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Advanced Simulation Analysis of Voltage Balancing Techniques in Lithium-Ion Battery Packs for EVs

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Abstract—

Electric vehicle (EV) lithium-ion batteries may not function as well as they should due to issues such thermal runaway, cell voltage imbalance, undervoltage, overcharge, and overdischarge. When the voltage inside a battery pack differs between individual cells, a phenomenon known as cell voltage imbalance occurs. The battery's capacity decreases quickly due to this imbalance and the long charging and discharging cycles. The key to prolonging the life of battery packs is consistently improving the voltage uniformity of the cells, sometimes known as "equalizing" them. There are a plethora of approaches of regulating cell voltages, the most of which fall into one of two broad classes: passive and active. In this research, 4-cell Lithium-ion EV batteries are modeled and analyzed using MATLAB. For passive cell voltage balancing, switched shunt resistors are used, while for active cell voltage balancing, inductive shuttling is used. We put all of the proposed solutions through our paces. "battery management system," "battery response time," "state of charge," "state of health," "cell voltage," and "lithium-ion battery" are all terms that belong to the battery category.

INTRODUCTION

Portable electronics, electric vehicles, microgrids, communications, and industrial machinery are just a few of the many uses for the ubiquitous battery. The automotive industry has come to rely on rechargeable Lithium-Ion batteries because to its many advantageous characteristics, including their low weight, high energy density, big volume, quick charging, and environmental friendliness [1]. For safer operation, it is vital to precisely maintain the control variables at the levels of the Lithium-Ion cells and packs. These variables are closely monitored and protected by the Battery Management System (BMS), which acts as the brains of the battery pack. The temperature, voltage, and current of the battery pack are just a few of the metrics that the battery management system (BMS) monitors. It also collects data for analytical purposes and may forecast and prevent failures. Output, among other things, is monitored, and it safeguards against catastrophic damage [1, 5, 9, and 12]. The battery management system keeps an eye on all of those indicators, makes power adjustments, and gives you a lifespan estimate for the battery pack [1]. The State of Charge (SoC) of a battery shows the percentage of its capacity that is still stored energy. One of the main duties of the BMS is to carry out cell balancing processes [2][6]. A cell imbalance is among the most significant of the many potential issues that could impact battery systems. Without a reliable method of balancing the voltages of the individual cells, the battery pack's capacity would quickly deplete, and the system would fail. Thus, cell balancing is a huge help in keeping a battery healthy. To achieve this goal of cell balance in battery packs, many methods have been suggested [1][5]. Because of variations in manufacturing processes, measurement mistakes, and environmental conditions, no two Lithium-Ion battery cells are identical. Mistakes could be worsened by changes in operating temperature and charge/discharge cycles. A cell imbalance might result from the above indicated situation. This imbalance situation may lead to issues such as undercharging (in one or more cells), overcharging (above rated levels), underdischarging (if one cell reaches a lower level while others have ample charge), and overdischarge (below rated level). Damage to either the cell or the battery pack might occur in such a situation. A change to cell balance techniques is necessary [6]. Depending on whether they use CV or SoC, the many cell balancing algorithms developed for Lithium-Ion batteries may be categorized as either active or passive approaches [2][5]. To prevent overcharging of fully charged cells, passive equalization methods use resistor components to bring all cells' charge levels down to the lowest one. Passive techniques, such as those using switching shunt resistors or fixed shunt resistors, are well-suited to the Lithium-Ion battery cell. Passive techniques are often used because they are simple, cheap, efficient, compact, lightweight, and long-lasting [6][9]. However, active balancing methods transfer power from higher-level cells to lower-level ones in a battery pack by use of components such as inductors and capacitors [7-8]. The referenced works are [10][11][15]. When comparing and contrasting different Lithium-Ion battery balancing approaches, the key factors to consider are the control complexity and the speed of cell balancing, both of which are essential for maintaining cell balance and evenly distributing charge during charging and discharging [1]. Essential to the proper functioning of electric car battery packs, the cell balancing algorithm increases efficiency across the system, prolongs life when charged conventionally, and guarantees consistent performance [2–5]. Additional goals include enhancing the system's capacity to operate and charge efficiently. A number of proposed systems for battery balance are examined and contrasted in detail. The comparison includes electronic engineering, virtual balancing, and system efficiency assessment. This research compares active cell balancing algorithms against passive ones using MATLAB Simulink, and then we look at how they stack up against each other in terms of SoC and convergence time. Section I: Cell Balancing Practices The two primary metrics that the BMS measures and monitors are SoC and SoH, and cell balancing is a vital operation of the BMS. When building battery packs with cells connected in series, cell

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balancing is very necessary. As shown in Figure 1, there are two main categories of cell balancing techniques: passive and active [1] [4].

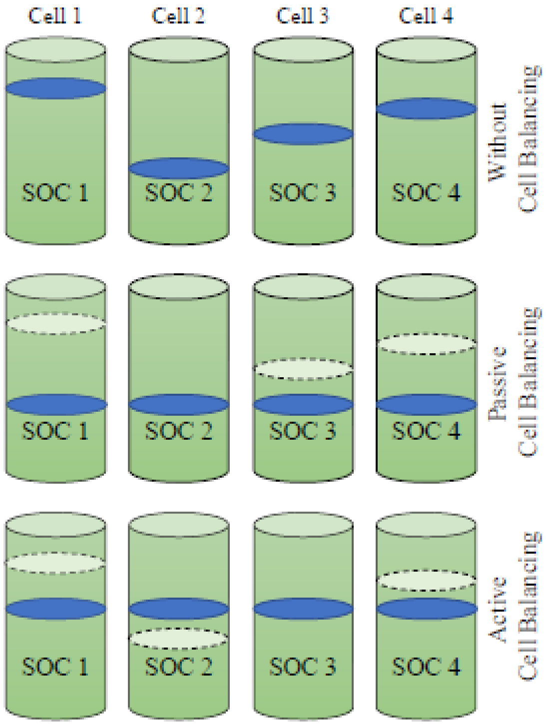
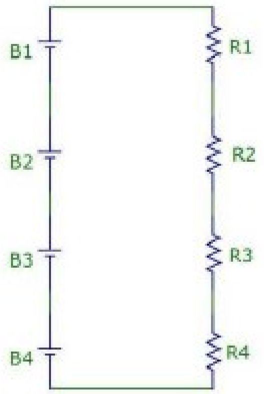
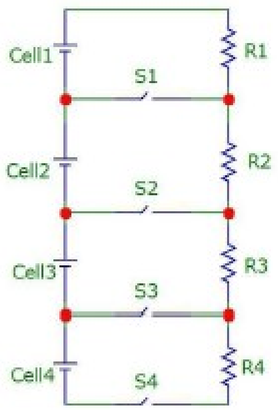


Fig. 1. Illustration of cell balancing methods for Lithium-Ion batteries

Using the above example as a guide, let's say there are four interconnected cells labeled 1, 2, 3, and 4. Prior to cell balancing, the relative concentrations of these cells are as follows: Cell 1 has 80% of the total concentration, Cell 2 has 30%, Cell 3 has 50%, and Cell 4 has 70%. The highest level cell releases its stored energy as heat and reaches the level of the lowest level cell 2 at 30% when passive balancing is implemented, as shown in Figure 1. As seen in Figure 1, active balancing also transfers the energy level from higher state of charge (SoC) cells 1 to lower states of charge (SoC) cells 2 and 4, and then to cell 3, bringing the cell into balance without releasing its stored energy. [1] [4]. A. Precautionary Cell Balancing Shunt resistors are connected across all of the batteries in the pack as part of the passive balancing procedure. The cells in the pack with greater voltage levels are distinguished by their strategically placed resistors, which are designed to dissipate the excess charge as heat. Resistors play a crucial role in balancing circuits by distributing excess energy from cells with higher voltages and bringing the voltages of individual cells into harmony. The result is that all of the cell voltages will be in sync with the lowest cell voltage. As can be seen here, there are two primary types of this method: fixed shunt resistor techniques and switching shunt resistor methods. Ref. 2. It must be noted that this strategy is generally used while charging. Due to the absence of reverse switching in the discharge mode, which might exacerbate imbalance concerns with particular cycles, this precaution is important. the first four [6] References [9] and [13].



(a)



(b)

Fig. 2. Passive cell balancing (a) Fixed resistor method, (b) Switched resistor method

A. Active cell balancing To ensure that all cells reach equilibrium, a technique called non-dissipative balancing transfers energy from cells with greater charges to cells with lower charges using storage devices like inductors or capacitors. Capacitors, inductors, and power electronic converters are the three main types of storage elements employed in this method. Not only that, but it works well for both charging and discharging. It effectively and rapidly balances cells, in contrast to passive balancing approaches. Nevertheless, the system's extensive complexity considerably increases system costs. Although the balancing speeds are slower, the capacitor-based solution offers a cost-effective implementation. The inductor-based approach, on the other hand, achieves better performance while still being relatively inexpensive to execute. For methods that rely on capacitors, a "flying capacitor" acts as a charge shuttling device; while charging, it is linked to the higher voltage, and when discharging, it is linked to the lower voltage cell. The basic idea is to charge or discharge a common balancer to keep the charges of different cells in equilibrium. the first four (1), (2), (3), and (14), among others. The switching network topology of the inductor approach is identical to that of the capacitor method (Fig. 3). This technology is easy to operate and allows for speedy balancing periods since it does not need sophisticated control methods for semiconductor switches.

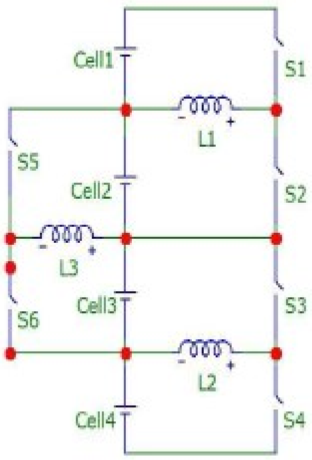


Fig. 3. Active cell balancing using inductor method for 4-cells

Active and passive cell balancing strategies compared You can see the results of the other literature's comparison of cell balancing strategies in Table I. Inductive shuttling and the balanced properties of switched resistors are taken into account [3] [14].

TABLE I. COMPARISION OF CELL BALANCING TECHNIQUES FROM OTHER LITERATURES (DURAISAMY THIRUVONASUNDARI ET.AL., 2021, RIGVENDRA KUMAR VARDHAN ET.AL.,2017)

Balancing Parameters	**Passive**	**Active (Inductor based balancing)**
Mode	Charging	Charging
Balancing speed	Slow	Fast
Size	Small	Medium
Cost	Economical	Moderate
Modularization	Simple	Moderate
Efficiency	Less than 90%	Less than 95%
Control complexity	Simple	Moderate
Implementation	Simple	Complex
Advantages	Simple to realize Low cost	Faster balancing, good efficiency, relatively cheap
Drawbacks	Energy is dissipated as heat, slow balancing	Filtering capacitors are required for high switching frequency

The active cell balancing approach using MATLAB/Simulink: A methodology Figure 4 shows the steps to take when using an active cell balancing technique, which can be implemented using either a floating capacitor or an inductor-based method. The goal is to ensure that all of the cells in an electric vehicle's battery pack are in a constant state of charge, which increases the battery's run time, prevents energy loss, speeds up cell balancing at full charge, and improves the vehicle's overall efficiency.

Apply the active cell balancing technique-designed model to MATLAB Simulink using the specified lithium-ion battery values shown in Table II. The initial state of charge (SoC), basic resistance (BRS), current, and voltage for every Lithium-Ion cell in the battery pack are calculated first. Next, we determine whether the battery pack is balanced or not by checking the state of charge of each individual cell. In an imbalanced system, the pulse width modulator allows higher-order cells to disperse their energy along a specific flow channel. To rectify the imbalance, the inductor stores the wasted energy and distributes it to the lower layers of the stack. Afterwards, every cell in the battery pack is examined. whether the two are equal. The simulation will end when the cells reach a state of equilibrium within the allotted period.

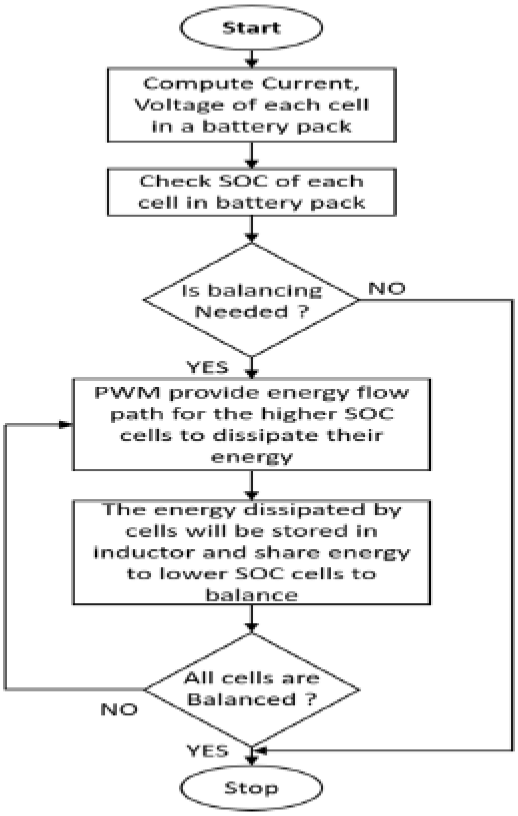


Fig. 4. Active cell balancing method using MATLAB

TABLE II. SIMULATION PARAMETERS

Lithium-Ion Battery Parameter	Range Selected for simulation
Nominal Voltage	3.7 Volts
Rated Capacity	5.4 Ah
Initial State of Charge	40 to 45 %
Resistor	1 Ω
Inductor	1 mH
Generator	1 W
Converter	2 level
Bridge	Single phase half bridge -2 pulses
Frequency	500 Hz

SIMULINKMODELING

The fixed resistor approach is shown in Figure 5 using a MATLAB Simulink model. A fixed resistor is linked in parallel with a series-connected cell in this manner to equalize the voltage of individual cells. The nominal voltage and rated capacity of each cell within the pack are 3.7V and 5.4Ah, respectively. Furthermore, each cell has its own load resistance of 1 ohm. Initial SOC of lithium ions in cells 1–4 is 40%, 2–3 is 41%, 3–4 is 44%, and 4–5 is 45%.

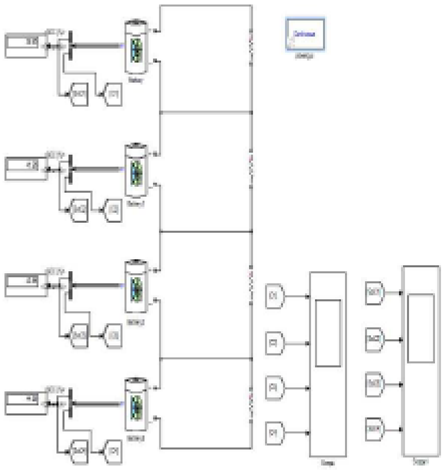


Fig. 5. MATLAB Simulink model for fixed resistor method.

The voltage of each cell is controlled by the balancing current, which flows via the resistor. This method is suitable for balancing circuits including nickel and lead acid batteries, which can withstand overcharge conditions without damage, although it does result in energy losses due to heat dissipation in each cell during the balance process. The MATLAB Simulink model illustrating the switched shunt resistor method's passive balancing approach is shown in Fig. 6. This method achieves voltage balance in the cells by connecting resistors in parallel with each series-connected cell and turning them on and off using controlled switches or relays. The resistor value is chosen appropriately in accordance with the intended balancing current. This method necessitates the use of a controller to monitor the circuit in two distinct modes. A voltage sensor monitors the voltage of each cell in sensing mode, while switches are coordinated concurrently in continuous mode. In the event of a cell imbalance, this sensor will determine the appropriate resistor to bypass. This method is often used in balancing circuits for Lithium-Ion batteries and is also known as the charge shuttling technique. More reliable than fixed-shunt resistor balancing circuits, it claims. As the balancing procedure progresses, however, more current flows through the switches and resistors, leading to energy loss.

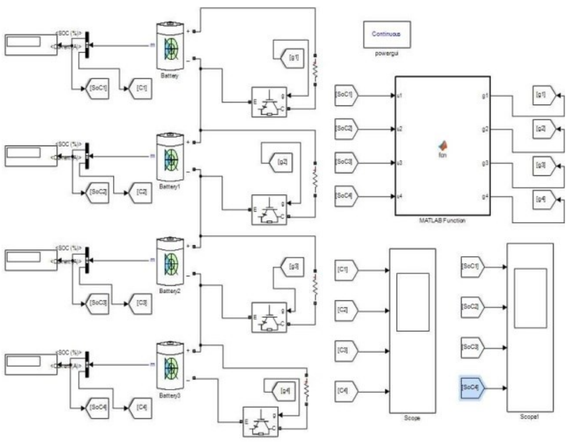


Fig.6.MATLABSimulinkmodelforswitchedshuntresistortechnique

Figure 7 shows how a switching circuit and inductors are used to accomplish active cell balancing. The switching circuit in this method makes use of a buck-boost converter. Through the buck-boost converter, the inductor transfers the charge that has accumulated in the high-voltage cell to the low-voltage cell. A buck-boost converter and four cells make up the inductive converter shown in Fig. 7. This is when inductors come into play, transferring charges across neighboring cells.

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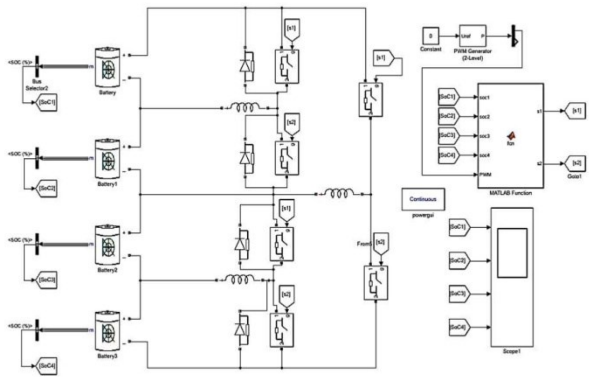

Fig.7.MATLABSimulinkmodelforactivecellbalancing modelusinginductormethod.

The inductor-based approach, also known as the continuous cell-to-cell method, is a remarkable circuit operation that is both faster and more efficient than capacitor shuttling. What's more, it doesn't require any sophisticated controller techniques designed for semiconductor switches, so it's easy to manage and guarantees rapid balancing times. The inductance bench is used to balance the battery by transferring energy from the battery pack to the cell via a system of connected devices (SoC). I. Findings and Analysis from the Simulation Using a fixed shunt resistor approach, the charge state graph is shown in Figure 8. Eliminating the IGBT switching device from the model yields this graph. By connecting each series-connected cell to a set resistor and adjusting it according to the current needed force, this method achieves cell voltage balancing. A cell's voltage is limited as a consequence of the current flowing through the resistor. Less complexity means fewer parts and less costs. One drawback of the method is the energy wasted as heat from each cell as seen in Figure 8 during the balancing process, which takes 2000 seconds to complete, meaning the balancing is slower than expected.

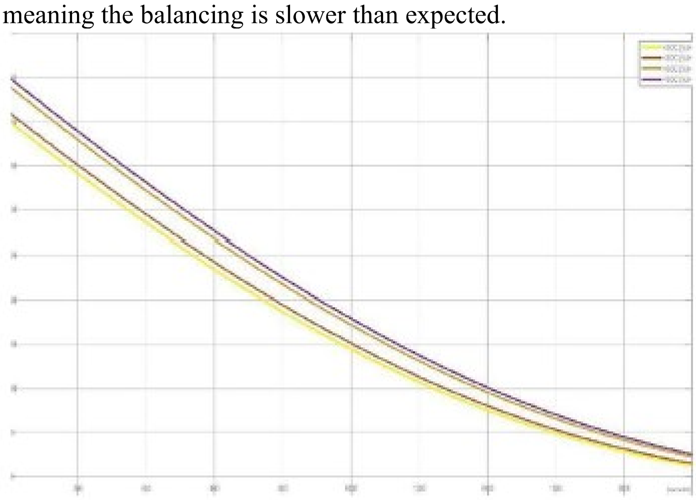

Fig. 8. Fixed resistor method simulation results

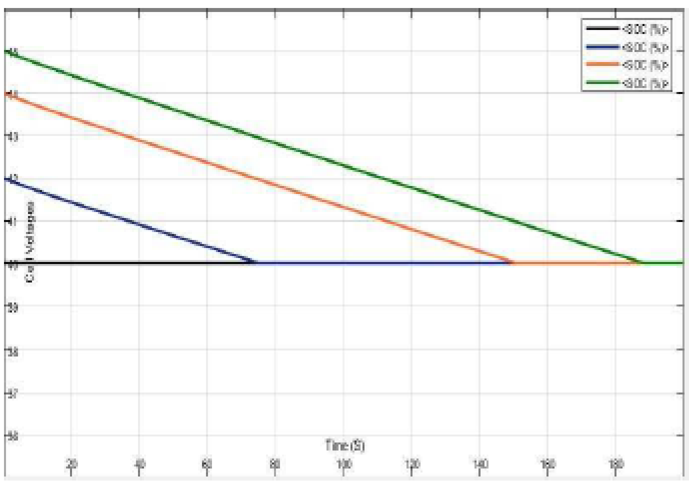

Fig. 9. Switched shunt resistor method simulation result

Figure 9 shows the system-on-a-chip (SoC) graph for a Lithium-Ion battery pack that uses the switched shunt resistor approach

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Vol 19, Issue 2, 2025

for passive balancing. Four series cells embedded in two parallel strings make up the battery pack. Discharging cells with higher states of charge via a resistor will bring the SoC of all cells down to a consistent value. The rated capacity of each cell within the package is 5.4 A and the nominal voltage is 3.7 V; the remaining parameters are adjusted as stated in Table II. Every single cell also has an IGBT connection to a 1 ohm load resistance. Each battery's state-of-charge determines the IGBT gate signal (switch activation). In cells 1-4, the initial SOC of the lithium ion is 40%, 40%, 41%, and 44%, respectively. Due to variations in the state of charge (SoC) of individual batteries, damage to the battery pack may occur when cells are charged or discharged at various voltages in the absence of a passive element. Cell balancing is accomplished during T=185 s using passive balancing, which is an improvement over the fixed resistor technique, and the state of charge of each battery will reach 40% throughout the duration of T=200 s. Figure 10 shows the inductive charge shuttling mechanism in action, demonstrating how energy may be transferred between cells for active balancing. It is acknowledged that this strategy effectively directs energy to where it is needed, hence preventing waste. However, in order to implement it, more components will need to be added to the system, which would increase the expenditures. The initial balance of the battery pack is imbalanced since the SOC of cell 1 is 40%, cell 2 is 41%, cell 3 is 44%, and cell 4 is 45%, and the parameters are adjusted as indicated in table II. To achieve cellular equilibrium, this method involves the higher-order SOC cell dissipating energy that would otherwise be stored in an inductor and then sharing that energy with the lower-order SOC cell. Therefore, theSoC is 41.53% after balancing all cells. Compared to the ways of balancing cells using a fixed resistor and a switched resistor, this one works better across the 200-second time interval, reaching equilibrium at around 158 seconds. The simulation findings show that the four cells have varying state-of-charge (SoC) values even when no balancing procedures are used. The lithium-ion chemistry is particularly vulnerable since there are only a small number of molecules inside the cell, which makes it relatively resistant to overcharging. The potential for these compounds to undergo internal reactions in response to sensitive voltage, similar to a chemical short circuit inside the cell, raises the danger of explosion or leaking. Considering the rate capability, cooling, and other charging system parameters occurs simultaneously with the assessment of the cell balance requirement. Discordances between cells arise major problem with large battery packs, which causes the performance of the battery to decline, as shown by the state of health of the battery. You can tell which cell is weakest in a succession of linked ones by looking at its SoH; it controls the string's total strength. When the battery pack is discharged past its limitations, this imbalance has the potential to generate safety concerns and produce thermal runaway.

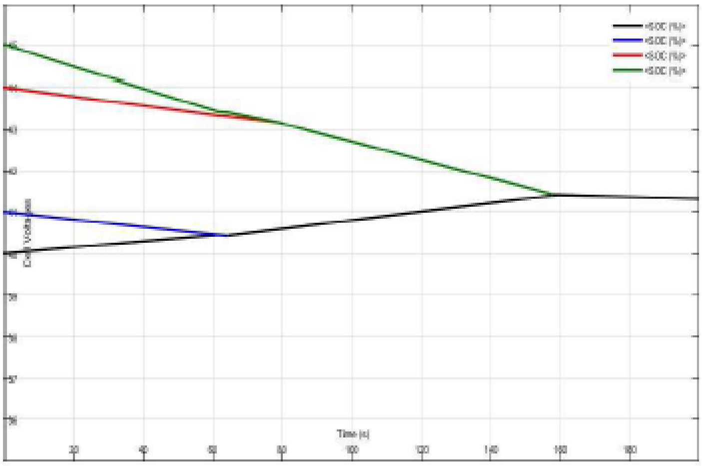

Fig. 10. Active cell balancing simulation result for inductor method.

CONCLUSION

It is evident from the results of the simulations that the fixed resistor method considerably decreases the SoC of each cell and requires more time than T = 2000s to balance all four cells. There is a very low rate of balance. On the other hand, when all four cells' states of charge (SoCs) are balanced using the switched shunt resistor method, it takes 185 s, and cell-1 converges at 40% with the lowest charge. The inductor charge-shuttling active cell balancing method takes T= 158s to balance 4 cells, while the latter is faster. An improvement over passive cell balancing procedures using a fixed resistor and a switching resistor, the cells' state of charge (SoC) was 41.53%. System health may be enhanced via the use of active and passive cellular balancing methods that monitor and change the state of charge (SoC) of each cell. Activated cell balancing redistributes charge when charging and discharging, in contrast to passive balancing, which only drains energy during charging. Researchers set out to create an active cell balancing technique that employs the inductor method as an efficient means of maintaining cell equilibrium in battery packs after realizing that the passive cell balancing approach fails to function at full state of charge and instead loses energy via the discharge resistor. By distributing charge dynamically throughout charging and discharging cycles, this approach maximizes efficiency and extends the life of batteries. It improves the system's health and reliability by using inductors to transfer energy swiftly and effectively. However, further active balancing solutions that overcome the drawbacks of the ones just stated may be found via study.

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