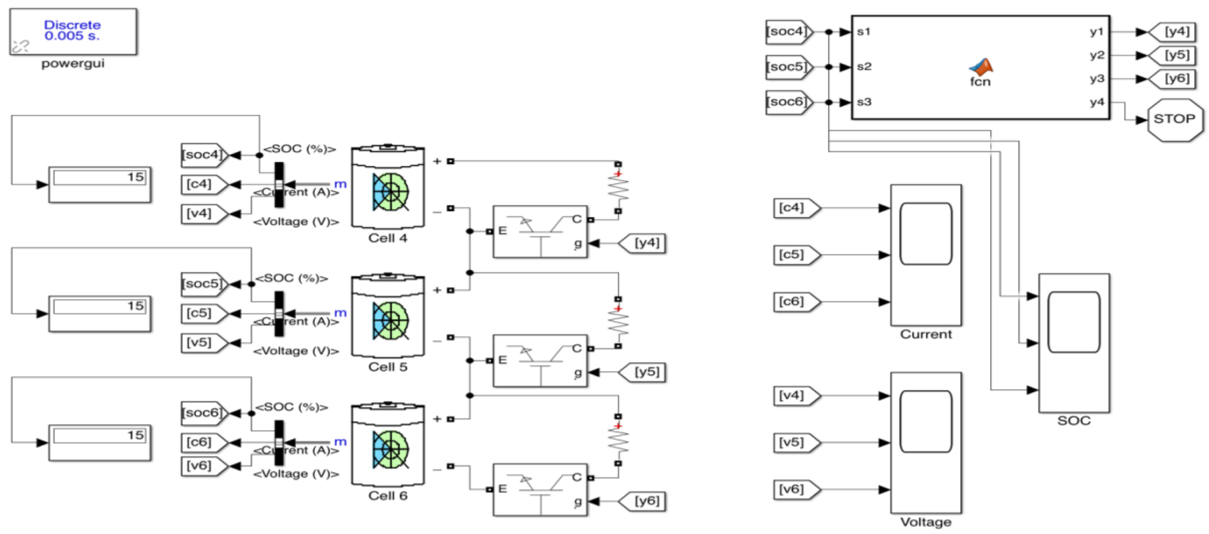


Figure 3. Diagram of Scheme 2's passive cell balancing circuit

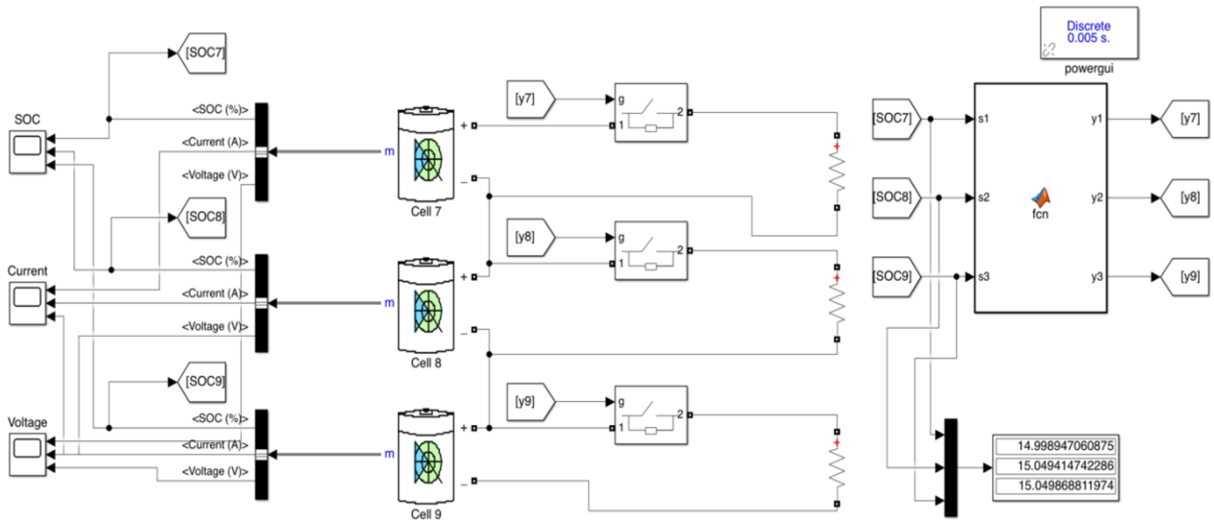


Figure 4. Diagram of Scheme 3's passive cell balancing circuit

The circuits include various components such as a resistor, switch, lithium-ion battery, MATLAB function, display, bus selector, and scope. The SoC, current and voltage is represented by the scope. The bus selector is interconnected with the battery, and measurable factors are selected within the battery, which are the voltage, current and SoC. Therefore, through this bus selector, the battery's voltage, current, and SoC are analysed and derived through the scope. In addition, the real-time state of the battery's SoC, current and voltage is observed through the display. The MATLAB function is designed by following an algorithm to balance the SoC of lithium-ion battery using switches. The algorithm activates the switch that charges the cell from the high-charge battery to the low-charge battery. In the SoC, the compiled code is given to the MATLAB function, and the SoC of each cell is compared. The system operation is relatively easy, as the charge in the high cell is reduced to the lowest cell and balanced. In this process, the charge of the high cell is dissipated by heat. The resistor connected to the cell is more resistant to the cell with more charges. The algorithm designed for passive cell balancing compares the SoC of all three cells and equalises the cell arrangement based on the battery cell in the lowest charged state. If all three cells have the same SoC, the switch is powered off.

The way this algorithm works is first predetermined by the algorithm system at the SoC of the battery. The algorithm system learns the SoC of each cell in the battery for passive cell balancing. Based on this, balancing is performed by comparing it with the cell voltage. In a typical operation, the system estimates the amount of charge in each cell and charges or discharges the battery. If it does not operate normally, the system will not be able to protect the battery and vehicle from any damage.

The algorithms of detailed passive cell balancing in the MATLAB function are designed differently, and the algorithm in Scheme 1 circuit uses the minimum value to design passive cell balancing. It is a design in which among the three cells, if the SoC of one cell is set to the minimum value, it is compared with another cell, and if they have the same value, only the other cell receives the load resistance. If the minimum value does not have the same value as the other two cells, the two cells receive the load resistance. Therefore, passive cell balancing is stopped when the minimum value and the other two cells have the same value. Unlike Scheme 1, the algorithm of Scheme 2 and 3 is a design in which the minimum value is not set but is compared one by one. That is, it is the design that the SoC of one cell is compared with the other two cells, and if it is larger than one of the two cells, the load resistance is applied. If it is less than two cells, the cell receives no load resistance and the next cell is compared to the other two cells in the same way. In the Scheme 2 circuit, one stop output is generated additionally to stop the balancing if all cells are equal. As a result, since they are designed with different algorithms, the results of passive cell balancing differ, and more efficient algorithm is adopted.

The passive cell balancing circuit is used when the BMS circuit is designed. After each circuit's results are compared among the Scheme 1, Scheme 2 and Scheme 3, the most efficient of them is used for BMS circuit which is as followed by Figure 5. The BMS circuit is designed to equalise cells with different SoC through passive cell balancing and then charge and discharge the cells equally. In the BMS circuit, the cells' SoC, current, and voltage are monitored in real-time by the display to prevent over-charge and over-discharge. The BMS circuit includes many components such as the bus selector, battery, scope, display, MATLAB function, resistor, switch, and a DC voltage source. The DC voltage source and the resistor are used for the charging and discharging of the circuit, and the switches control the charging, discharging, and balancing. The amplitude of the DC voltage source is 12.6 V. In the Switch that controls charging, discharging, and balancing, the Ideal Switch is adopted as a switching device. The remaining components have the same conditions as the components of the passive cell balancing circuit.

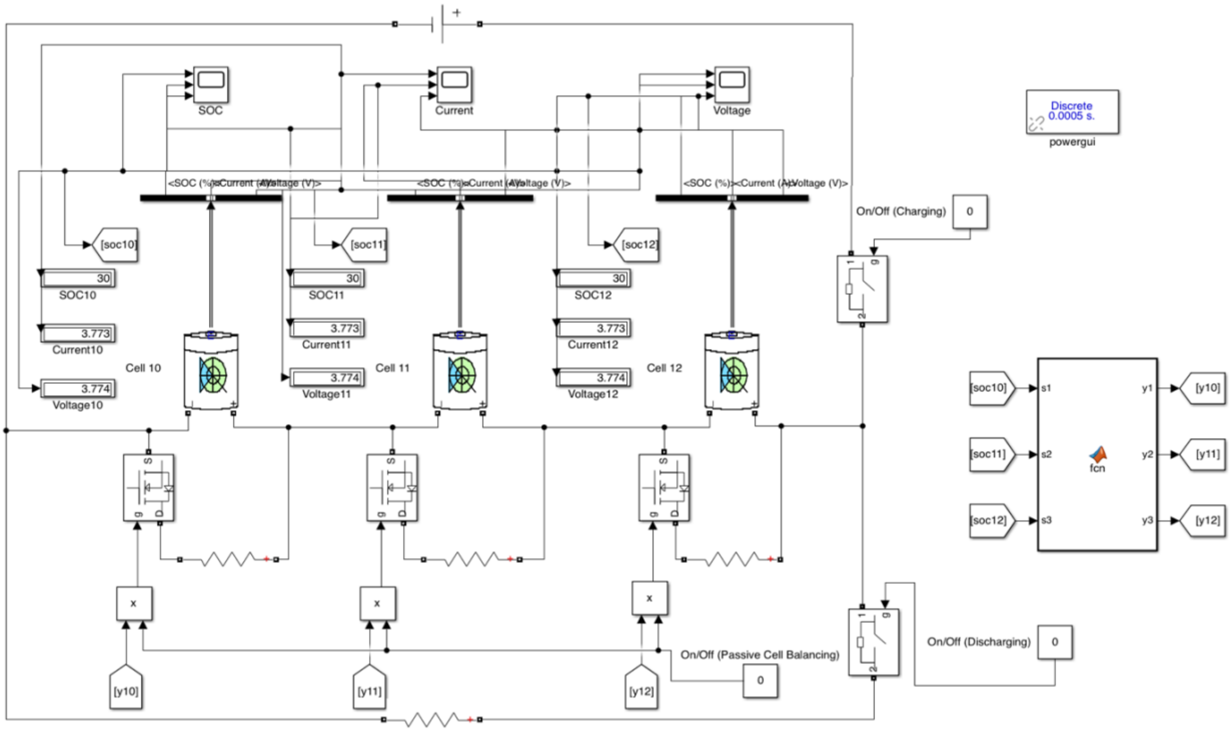


Figure 5. Diagram of BMS's circuit

Results

Graphs show the values of current and voltage at specific values of SoC, since the SoC decreases over time, the values of current and voltage change.

The following shows the results of SoC, current and voltage of Scheme 1, Scheme 2 and Scheme 3.

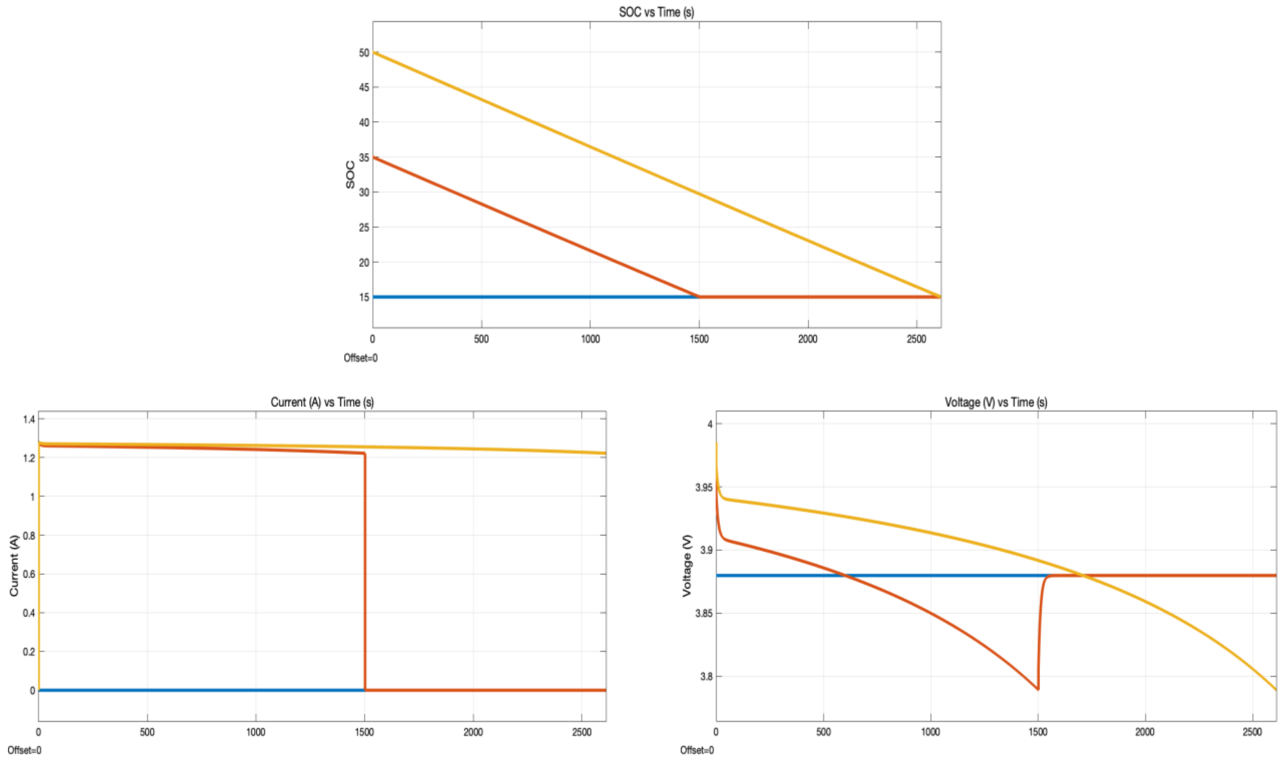


Figure 6. Graphs of Scheme 1's SoC, Current and Voltage versus Time

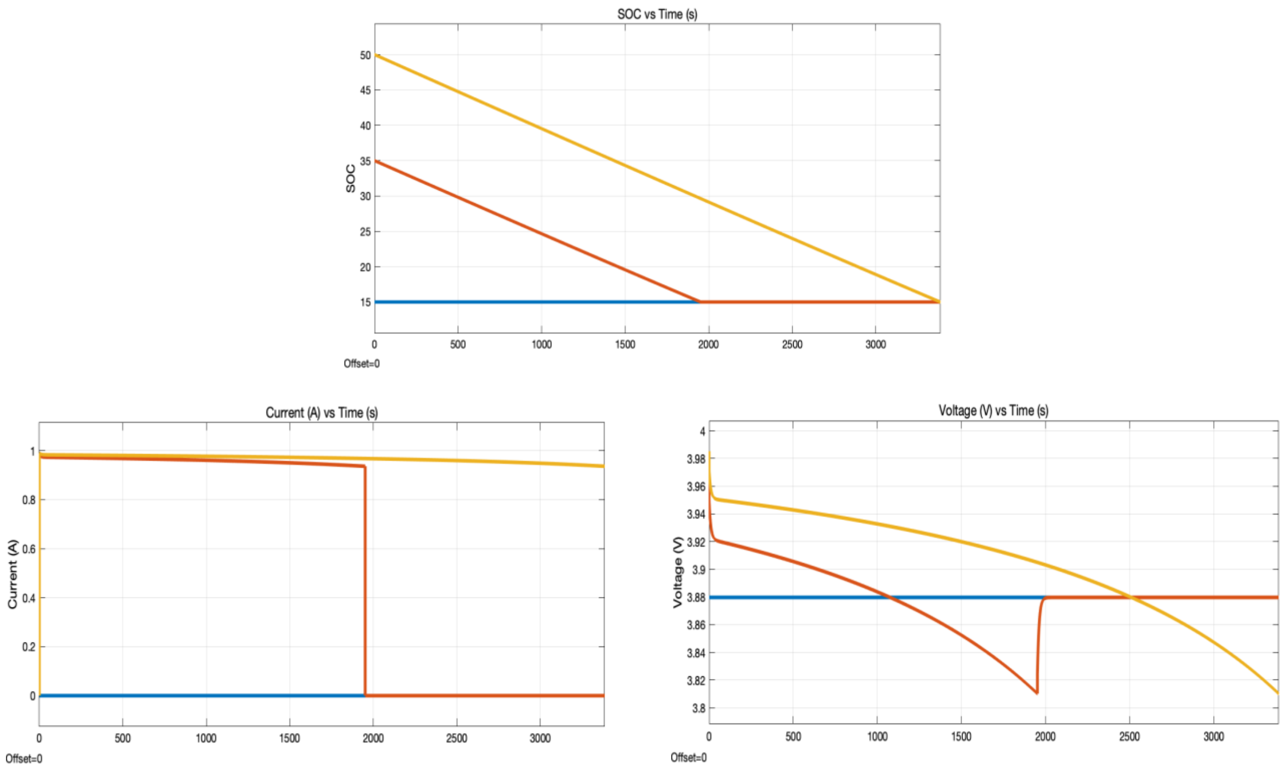


Figure 7. Graphs of Scheme 2's SoC, Current and Voltage versus Time

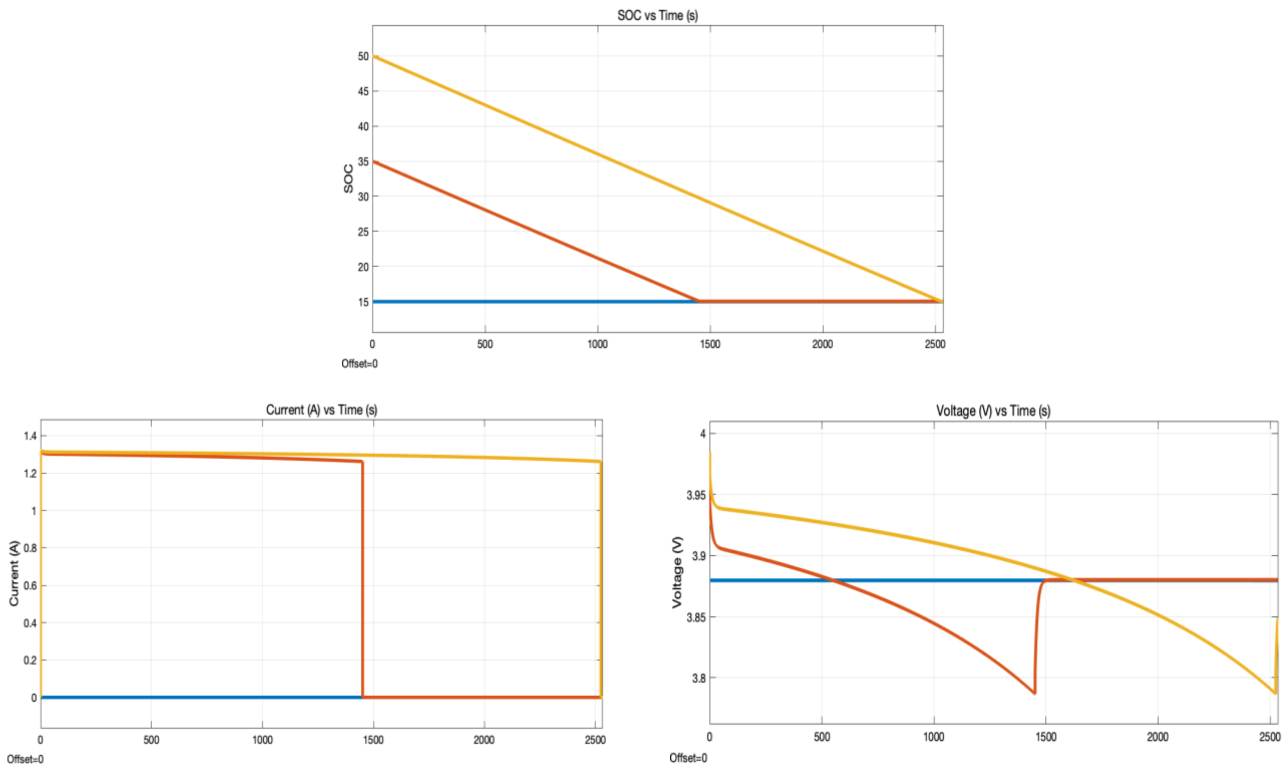


Figure 8. Graphs of Scheme 3's SoC, Current and Voltage versus Time

Firstly, Figure 6 shows the SoC, current and voltage values in Scheme 1 circuit. Cell 1 is blue, Cell 2 is red, and Cell 3 is yellow. In the case of SoC, the lowest SoC becomes a standard, and the remaining two SoC tend to decrease due to the load resistance. Cell 1 has the SoC of 15, and the original value is maintained until balancing is completed from the beginning. While Cell 1 continues to maintain the constant state of 15 from 0 s to 2,600 s, Cell 2 continues to have an initial value of SoC starting at 35 and equal to Cell 1's value of 15 at 1,500 s, after which balancing is completed. Cell 3 begins with an SoC of 50 and constantly decreases until 2,600 s before reaching 15. As a result, Cell 1, which is the lowest SoC, 15 remains constant from beginning to end, and Cell 2 and Cell 3, which are SoC of 35 and 50, reach 15 in turn. They are all equal to the lowest SoC value of 15. In the case of current of Scheme 1, The value of the current in Cell 1 is 0 A, and Cell 2 decreases slightly to 1.25 A for 1,500 s, then drops sharply to 0 A at 1,500 s and remains constant until 2,600 s. Like Cell 2, Cell 3 has an initial value of 1.25 A, but it is shown that it steadily decreases very slightly up to 2,600 s without a sharp decrease. For voltage, the voltage value of Cell 1 starts at 3.88 V and maintains constant until 2,600 s. Cell 2 starts at 3.95 V and decreases to 1,500 s, then decreases to 3.8 V at 1,500 s, and then increases rapidly to 3.88 V, like Cell 1. Cell 3 has an initial value of about 3.98 V and then gradually decreases to 2,600 s.

Secondly, Figure 7 shows the SoC, current and voltage in Scheme 2 circuit. Blue is Cell 4, red is Cell 5, and yellow is Cell 6. For the SoC of Scheme 2, Cell 4 begins with an SoC of 15 and remains constant for 3,500 s. Cell 5 decreases at an SoC of 35 up to 1,900 s and remains constant at the value of 15 at 1,900 s. Cell 6 starts with an SoC of 50 at 0 s, constantly decreases until 3,500 s, and then has the SoC of 15 at 3,500 s. As a result, the SoC of all cells of Cell 4, 5 and 6 is the same as 15. In the case of current, Cell 4 remains constant until 3,500 s at 0 A, Cell 5 decreases slightly at 1 A, then rapidly decreases to 0 A at 1,900 s and remains constant until the end. Like Cell 5, Cell 6 initially starts at 1 A but decreases slightly up to 3,500 s. For the voltage of Scheme 2, the voltage of Cell 4 remains constant at 3.88 V, up to 3,500 s. Cell 5 has an initial value of 3.96 V, then decreases to 3.81 V until 1900 s, then increases rapidly to 3.88 V like Cell 1 at 3,500 s. In the case of Cell 6, it tends to start at 3.98 V and gradually decrease to 3.81 V until 3,500 s.

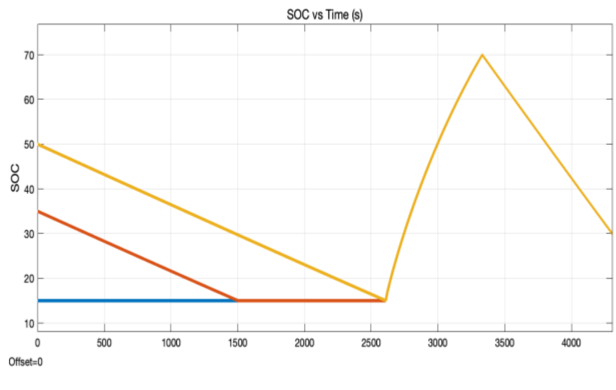
Lastly, Figure 8 shows the SoC, current and voltage results in Scheme 3 circuit. Cell 7 is blue, Cell 8 is red, and Cell 9 is yellow. In the case of SoC, the SoC of Cell 7 is maintained at 15 from the beginning to the end of the balancing. Cell 8 begins with the SoC of 35 and gradually decreases to 15 until 1,500 s before the value of the SoC of 15 remains at 2,600 s. Cell 9 shows a tendency to decrease from the SoC of 50 to the SoC of 15 from 0 s to 2,600 s. For Scheme 3's current, Cell 7's current remains at 0 A from 0 s to 2,600 s. On the other hand, the current of Cell 8 has an initial value of 1.3 A, decreases slightly until 1,500 s, drops sharply to 0 A at 1,500 s, and remains until 2,600 s. Cell 9 tends to be maintained with a very slight decrease of 1.3 A from the beginning to 2,600 s. In the case of voltage, Cell 7 starts at 3.88 V and constantly lasts for 2,600 s. Cell 8 starts at 3.95 V and decreases to 3.78 V until 1,500 s, then increases rapidly at 1,500 s, continuing until balancing is completed at 3.88 V, as shown in Cell 7. Cell 9 has an initial value of 3.98 V and gradually decreases to 3.78 V until about 2,600 s. As a result, in all Scheme 1, Scheme 2 and Scheme 3 circuits, the values of current and voltage change as the value of SoC is maintained and decreased. In addition, it is shown that the values of all circuits tend to be primarily similar graphs.

The overall graphs have similar tendencies, but time to balance among Scheme 1, Scheme 2 and Scheme 3 is different. For SoC, Scheme 1 and 3 take 1,500 s for a cell with the SoC of 30 to become the SoC of 15. However, Scheme 2 takes 1,900 s for the second-largest SoC cell to be equalised to the 15. In addition, Scheme 1 and Scheme 3 take 2,600 s for all cells to reach the SoC of 15. On the other hand, in the case of Scheme 2, it takes 3,600 s for all cells to be balanced. Scheme 1 and Scheme 3 are 1,000 s faster than Scheme 2 to balance, and as a result, they are more efficient than Scheme 2 based on the time to balance.

In the case of SoC, there are differences in each circuit in the current and voltage. In the case of current, the initial value of SoC of 35 and 50 of Scheme 1 and Scheme 3 is 1.3 A. However, for Scheme 2, it starts with 1 A. In the case of voltage, the initial values of Scheme 1, Scheme 2 and Scheme 3 are all the same, but Scheme 2 has a different minimum value from other circuits. The minimum value for Scheme 1 and Scheme 3 is 3.78 V, but for Scheme 2, it is 3.81 V. As a result, in the case of current, the initial value of Scheme 1 and Scheme 3 is 0.3 A higher, and in the case of voltage, the minimum value difference is 0.3 V.

There is a difference between Scheme 1 and Scheme 3, and all cells must be passive balanced with the SoC of 15. However, the cell results of Scheme 3 are 14.99, 15.04 and 15.04, respectively, which are slightly low or high, and are not entirely balanced. Although it is a slight error, Scheme 1 is more accurate and efficient based on the error of results than Scheme 3 because all cells are equally balanced at 15. Therefore, Scheme 1 is the most efficient and accurate circuit among Scheme 1, Scheme 2, and Scheme 3 circuits based on the time to balance and the error of the results. Accordingly, the circuit of Scheme 1 is applied in the BMS circuit.

Since the passive cell balancing circuit is applied in the BMS circuit, the result until all cells is balanced, it is the same as the result value of the passive cell balancing circuit. Therefore, according to Figure 9, since Scheme 1's circuit is applied, it is the same as the SoC, current and voltage values of Scheme 1 from 0 to 2,600 s. Charging starts from the same SoC after all cells have an equal SoC of 15. All cells are discharged after the SoC is equally charged. After being charged with the SoC of 70 up to 3,400 s, the SoC of 30 is discharged from 3,400 s to 4,500 s. In the current case, it changes from -24 A to -5 A when charged. It remains constant at 4 A from the beginning of the discharge. The voltage remains constant at 4.2 V during charging and decreases from 3.88 V to 3.78 V after discharging begins.



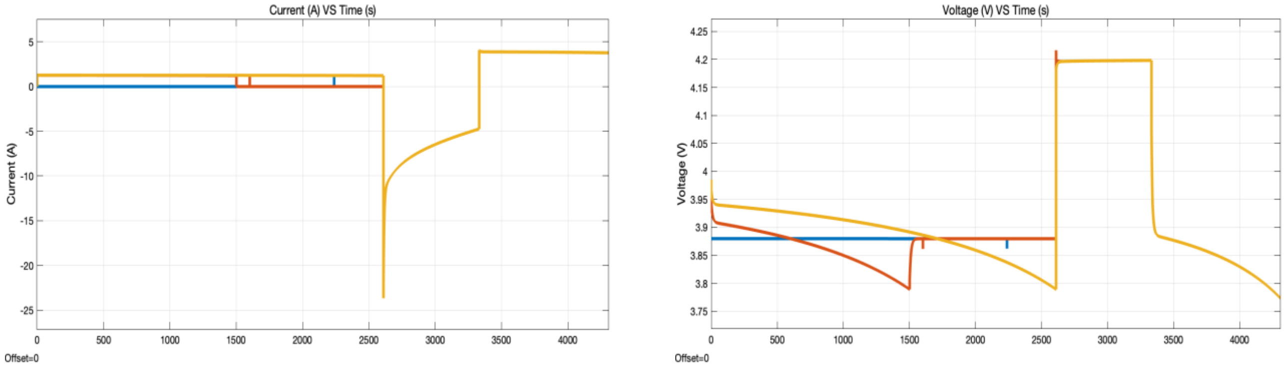


Figure 9. Graphs of BMS's SoC, Current and Voltage versus Time

Discussion

The graph showing the results of the passive cell balancing circuits shows the relationship between the battery's SoC, current and voltage. Through the graph of Scheme 3, cells with the SoC of 15 have the constant current of 0 A while they are still maintained at 15. Therefore, if there is no change in SoC, the current is 0 A, indicating that no current flows. In the case of voltage, the initial value of 3.88 V continues until balancing is end without any change. Unlike the case of SoC of 15, in the case of SoC of 35, when 30 decreases to 15, the slight decrease is shown at 1.3 A, and as soon as it reaches 15, it rapidly decreases to 0 A and maintains 0 A until the end. Similarly, in the case of the SoC of 50, the slight decrease is shown until the value of 1.3 A reaches 15, and through this, when the SoC decreases in the process of balancing, the current also shows the slight decrease. In the case of voltage, similar to current, the voltage also decreases as the SoC decreases during passive balancing. Both the SoC of 35 and 50 decreases to 3.78 V and then become the same as the SoC of 15 and remain at the initial value of 3.88 V. In addition to Scheme 3, all result values of Scheme 1 and Scheme 2 circuits show the same pattern. Therefore, it is related to current and voltage during passive cell balancing.

The relationship between SoC, current and voltage is also compared in the BMS circuit, and mainly, it is necessary to focus on the relationship between SoC, current, and voltage when charging and discharging are in a state. In the current case, the current value is negative because the current direction is the opposite when in the charged state, thus the resultant value is compared as an absolute value. When the SoC is being charged from 15 to 70, it progresses from 2,600 s to 3,400 s, and when the charge begins, it increases rapidly from 0 A to –24 A, and then to –10 A again, and gradually decreases to -5 A. In the early stage of charging, the current value increases and gradually decreases. On the other hand, it tends to maintain constantly at 4 A during discharge. Accordingly, when the battery is charged, the more current value is required, and as the charging time elapses, the current value gradually decreases. In addition, more current value flows when the battery is discharging than during balancing. In the case of the voltage, it has a constant value of 4.2 V during charging, but in the case of discharging, the voltage value decreases rapidly to 3.88 V and then gradually decreases to 3.77 V. As a result, even in the case of charging and discharging, it indicates that there is the relationship between current and voltage.

In the passive cell balancing circuit, although the original initial set values are the same, the time or result value of passive cell balancing is different because the only different conditions, switches and the algorithm, are different. In the case of algorithms, Scheme 2 and Scheme 3 are compared to Scheme 1 because the algorithms of Scheme 2 and 3 are similar. Algorithms are essential because the time to balance varies due to algorithm differences. Since the efficiency of the circuit can differ due to the difference in algorithms, which algorithm is used is the key. The algorithm of Scheme 1 is an algorithm that compares the minimum value of the other two cells by adding the minimum function. However, in the case of Scheme 2, the minimum value is not specified, and it is an algorithm that is compared between cells one by one. This means that each cell's SoC is compared to which cell is large or small, and because of this process, balancing takes longer than Scheme 1. However, although Scheme 2 and Scheme 3 have similar algorithms, Scheme 3 has the similar time to balance with Scheme 1. Through this, Scheme 1, Scheme 2, and Scheme 3 therefore differ in time or result because of the switch other than the algorithm.

There are three types of switches in all Schemes' circuits: MOSFET, IGBT and Ideal Switch. In addition to the algorithm difference, the time and results of passive balancing can differ because they have different switches. Scheme 1 has MOSFET, Scheme 2 has IGBT, and Scheme 3 has Ideal Switch. First, in the case of MOSFET and IGBT, although they have very similar properties, there are differences between them. IGBT has characteristics of low frequency (<20 kHz) and high voltage (>1000V), whereas MOSFET has characteristics of high frequency (>200 kHz) and low voltage (<250V) (Blake, Bull and Rectifier, 2001). In addition, In the case of rated voltage, IGBT is 1200 V and MOSFET is 800 V, and in the case of threshold voltage, IGBT is 5.5 V and MOSFET is 3 V, thus, IGBT has a higher voltage than MOSFET (Jang et al., 2012). Secondly, there are differences between MOSFET and Ideal Switch. MOSFET has an output voltage of 250 V, while an Ideal Switch is 10 V. In the case of switching frequency, MOSFET must be less than 20 kHz, and the result is 5 kHz. The Ideal Switch is 500 kHz, the highest value among the frequency of MOSFET, IGBT and Ideal Switch (Das, De and Mandal, 2018). Therefore, the difference in voltage and frequency of each switch is clear, and if a switch is present in a circuit, resistance is generated, and since each switch is different, the switch can affect the result. As a result, it can be considered that the time to balance and the slight difference in result of the circuit are caused by the difference between the algorithm and the switch.

Since the principle of passive balancing is to balance with resistance, heat is generated whenever resistance occurs. When such heat is excessively generated, the temperature of the cell increases and the life and capacity of the cell decreases, resulting in a decrease the efficiency of battery. Therefore, it is crucial to managing the heat for passive cell balancing. Therefore, strengthening the cooling system of the BMS will make a more efficient BMS circuit. The cooling system of the lithium battery cell is composed of four types: air cooling, fin cooling, indirect liquid cooling, and direct liquid cooling (Chen et al., 2016). It would be a more economical and efficient BMS if such a cooling system could minimise heat by attaching or using a more appropriate efficient coolant (Deng et al., 2018)

Conclusions

As environmental interest increases, various solutions are emerging, and one of them is electric vehicles. Batteries, which are an essential part of electric vehicles, are managed by the battery management system and prevented from reducing life and capacity of battery. Thus, cell balancing is a key issue in the battery management system as it increases battery life and capacity, ensures safe operation, and improves battery performance.

MATLAB/Simulink is used to model three passive cell balancing circuits and compare the results of SoC, current and voltage to apply a more efficient circuit to the circuit of the battery management system, consequently increasing the efficiency of the circuit of the overall battery management system. This efficiency is based on the time to balance and the error of the results. The three circuits have different algorithms and switches, which means that the algorithm and switch act a key role in increasing the efficiency of the cell balancing circuit.

Passive cell balancing is thermodynamically inefficient because the heat is generated due to resistance. However, it is possible to prevent such a problem from being lowered in efficiency by enhancing the cooling system as much as possible. Furthermore, since the cooling system becomes more efficient depending on the coolant, the next step is to prove through further study that an appropriate cooling system and coolant make the battery management system more efficient.

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Appendices

```
a = min([s1 s2 s3]);


if(s1 == a)
    if (s1 == a && s2 == a)
        y1 = 0;
        y2 = 0;
        y3 = 1;

    elseif (s1 == a && s3 == a)
        y1 = 0;
        y2 = 1;
        y3 = 0;

    elseif (s1 == a)
        y1 = 0;
        y2 = 1;
        y3 = 1;
    else
        y1 = 0;
        y2 = 0;
        y3 = 0;
    end
```

Figure A1. Diagram of Scheme 1's algorithm

```
if ((s1>s2)|| (s1>s3))
    y1 = 1;
else
    y1 = 0;
end

if ((s2>s1)|| (s2>s3))
    y2 = 1;
else
    y2 = 0;
end

if ((s3>s1)|| (s3>s2))
    y3 = 1;
else
    y3 = 0;
end

if ((s1 == s2) && (s2 == s3))
    y4 = 1;
else
    y4 = 0;
```

Figure A2. Diagram of Scheme 2's algorithm

```
if((s1>s2) || (s1>s3))
    y1 = 1;

else
    y1 = 0;

end


     if ((s2>s1) || (s2>s3))
         y2 = 1;

     else
         y2 = 0;

     end

            if ((s3 >s1) || (s3 > s2))
            y3 = 1;

            else
            y3 = 0;

            end
```

Figure A3. Diagram of Scheme 3's algorithm