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Cell Balancing in Lithium-ion Batteries – A Comparative Evaluation

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Abstract

Balancing the cells within a battery system is essential for safeguarding against overvoltage, overcharge, and over-discharge, which can lead to system failures and safety hazards. Two commonly employed methods for cell balancing are passive and active balancing. In passive balancing, excess charge is dissipated through resistors, while active balancing involves the controlled flow of charge within the circuit. This paper focuses on the comparison and analysis of passive and two specific active balancing techniques: single switched capacitor and single inductor balancing. The utilization of pulse width modulation (PWM) signals with a duty ratio of 50% for all switches is employed in both techniques. The objective is to transfer charge from cells with a higher state of charge (SOC) to cells with a lower SOC, thereby achieving balance within the battery system. In this paper the performance of the single switched capacitor and single inductor-based balancing techniques using MATLAB Simulink are being compared. The simulations are conducted under various operating conditions including idle, charging, discharging states. The objective is to assess the effectiveness and efficiency of these techniques in achieving cell balance. The single switched capacitor and single inductor-based balancing methods offer advantages over passive balancing in terms of balancing time and efficiency.

Keywords: Battery management system (BMS), State of Charge (SOC), cell balancing, passive balancing, active balancing

INTRODUCTION

In recent years, the widespread adoption of battery technologies in various applications, including electric vehicles, renewable energy systems, and portable electronics, has highlighted the critical need for efficient and reliable energy storage solutions [1, 2]. Battery packs consist of multiple individual cells connected in series or parallel configurations, forming a complex electrochemical system [3]. However, due to manufacturing variations, aging effects, and operational disparities, these cells often exhibit unequal states of charge or voltage, leading to performance degradation, reduced capacity utilization, and potential safety hazards.

Cell balancing, has an essential aspect of battery management systems (BMS), has emerged as a key technique to address the disparities among individual cells within a battery pack [4]. The goal of cell balancing is to equalize the state of charge or voltage among cells, ensuring optimal battery pack performance and prolonging overall battery life. By actively redistributing energy or charge, cell balancing techniques aim to harmonize cell characteristics and mitigate the effects of cell-to-cell variations.

This research paper delves into the topic of cell balancing, exploring the different methods employed to achieve balance within battery packs.

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Specifically, the paper focuses on passive and active balancing techniques and compares them against a comprehensive cell balancing approach. Understanding these techniques and their respective advantages and limitations is crucial for developing efficient and reliable battery management systems that optimize battery performance, enhance safety, and prolong overall lifespan.

Passive balancing is one of the commonly used methods in battery management systems. It relies on dissipating energy across resistors or bypassing it through auxiliary circuits to equalize cell voltages. Passive balancing offers simplicity and cost-effectiveness, as it does not require additional active components or complex control algorithms. However, its efficiency is limited, particularly in cases of large voltage differentials or imbalanced cells. Additionally, passive balancing may dissipate significant amounts of energy as heat, reducing the overall efficiency of the battery pack.

In contrast, active balancing techniques provide a more dynamic and efficient approach to cell balancing. These techniques utilize additional circuitry, such as switches or converters, to actively transfer energy between cells. Active balancing can achieve higher balancing efficiency, effectively redistributing energy from cells with higher charge or voltage to those with lower values. By actively controlling the energy transfer, active balancing systems can adapt to varying cell characteristics and effectively maintain balance within the battery pack. However, the implementation of active balancing techniques may introduce additional complexity and cost, requiring more sophisticated control algorithms and suitable power electronics.

CELL BALANCING TECHNIQUES

Passive Balancing

Passive balancing is a technique used to balance the charge among cells in a battery pack. In passive balancing, each cell in the battery pack is connected to a resistor as in Fig.1. These resistors allow excess charge in cells with higher state of charge (SOC) to flow through and be dissipated as heat. By dissipating the excess charge, passive balancing helps equalize the SOC levels among the cells. The principle behind passive balancing is that as the cells reach their maximum SOC, any excess charge is redirected through the resistors. As a result, the charge is redistributed among the cells, promoting a more balanced state in the battery pack [5, 6].

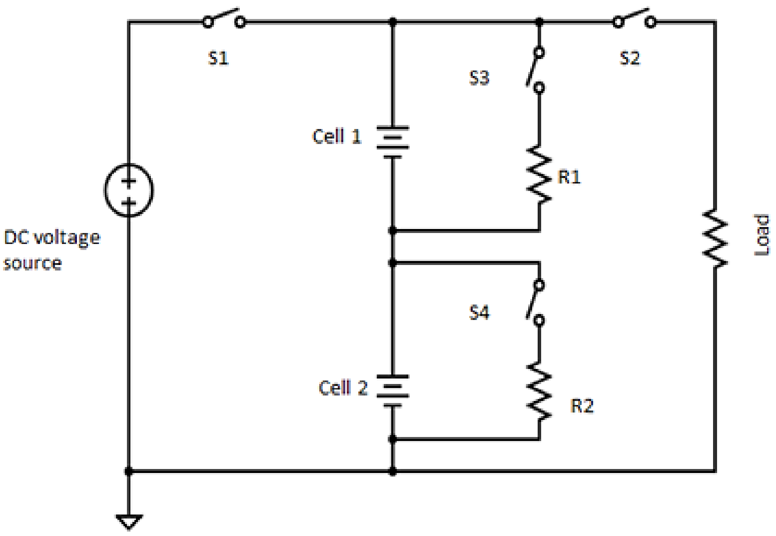

Figure 1. Passive balancing circuit diagram.

Passive balancing is a self-regulating process, as the flow of current through the resistors adjusts automatically based on the SOC differences between the cells. However, it is important to note that passive balancing is a slower process compared to active balancing techniques. It relies on the natural discharge of cells through the resistors, which may take longer to achieve complete balancing.

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Passive balancing is commonly used in applications where cost and simplicity are important considerations. It can be effective in maintaining the SOC levels. Balancing does not introduce additional complexity or energy losses associated with active balancing techniques, making it a practical choice for certain battery systems.

The balancing is done under different conditions. For idle mode shown in Figure 2a the balancing is done by transferring the charge between the cells. Figure 2b shows the balancing of cells while charging mode is ON. Cells discharges through a resistive load and balancing is shown in Figure 2c.

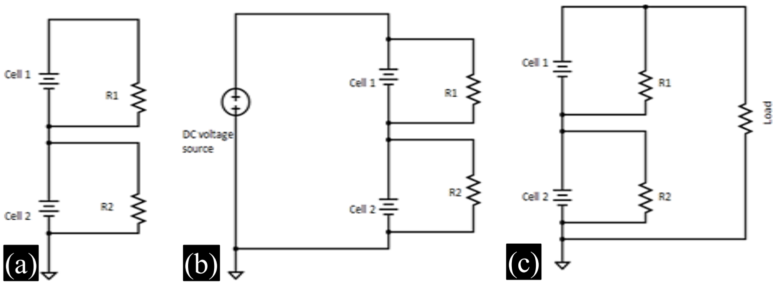

Figure 2. Different Modes of Operation (a) Idle (b) Charging (c) Discharging.

This method is a fairly low cost method for balancing cells, but wastage of energy in the discharge resistor makes the system reduces the efficiency.

Active Balancing

Active cell balancing techniques employ various topologies, including capacitor based, inductor based, transformer based and converter based. The DC-DC converter-based topologies includes Buck boost converter, cuk converter, flyback converter, forward converter etc. Capacitor-based topologies includes switched capacitor, double tiered capacitor, single switched capacitor. These all methods offer efficient energy transfer and which leads to faster balancing of cells. Each topology has unique advantages, control strategies, and considerations for factors such as voltage imbalances and efficiency are crucial for effective active cell balancing like for example capacitor-based topologies utilize capacitors to store and transfer energy between cells, integrating with other converter topologies for customized solutions. The basic principle is transferring of charge between the highest cell and lowest cell. Transfer of energy can be done among the cell or group of cells and it can be achieved more quickly in converter-based methods. This paper discusses mainly on single switched capacitor and single inductor based active cell balancing.

Single switched Capacitor Balancing

In this method of cell balancing, a single capacitor is utilized to equalize the charge among a series of connected cells as shown in Figure 3. The number of switches required for this circuit is twice the number of cells. For instance, if there are four cells in the series, eight switches will be employed. Pulse-Width Modulation (PWM) pulses are applied to control the switching of these switches.

The fundamental principle of this balancing circuit is to transfer charge from a cell with a higher state of charge (SOC) to a cell with a lower SOC by means of a capacitor. Initially, the switches connected to the cell with the highest SOC are turned ON. The capacitor stores energy during this connection phase. Afterward, the switches connected to the cell with the lowest SOC are turned ON enabling the energy stored in the capacitor to be transferred to this cell. This process helps balance the charge levels among the cells. Meanwhile, all other switches in the circuit remain in the off condition to ensure that only the intended charge transfer occurs [7, 8].

A threshold voltage limit is given so that the balancing process can be more precise. Once this threshold voltage is reached, indicating a balanced state, the balancing is considered complete.

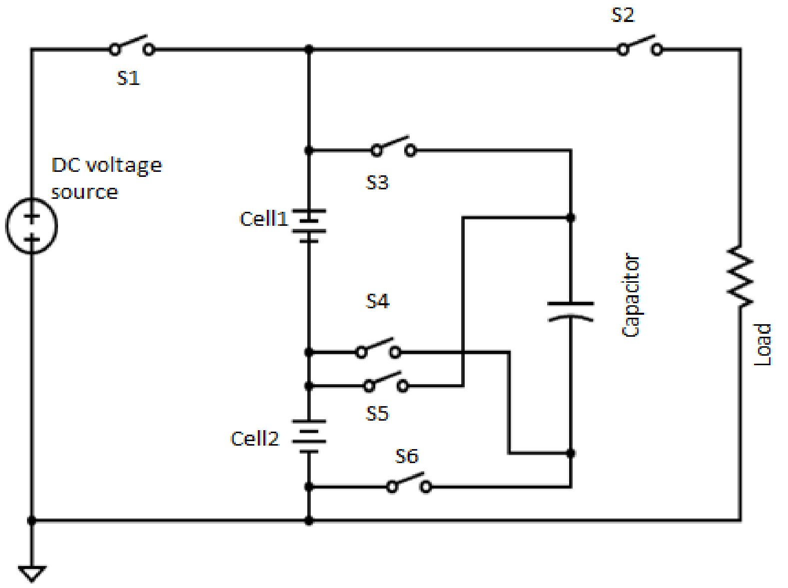

Figure 3. Single Switched Capacitor Balancing Circuit.

While this method is relatively simple to implement, it can be time-consuming. Achieving full balancing may require multiple iterations of charge transfer between the cells and the capacitor. Additionally, the effectiveness of this method is influenced by factors such as the capacitance value, the charging and discharging rates, and the SOC differences between the cells.

Despite its time-consuming nature, the simplicity of this method makes it a viable option for certain applications. However, in cases where faster balancing is desired, alternative techniques such as converter-based balancing methods may be more suitable. Balancing between the cells is done in Idle mode shown in Figure 4a, Figure 4b represents the charging mode using a DC voltage source, Discharging using a resistive load is done as shown in Figure 4c and the balancing of cells are achieved.

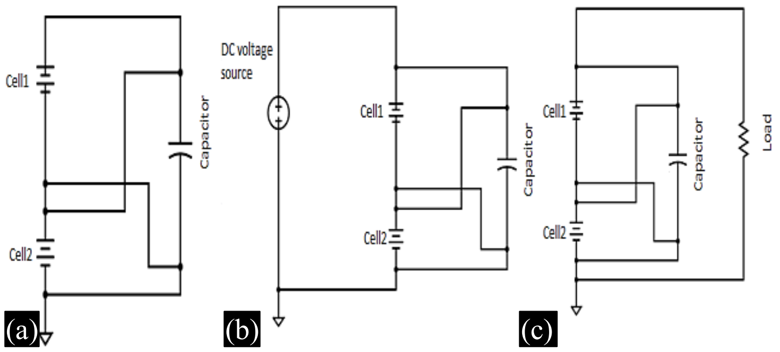

Figure 4. Different Modes of Operation (a) Idle (b) Charging (c) Discharging

Single inductor-based Balancing

In this circuit, an inductor is used to connect the ends of each cell together as shown in Figure 5. This configuration allows for the transfer of charge between the cells. The operation of this circuit is similar to that of a buck-boost converter [9, 10].

The circuit takes advantage of high balancing currents, which results in a shorter equalization time. The main principle behind the circuit's balancing operation is to facilitate controlled charge transfer from a cell with a higher state of charge (SOC) to a cell with a lower SOC using the inductor. This process is often referred to as "inductive" charge shuttling. To initiate the balancing process, PWM (Pulse-Width Modulation) pulses are applied to the switches in the circuit. These pulses control the

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switching of the switches, allowing the charge to be transferred between the cells in a controlled manner. By properly controlling the switching operation, charge from cell which has a higher SOC, can be transferred to cell which has a lower SOC. This charge transfer process helps to equalize the SOC levels among the cells, promoting a balanced state in the battery system.

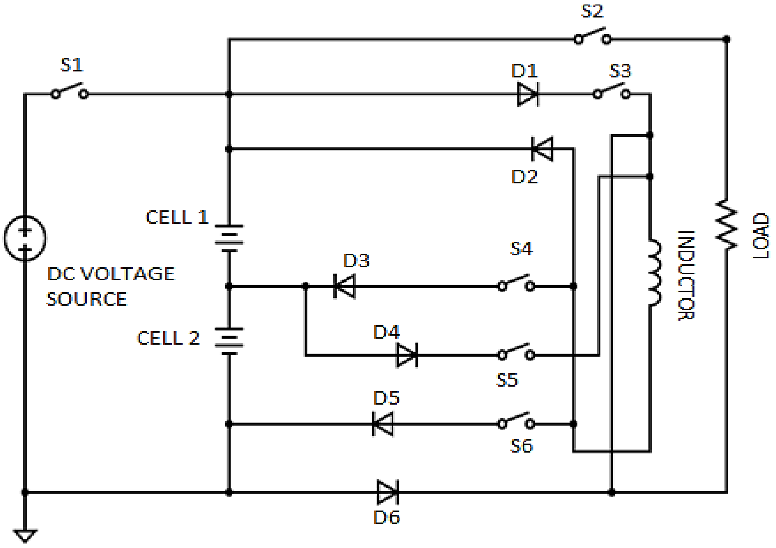


Figure 5. Single Inductor Based Balancing Circuit.

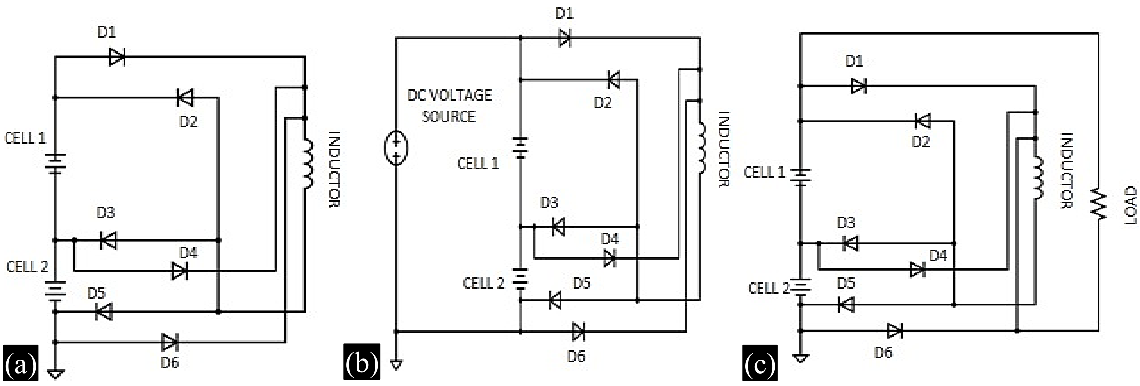


Figure 6. Different Modes of Operation (a) Idle (b) Charging (c) Discharging.

The use of an inductor in this circuit enables efficient charge transfer and provides a means for precise control over the balancing operation. By carefully designing the circuit and optimizing the switching control strategy, the circuit can effectively balance the cells and maintain an optimal SOC distribution, thereby enhancing the overall performance and longevity of the battery system. The various operation modes such as the idle, charging, discharging modes of balancing are shown in Figure 6a, Figure 6b and Figure 6c respectively.

NUMERICAL RESULTS

In this section, several simulations results performed in MATLAB Simulink to demonstrate the effectiveness of various balancing techniques are presented. Simulation is carried out with 4 cells, each of 3.7V and 2.6Ah with different SOCs. For each balancing technique, the simulations are conducted under various operating conditions including idle, charging, discharging states.

The passive balancing uses resistors to dissipate the excess charge from the cells. Initial SOCs taken were 50%, 45%, 40% and 35% for the four cells respectively. Figure 7 shows results for various modes of operation.

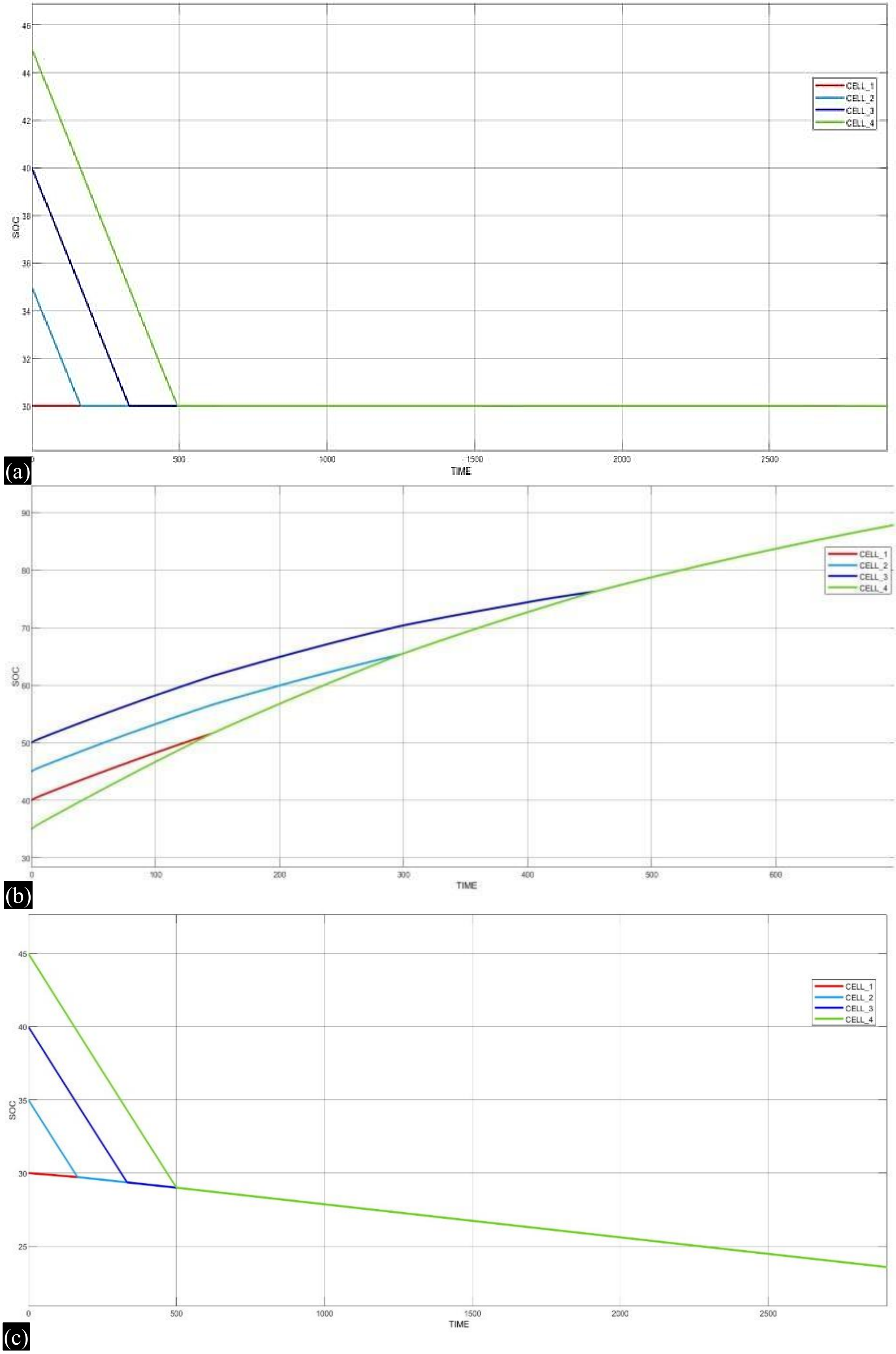
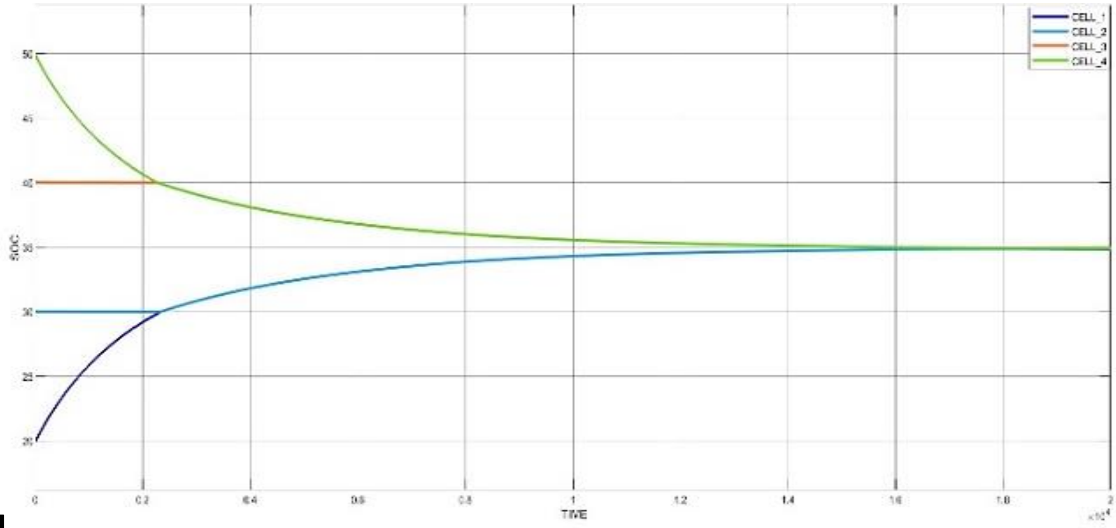
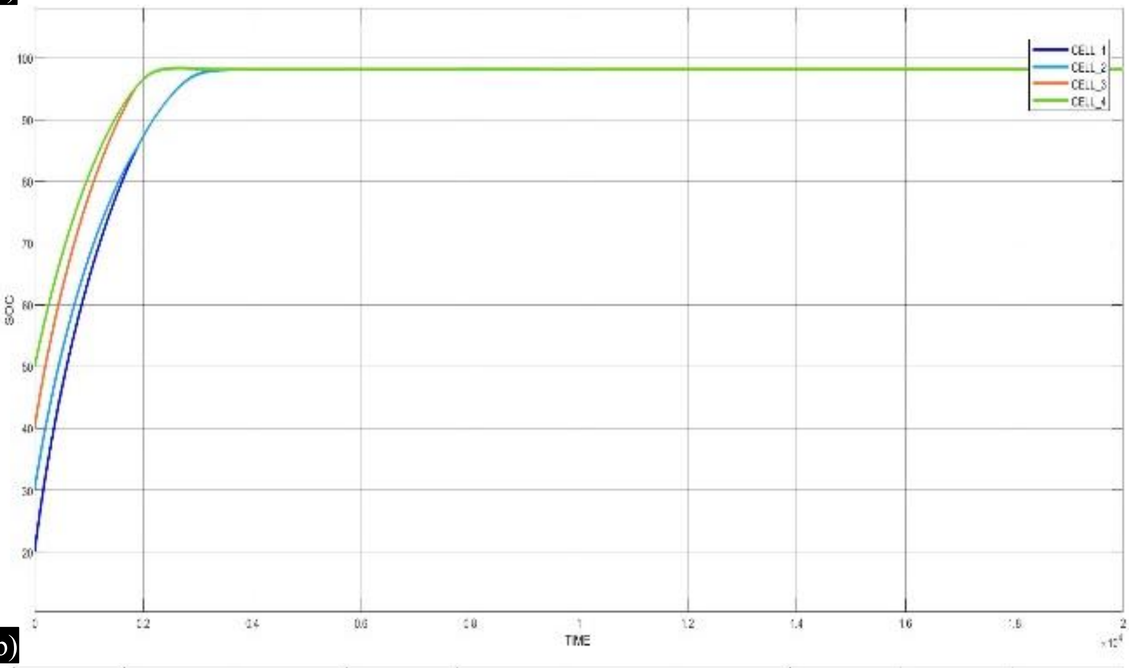


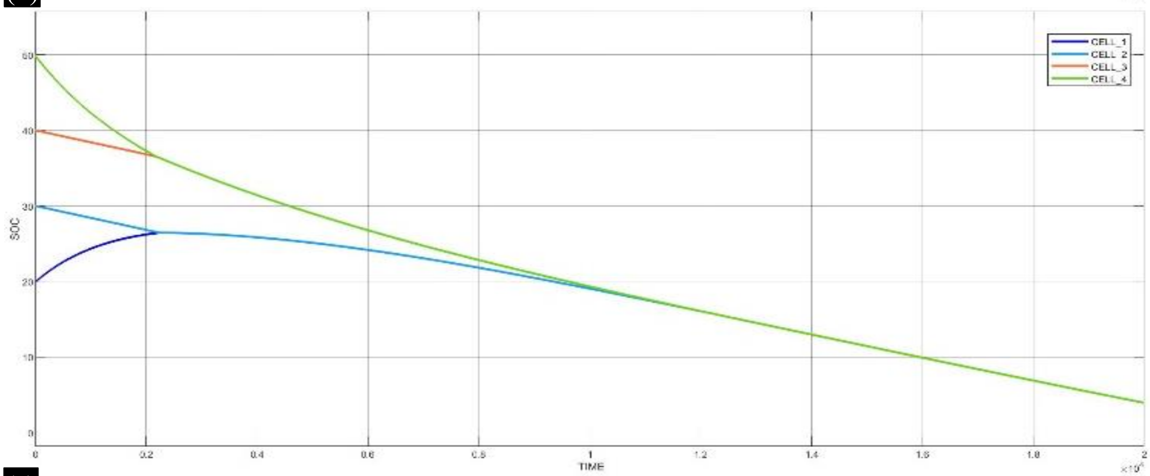
Figure 7. SOC Balancing of 4 Cells in Passive Balancing (a) Idle (b) Charging (c) Discharging modes.



(a)



(b)



(c)

Figure 8. SOC Balancing of 4 Cells in Single Switched Capacitor Balancing (a) Idle (b) Charging (c) Discharging Modes.

In active cell balancing excess charge is transferred within the cells so there is no wastage of energy. A single capacitor of farad range is taken as an active element for balancing purpose in switched capacitor balancing. In this topology, four cells are used with eight switches such that two switches for each cell. Simulation results are shown in Figure 8.

As capacitor-based balancing takes a long period for balancing converter based is done. Inductor is the active element used for balancing. Results are shown in Figure 9 for various operating modes. In the previous section it is seen that capacitor-based balancing takes 20,000s for attaining balancing whereas in the case of converter-based balancing it takes only 100s. So, converter based is preferred.

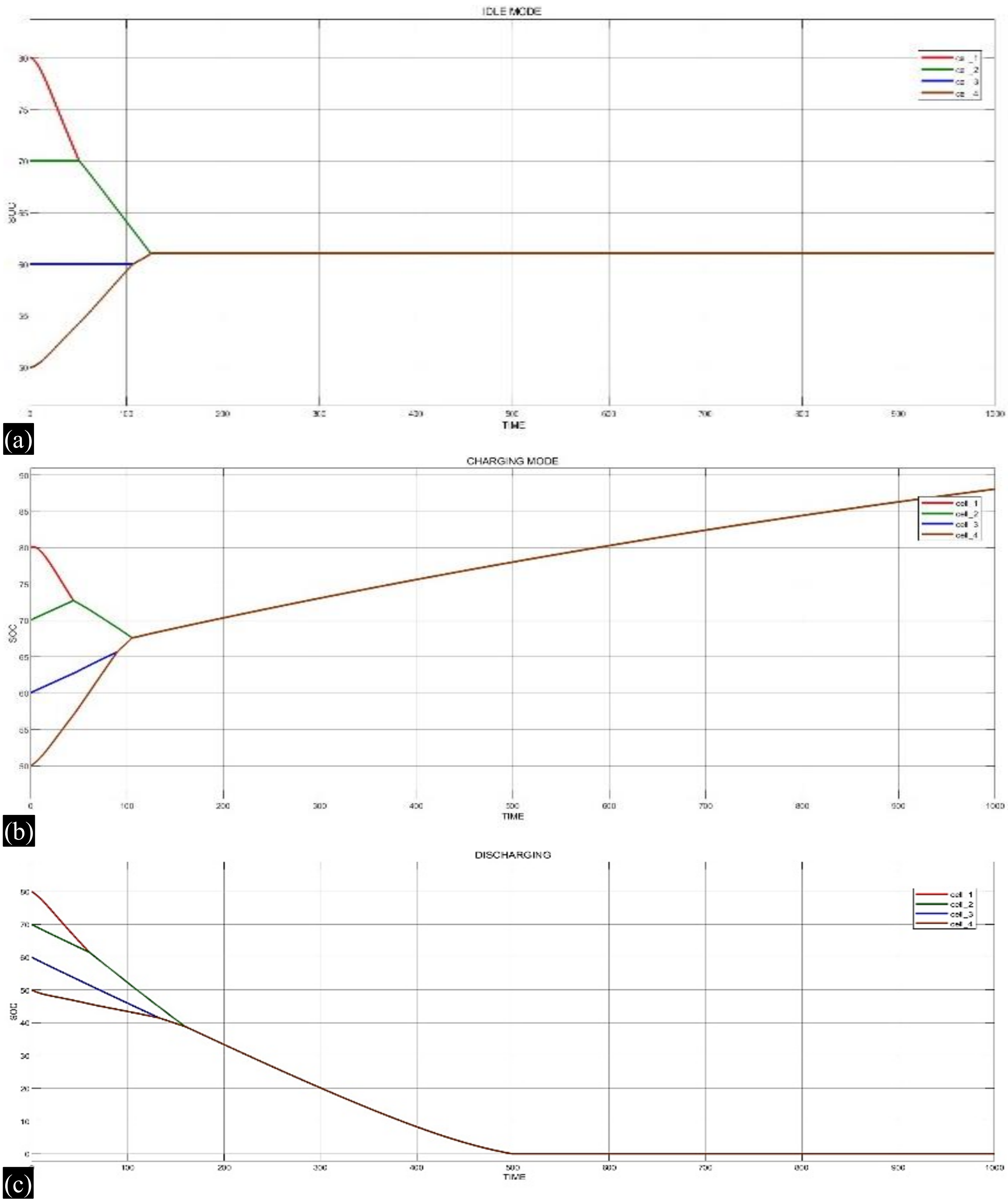


Figure 9. SOC Balancing of 4 Cells in Single Inductor Based Balancing (a) Idle (b) Charging (c) Discharging Modes.

As mentioned earlier, through resistor charge is dissipated as heat in passive balancing and it causes energy loss. Fig.8 shows the capacitor based active cell balancing which is a lot of time consuming and it requires a capacitor of high capacitance value. The inductor-based method shows how quickly cell balancing can be achieved when compared to the other two methods.

CONCLUSIONS

Cell balancing is an important task of the BMS that increases battery pack life, the safety of the battery system as well benefit from the whole battery pack energy. Passive balancing, Single switched capacitor battery balancing topology and single inductor-based topology are simulated using MATLAB/Simulink and detailed comparison has been presented. This paper investigated the use of single switched capacitor and single inductor-based cell balancing techniques, comparing active and passive methods. Active balancing methods, utilizing converters, demonstrated faster and more efficient charge transfer between cells, optimizing system performance. Passive balancing, dissipating excess charge through resistors, provided a simpler and cost- effective approach. The comparison highlighted the trade- offs between balancing speed, complexity, and cost. Active methods were suitable for applications requiring precise balancing, while passive balancing was viable for simpler systems. It is seen that single inductor-based method is faster than the other methods.

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