International Journal of Electrical and Computer Engineering (IJECE)
Vol. 14, No. 4, August 2024, pp. 3640~3648
ISSN: 2088-8708, DOI: 10.11591/ijece.v14i4.pp3640-3648

Active balancing system in battery management system for Lithium-ion battery

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Article Info

Article history:

Received Feb 10, 2022
Revised Apr 18, 2024
Accepted Apr 22, 2024

Keywords:

Balancing
Battery
Energy
Management
State of charge

ABSTRACT

The existing battery management systems perform many functions, such as simply monitoring the battery's voltage, current, and temperature for the most basic and compensating energy imbalances between battery cells for the most advanced systems. In this last example, the function balancing helps protect the battery from obtaining a better lifespan. However, these systems with such functions remain complex because they involve techniques specific to power electronics and energy conversion. The number of components, implementation complexity, and cost increased. The work presented in this paper fits directly into this context. The main objective is to provide a solution to the problem of battery management and careful pack cell balancing. The proposed system aims to balance the battery pack cells based on the intermediate state of charge by charging or discharging the imbalanced cell. The implementation of the proposed control strategy was for a battery pack composed of five cells under MATLAB/Simulink.

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1. INTRODUCTION

An imbalance results from the cyclical charging and discharging processes in a lithium-based battery system, as the charge level in each battery increases and decreases over time [1]. Temperature, the chemical composition of each cell, and the initial state of charge can all contribute to this imbalance [2]. Figure 1 illustrates the visual representation and succinct overview of the imbalance issue that arises in the cell pack throughout the charging and discharging process. In the provided example, the battery is deemed discharged when a single cell (represented as cell 1) reaches its maximum capacity, irrespective of the states of the remaining cells. The longevity of this cell is compromised as a result of its inability to maintain discharge. A comparable situation emerges during the charging procedure: when a specific cell (in this case, designated as cell number 2) reaches complete charge, the charging of the entire pack must cease. If it is not protected from the charging of the other cells, it will sustain injury. The principal aim of this research is to examine the function of the battery management system in mitigating this issue by harmonizing battery cells, increasing energy efficiency, and extending battery life.

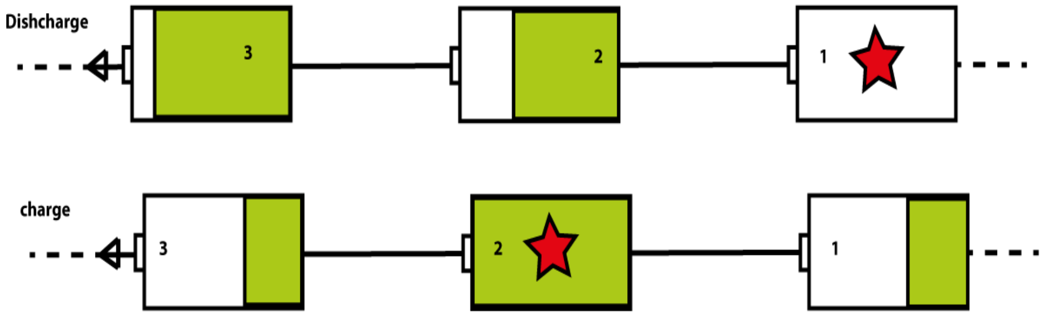

Figure 1. Example of an imbalanced problem for the battery pack

The primary function of the battery management system (BMS) is to oversee and maintain the balance of individual battery cells that make up a battery charge [3]. A disparity in cells may result from extrinsic or intrinsic factors. The extrinsic aspects encompass the attributes of heat dissipation, charge/discharge current, and parallel/series contact [4], [5]. Conversely, intrinsic factors concern the manufacturing processes that influence the internal resistance and quantity of active material. An example of state of balance is achieved in a battery pack when each cell exhibits an equivalent state of charge (SOC).

The BMS is responsible for charging the battery cells to their maximum capacity, and protect the battery against overcharging and over discharging during battery function [6], [7]. On the other hand, improperly balanced lithium battery cells can experience prolonged heat and/or charge dissipation, reduced energy efficiency, and accelerated disintegration [8]. Failure to replace even a single battery cell in the pack expeditiously will result in catastrophic consequences. However, substituting the defective cell in a battery pack is an unreliable course of action because the chemical properties of the new cell are more complex than those of the old cell, thereby increasing the probability of failure. In order to maintain consistency in the SOC of a battery pack, it is advisable to use cells that possess uniform chemical properties. Cell balancing is a technique utilized to optimize the energy output of the cells during the discharging phase and to ensure that the charge is distributed uniformly among all battery cells during the charging phase [9]. Electric vehicles use a battery pack consisting of numerous multi-cell batteries to achieve elevated operational voltages.

Failure is more probable when a battery pack contains a large number of cells. Moreover, this will significantly impact dependability, as multiple battery cell failures are more likely than a single one. The variability of battery cells gives rise to discrepant rates of charge and discharge. As a result, the voltage across the battery cells in the pack is different. Overcharging or undercharging of cells may happen because of this phenomenon. This shortens the battery pack's useful life, makes security holes worse, and causes the cells to lose capacity slowly over time [10]. Battery pack balancing devices have been the subject of numerous studies documented in the literature. The balancer charger transfers energy from one cell back to the pack in the cell-to-pack mode during the cell discharging balancing mode. Conversely, cell charging mode balancing occurs when the pack-to-cell mode is utilized by the balancer charger to transfer power from the pack to a low-capacity cell. In the absence of a functioning cell charger balancer, the idling balancing mode activates. Active and passive strategies [11] are the principal methods for attaining cell balance in batteries. Implementing passive cell balancing will affect the battery's operational time through the dissipative bypass method. By releasing surplus energy from the cells in the form of heat, this process continues until the charge level of the pack or charge reference matches that of the weakened cells [12]. By employing resistors to induce dissipative behavior, the passive technique signifies the absence of power distribution among the cells due to the conversion of their energy into heat [13]. Consequently, the discharge or dissipation of a resistor's charge into the surrounding atmosphere significantly increases the generated heat and reduces the process's efficiency. To balance cells the old way, using passive mechanisms makes them less energy efficient because extra charge from cells in a high SOC is turned into heat through resistor passage. However, in the case of low-cost system applications where equalization is achieved without the need for active control, this approach remains effective. As a result of the significant potential for detonation [14], the use of lithium batteries with it is not feasible. The resistor size, which connects in parallel with each individual cell in the passive technique, governs the balance rate. Two models of passive cell-balancing topologies are offered [15]. Among these components are the resistors used for toggling and fixed shunting.

The active cell balancing method transfers charge from the cell with the high charge to the cell with the low charge via a capacitive or inductive charge shuttle. This describes how the active balance technique balances differences between cells connected in series by transferring electrical energy from cells with a higher SOC to cells with a lower SOC with minimal loss. When a cell's expenses exceed the balancing module's maximum charges, the module transfers the excess costs to the cell with lower charges. By transferring surplus energy to the low-energy cell as opposed to dissipating it, this methodology significantly improves the complexity of the balancing circuit and demonstrates remarkable efficiency. On the contrary, lithium-ion batteries exhibit remarkable performance [16]. As its fundamental components, active cell balancing utilizes DC-DC connectors, current transducers, and relays. The system is composed of five primary subcategories [17]: cell-to-pack, pack-to-cell, cell-to-cell, cell-to-pack, and cell-to-pack-to-cell. Three methods comprise the cell bypass technique: the shunt resistor method, the shunt transistor method, and the total shunting method [18]. Implemented in the concluding phase of the charge procedure, this methodology is straightforward to implement, economical, and easily subdivided into modules [19].

Cell bypass: for optimal performance, all cells within a battery pack should possess identical characteristics, which would allow them to respond uniformly to a diverse range of specific conditions. Nevertheless, as time passes, the specific characteristics of every cell undergo modifications as a result of fluctuations [20], external factors including the localized temperature of the battery pack, or the fluctuating condition of the cell's losses [21]. Elevated temperatures can induce an increase in voltage in certain cells. Certain objects may experience thermal expansion, leading to changes in electrical potential due to increased inherent resistances. Every battery pack frequently comprises discrete cells, each of which exhibits distinct qualities that differentiate it from the remaining cells in the pack [22]. By utilizing the current of cells operating at their maximum and minimum voltage levels, cell bypass equalization strategies enable cells to delay the transmission of their voltage until the remaining cells complete their task. These techniques are practical and economical to implement.

Pack environments necessitate cell-to-cell approaches owing to the possibility of localized pack degradation or alterations in battery cell capacities. As a result, discrepancies among individual cells exert a substantial impact on the estimation of the SOC and undermine the efficacy of regulation by the BMS. Temperature gradients may manifest internally in original battery packs because of the multiple cells contained therein [23]. By transferring excess energy from one cell's storage to neighboring cells that possess larger energy reserves, cell-to-cell processes occur. Although they might exhibit enhanced efficacy, they pose difficulties with regard to governance.

Cell-to-pack methodologies extract energy from specific charged cells within the pack and distribute it uniformly among all cells connected to the pack terminals. By uniformly distributing the opposing charge that produces heat among the other cells in the pack, this method ensures the preservation of all energy as heat, making it a safe technique. Pack-to-cell operations facilitate the energy transfer from the pack to the cell, which has the lowest charge. This approach ensures that no energy dissipates and the charge level stays constant throughout the charging procedure. Cells exchange energy in cell-to-pack-to-cell processes via cell-to-pack and pack-to-cell mechanisms. Traditional arrangements that depend on DC/DC converters may be complex, expensive, and demonstrate inadequate performance when it comes to operations involving cells, packs, cells, and cells-to-pack-to-cells [24]. In order to safeguard the battery pack's integrity and longevity, these configurations typically restrict the likelihood of overcharging or over discharging specific battery cells. These balancing configurations typically utilize flyback transformers or multi-winding transformers. As a result, spatial constraints necessitate specifying the minimum number of series-connected cells that can achieve equilibrium in these structures [25].

We introduced a hierarchical active balancing structure after conducting a comprehensive literature review on different active cell balancing architectures. Compared to the conventional cell-to-cell arrangement, the hierarchical active balancing structure reduces the current rating of the balancing circuit, eliminates the need for repetitive charge and discharging, and reduces the time and energy expenditure related to balancing. This method divides the series-connected battery into numerous groups. The uppermost layer interconnects the packs, enabling efficient bidirectional energy transmission between any two packs.

When utilizing series-connected cells of a battery to regulate time, the principal aim of an active balancing strategy is to attain a consistent charge distribution [26]. It is preferable for this process to occur without incurring any energy losses throughout the equalization phase. Furthermore, it is important to understand that the basic idea behind all active balancing systems is to move charge from cells with a higher SOC to cells with a lower SOC by using switching capacitors as storage units in between [27]. By ensuring that every bit of energy contained in the battery is utilized, active cell balancing maximizes the battery's capacity while consuming considerably less energy than passive balancing.

In order to accomplish this, each active balancing circuit utilizes a reservoir consisting of a non-dissipative element, such as a capacitor or inductor, which transfers energy between the cells of the battery. This technique, by connecting the circuit in parallel with each individual cell, is capable of independently redirecting the current in the event that the cell's voltage exceeds its specified value. The system operates efficiently in situations involving frequent and high-demanding requests, minimizes energy waste during periods of inactivity, and promotes an equitable distribution of energy among cells. This methodology outperforms passive balancing in multiple respects, including the expansion and durability of the battery cell. Nonetheless, this approach effectively addresses the concern of requiring an additional component, thereby augmenting both expense and unpredictability, in addition to the disadvantage of prolonged equilibrium of the cells.

The technique used to balance the cells of an electric vehicle's batteries is the primary source of malfunction. It improves the battery pack's efficacy, extends its lifespan, reduces maintenance requirements, and ensures consistent secure operation. We conducted an evaluation of several battery balancing solutions to highlight the diverse manifestations of battery imbalance and its consequential effects on battery functionality. Active balancing techniques will be employed in this research endeavor to equate the SOC of every cell within the battery pack with the pack's average SOC. Furthermore, the present integration methodology will be utilized for the purpose of state-of-charge estimation.

The rest of this paper consists of the following sections: a description of the battery system under investigation is presented in section 2. The proposed balancing mechanism is introduced in section 3. The findings and analysis are summarized in section 4. The paper concludes by recommending further investigation.

2. STUDIED BATTERY SYSTEM

Lithium-ion batteries have become the preferred choice for many storage system applications due to their numerous advantages over other battery types. Despite their benefits such as high energy density, long life cycle, and absence of memory effect, it is important to handle them with care. Unlike other battery types, the electrolyte in lithium-ion batteries is a volatile and highly flammable solvent, which can burn vigorously and rapidly. In this study, the battery storage system serves as a power source when renewable sources are unable to meet the load demand, and as a load when excess power is available, maintaining system balance. Modeling lithium-ion batteries is complex due to the nonlinearity of their voltage response. This paper utilizes the dynamic battery model from the SimPowerSystems library in Simulink, as shown in Figure 2. The model proposed in [6] is based on an equation that provides an excellent description of a wide range of cell and battery discharges.

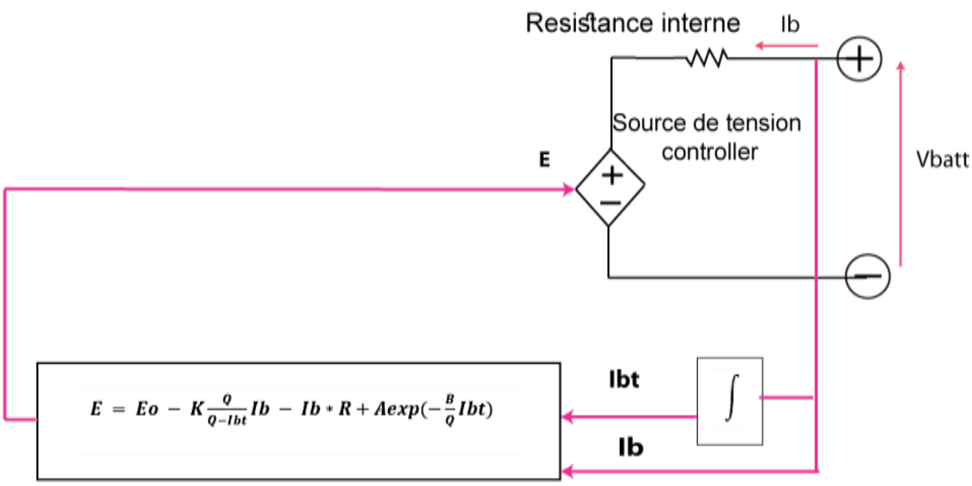

Figure 2. Battery standard model

3. PROPOSED BALANCING SYSTEM

In the proposed lithium pack balancing system, the terminal voltages and currents of the battery cells are initially determined. Subsequently, the SOC of each battery cell is estimated using an integration method to calculate the mean SOC, thus evaluating the pack's imbalance. If an imbalance is detected, charging and discharging balancing procedures are conducted for each cell based on the difference between the cell's SOC and the mean SOC. Various balance strategies, as discussed in the literature review, are employed for active cell balancing. During charging, cells with SOC higher than the average SOC are balanced using a charging strategy, while during discharging, cells with SOC lower than the average SOC are balanced using a discharging strategy. The proposed balancing system is illustrated in the following flow chart in Figure 3.

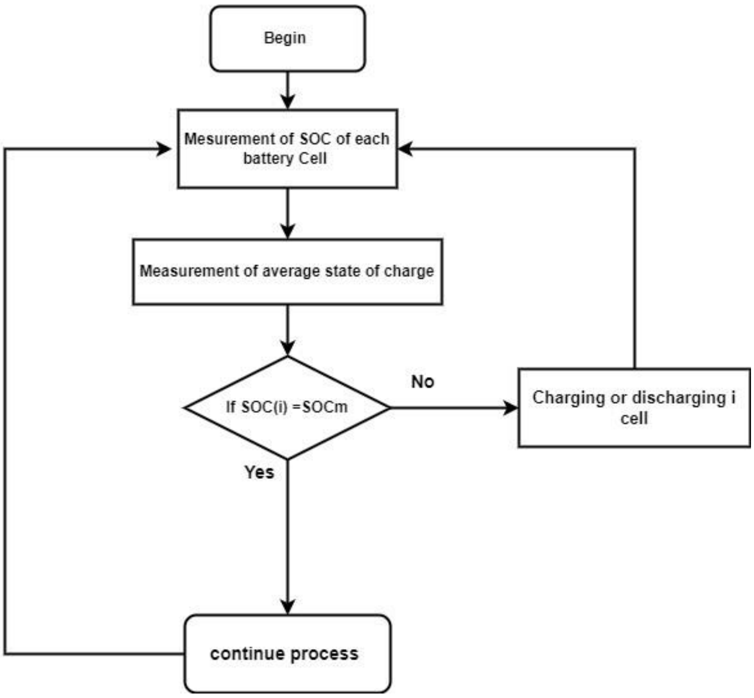

Figure 3. Balancing flow chart of the battery pack

4. RESULTS AND DISCUSSION

In this study, the battery system consists of five cells connected to the loads and sources via a bidirectional DC/DC converter, as depicted in Figure 4. Each cell is equipped with a buck-boost converter, along with a dedicated controller, to regulate charging and discharging and to ensure battery pack balancing. The SOC of each cell is continuously compared to the average SOC of the battery pack to monitor the pack's balance. If any cell's SOC deviates from the average, the corresponding buck-boost converter adjusts its charging or discharging to restore balance within the pack.

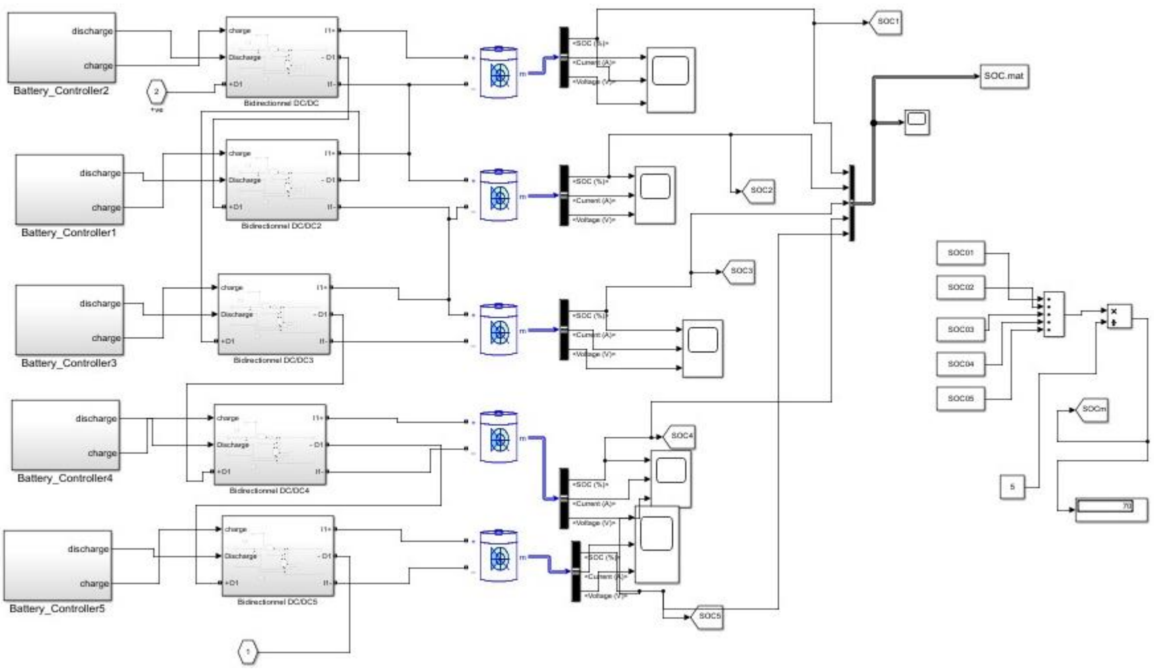

Figure 4. Balancing system for the battery pack

The simulation was conducted for a duration of 20 seconds, with a sampling time of 1e-5. The battery pack used in the simulation comprises five lithium cells, each with a different initial state of charge, as detailed in Table 1. The primary objective of the proposed balancing system is to equalize the state of charge (SOC) among all battery cells. To achieve this, the average SOC is calculated based on the initial SOC values of each cell. Subsequently, this average SOC value is utilized by the control block to determine the charging or discharging of each cell, ensuring balanced operation of the battery pack.

Table 1. Initial State of charge for each battery cell

Cell	Initial state of charge
Cell 1	70%
Cell 2	69%
Cell 3	75%
Cell 4	68%
Cell 5	73%

During cell discharge, the individual cells within a battery pack may exhibit varying SOC due to factors such as manufacturing processes, material impurities, differential heating, and variations in initial states of charge. Figure 5 illustrates the SOC variation of each cell in the battery pack during the discharge process without a balancing system. As depicted, the SOC of the cells diverges significantly, with some cells discharging more rapidly than others. This discrepancy underscores the necessity of a balancing system to equalize the SOC among all cells, ensuring optimal performance and longevity of the battery pack. During the charging process, the principal factors of the difference in the battery states of charge are the differences in the initial state of charge values, as shown in Figure 6.

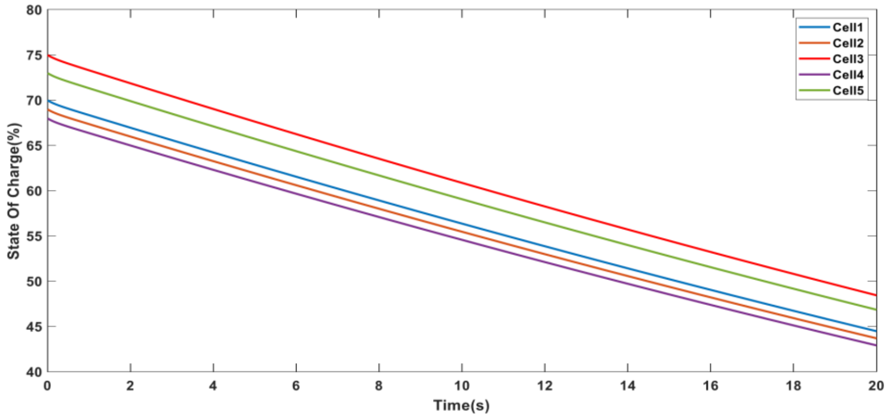

Figure 5. Discharging of battery cell without balancing system

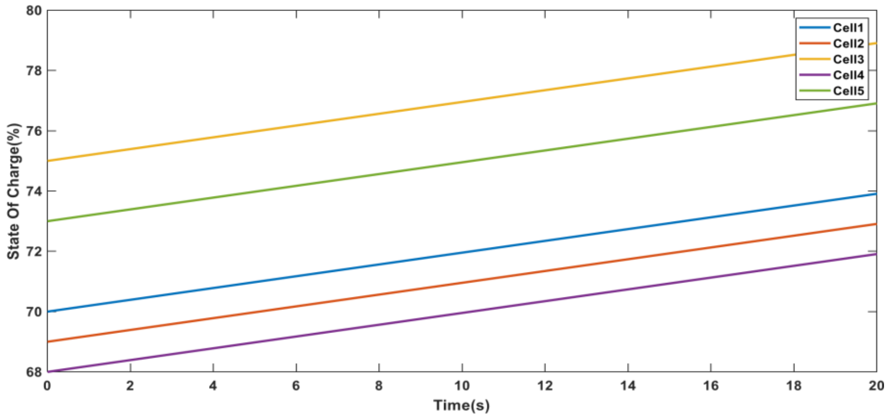

Figure 6. Charging of battery cell without balancing system

Imbalances in the SOC of battery cells can lead to overcharging or over-discharging of certain cells within the battery pack. This imbalance not only reduces the battery's lifespan but also increases the risk of explosion. Therefore, implementing a balancing system for the battery cells is crucial. Figure 7 presents the results of comparing the battery cell state of charge after applying the proposed balancing system. As shown in the figure, the SOC of the battery cells is much more uniform and balanced, highlighting the effectiveness of the proposed balancing system in mitigating SOC imbalances and enhancing the battery pack's performance and safety.

The calculated average SOC is found to be 71%. Subsequently, each cell's SOC converges towards this average value through either charging or discharging, depending on its initial SOC. For instance, Cell 3 discharges because its initial SOC is 75%, which is higher than the average value of 71%. Conversely, Cell 4 has an initial SOC of 68%, which is lower than the average value, necessitating charging to reach the 71% average, as depicted in Figure 7. The results in Figure 7 clearly demonstrate the effectiveness and robustness of the proposed system in balancing the SOC of each cell within the battery pack, ensuring optimal performance and longevity.

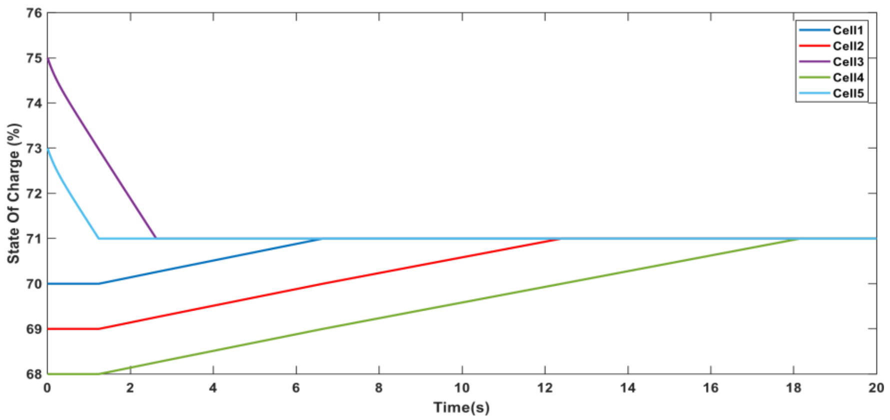

Figure 7. Variation cell state of charge during balancing

5. CONCLUSION

The BMS serves as a critical real-time control system, managing various functions essential for the correct and safe operation of the battery. These functions include monitoring temperature, voltages, and currents, cell balancing, maintenance planning, optimizing battery performance, forecasting, and collecting battery data. This paper has specifically focused on the development of a balancing system aimed at equalizing the SOC of all battery cells. To address the balancing challenge, we have proposed and validated a novel topology that offers an innovative solution compared to existing methods. Our approach leverages the use of buck-boost converters, enabling seamless energy transfer between the cells within a battery pack. Moreover, our system allows for effortless operation without the need for instrumentation of cell or balancer currents and voltages, particularly during natural balancing. However, it is important to acknowledge the limitation of this research. The temperature used for testing has been limited to an average ambient temperature of 20-25 degrees Celsius, which may not be feasible in all environments. In our future work, we plan to incorporate temperature balancing for all battery cells into our balancing system.

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