IJARSCT

International Journal of Advanced Research in Science, Communication and Technology

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429 Volume 5, Issue 3, July 2025 Impact Factor: 7.67

Comparative Study of Lithium-Ion Battery Cell Balancing Strategies for Electric Vehicle Systems in MATLAB

Pooja[1], Kuldeep Sharma[2], Rajnish[3]

M.Tech. Scholar, Department of EE[1]

Assistant Professor, Department of EE[2,3]

BRCM College of Engineering and Technology, Bahal (Bhiwani), India

Abstract: *The performance, longevity, and safety of lithium-ion battery packs used in electric vehicles (EVs) heavily depend on effective cell balancing techniques. This research presents a comparative analysis of various cell balancing strategies implemented through MATLAB simulations. Passive and active balancing methods are examined to evaluate their efficiency, energy loss, balancing speed, and impact on overall pack performance. The study investigates techniques such as resistor-based dissipation, capacitor shuttling, and inductor-based charge redistribution under different operating scenarios. Simulation results reveal the trade-offs between system complexity, cost, and effectiveness for each method. The findings offer practical insights for selecting the most appropriate balancing approach in EV applications, aiming to enhance energy utilization and extend battery life.*

Keywords*:* Battery modeling, Active cell balancing, Passive cell balancing, Topologies

I. INTRODUCTION

The global transition toward electric mobility has placed lithium-ion batteries at the forefront of energy storage technologies due to their high energy density, efficiency, and recharge ability. However, the inherent variability among individual cells within a battery pack often leads to unequal charging and discharging behavior. Over time, this imbalance can reduce the overall capacity, shorten the battery lifespan, and increase safety risks [1].

To address this challenge, battery management systems (BMS) incorporate cell balancing strategies to equalize the voltage or state-of-charge (SOC) levels across all cells. These strategies are broadly classified into passive and active techniques, each offering distinct advantages and limitations. Passive balancing dissipates excess energy as heat, making it simple but inefficient. In contrast, active balancing redistributes energy among cells, achieving better efficiency at the cost of increased circuit complexity.

This research focuses on a comparative simulation-based study of popular balancing techniques using MATLAB. By analyzing key performance indicators such as balancing time, energy efficiency, and thermal behavior, the study aims to identify optimal methods suitable for electric vehicle battery packs. The results are intended to guide researchers and engineers in designing more reliable and energy-efficient battery systems for sustainable transportation[2].

Battery In EV applications, consistent cell performance is critical, as even slight discrepancies in cell voltages can trigger early cutoffs or overcharging, reducing overall pack capacity. These inconsistencies often stem from manufacturing tolerances, temperature variations, aging effects, and non-uniform internal resistances. Without proper balancing, the weakest cell dictates the operational limits of the entire battery pack, resulting in inefficient energy use and decreased driving range [3].

The integration of cell balancing circuits within a BMS not only enhances the pack's efficiency but also plays a pivotal role in improving safety and thermal stability. Among balancing techniques, passive balancing is favored for its simplicity and low cost, but it wastes significant energy as heat. Active balancing methods—including capacitor-based, inductor-based, and transformer-based circuits—redistribute charge from higher to lower SOC cells, conserving energy and improving the usable capacity of the battery system. However, these methods come with trade-offs in terms of circuit complexity, control strategy design, and scalability for high-capacity EV batteries [4].

MATLAB, with its robust simulation environment and control system modeling capabilities, offers a powerful platform to simulate and compare the performance of different cell balancing approaches. This study employs MATLAB/Simulink to develop and evaluate models of both passive and active balancing circuits, using consistent battery cell parameters and test conditions. The goal is to provide a quantitative comparison that highlights efficiency, speed of balancing, component stress, and energy losses. Such a comparative analysis can support EV developers and system integrators in choosing the right balancing method tailored to their performance and budgetary requirements [5].

As electric vehicles become more mainstream, the demand for scalable, efficient, and reliable battery management solutionsis growing rapidly. The choice ofa suitable balancing strategy not only affects the technical performance but also has a direct influence on the commercial viability of EV systems. For instance, fleet applications may prioritize balancing speed and efficiency, while economy-class EVs might lean toward simpler and cost-effective methods. Therefore, understanding the performance implications of each balancing strategy in various scenarios is crucial for designing adaptable BMS architectures that meet specific vehicle requirements.

Thispaperaimstoaddressthisneedbysystematicallyanalyzingandcomparingmultiplebalancingtechniquesthrougha unified MATLAB simulation framework.

II. SYSTEM DESCRIPTION

The system developed in this study represents a simplified yet realistic configuration of an electric vehicle (EV) battery pack composed of multiple series-connected lithium-ion cells. Each cell in the series has unique electrical characteristics such as internal resistance, capacity, and initial state-of-charge (SOC), which are key factors contributing to imbalance during operation. To simulate the cell behavior and evaluate different balancing techniques, the system is modeled in MATLAB/Simulink with a modular structure, allowing for easy integration of various balancing topologies[6].

At the core of the system is the battery pack model, consisting of 6 to 12 cells connected in series. The model includes parameters for initial voltage differences, aging effects, and thermal characteristics to reflect real-world conditions. A Battery Management System (BMS)block isincorporated to monitorcell voltages and control thebalancing circuits. ThisBMS module dynamically selects the appropriate control signals based on the selected balancing strategy—either passive or active—and sends commands to the respective balancing circuit.

For passive balancing, resistor-based dissipative networks are connected in parallel with each cell. These resistors are switched on when a cell voltage exceeds a predefined threshold, causing excess energy to be converted into heat and thereby bringing the cell into balance with the others. This method is simple and cost-effective but results in significant energy loss.

In contrast, the active balancing configurations employ energy transfer elements such as capacitors or inductors. In capacitor- based systems, a flying capacitor is used to shuttle charge between higher-voltage and lower-voltage cells in a timed sequence. The inductor-based design, on the other hand, temporarily stores excess charge and then redirects it to undercharged cells through controlled switching. These active methods aim to improve energy efficiency by preserving the redistributed charge rather than dissipating it.

The overall system is governed by a central controller that implements the logic for voltage monitoring, switching, and balancing duration. Various scenarios, including charge, discharge, and rest conditions, are simulated to analyze how each strategy performs over time. Data on SOC uniformity, balancing time, and power losses are recorded and compared to assess the effectiveness of each approach.

A. Lithium-IonBattery

Lithium-ion (Li-ion) batteries are the most widely used energy storage systems in electric vehicles due to their high energy density, long cycle life, and favorable power-to-weight ratio. Each cell within a Li-ion battery pack operates based on the reversible electrochemical movement of lithium ions between the anode and cathode during charge and discharge cycles.

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ISSN: 2581-9429 Volume 5, Issue 3, July 2025 Impact Factor: 7.67

Despite being manufactured under strict quality controls, individual cells exhibit slight variations in capacity, internal resistance, and voltage characteristics, which can lead to imbalances during operation. A typical Li-ion battery cell consists of a graphite anode, a lithium metal oxide cathode (such as $LiCoO_2$ or $LiFePO_4$), and an electrolyte that facilitates ion transfer. In EV applications, cells are usually connected in series to achieve the required pack voltage and in parallel to meet current demands. However, series configurations make the system vulnerable to performance degradation if one or more cells deviate significantly from the average state-of-charge (SOC).

In this study, the battery pack model includes multiple series-connected Li-ion cells, each represented in MATLAB/Simulink with independent voltage and SOC parameters. The model accounts for nonlinear behaviors such as capacity fade, Coulombic efficiency losses, and temperature effects to reflect real-world dynamics. These features are essential for accurately evaluating the impact of different balancing strategies under realistic operating conditions[7].

The effectiveness of any cell balancing method is largely influenced by the behavior of the individual cells during charging and discharging. Therefore, understanding and accurately modeling the characteristics of lithium-ion batteries is a crucial foundation. for analyzing balancing techniques as illustrated in Fig. 1,2. This detailed representation enables simulation of imbalanced states and the evaluation of how quickly and efficiently each balancing strategy restores uniformity across all cells

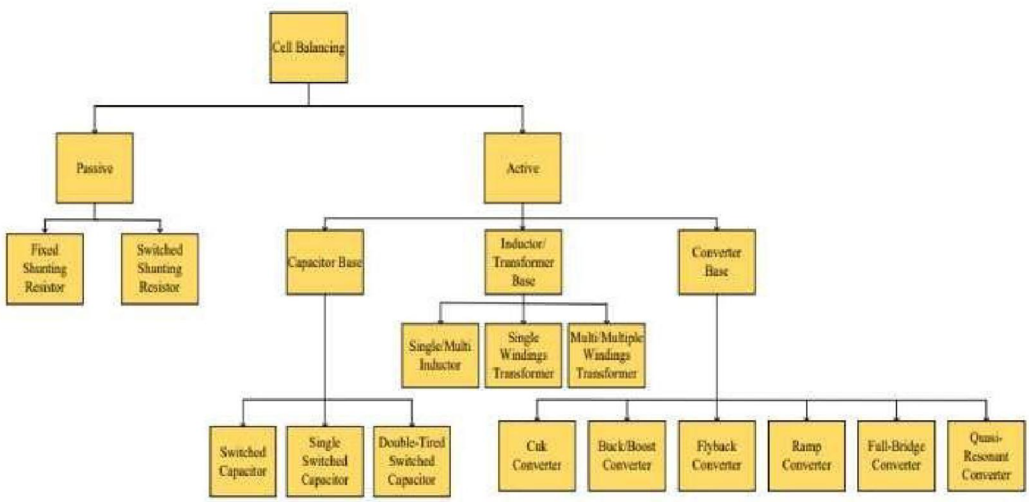

Fig.1.Cell balancing topologies

$$V_t = V_{ocv} - V_1 - V_2 - V_3$$

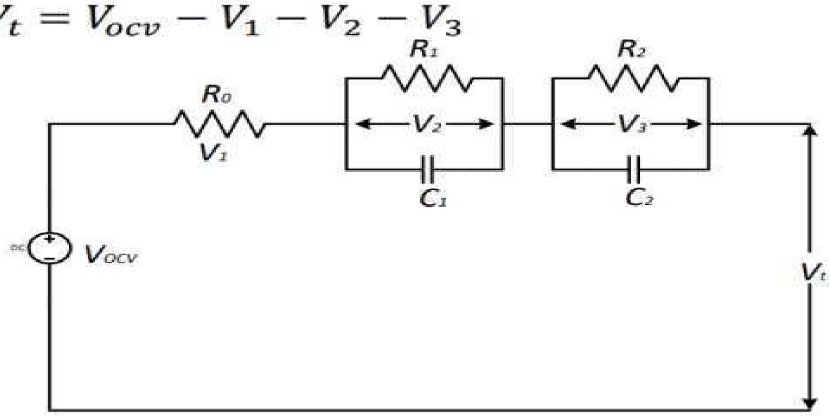

Fig.2.Equivalent electrical circuit–based Li-ion model

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$$Vt=Vocv-V1-V2-V3 \quad (1)$$

III. CELL BALANCING

Cell balancing isa vital function in battery management systems (BMS) designed to ensure uniform voltage and state-of-charge (SOC) across all cells within a lithium-ion battery pack. Due to slight manufacturing inconsistencies, temperature gradients, aging, and usage history, individual cells can behave differently during charging and discharging. If left unbalanced, these disparities can lead to overcharging or deep discharging of certain cells, which compromises the safety, efficiency, and longevity of the entire battery system.

The primary objective of cell balancing is to redistribute energy in such a way that all cells reach a similar voltage level, especially at the end of charging cycles. Effective balancing allows the pack to operate closer to its full capacity, enhances thermal stability, and reduces stress on individual cells. In electric vehicles, where performance and battery life are critical, a well-implemented balancing system contributes significantly to energy optimization and cost savings over the vehicle's lifespan.

Cell balancing strategies are generally categorized into two types: **passive balancing** and **active balancing**. Passive balancing involves discharging the excess energy of higher SOC cells through resistive paths, usually in the form of heat. Although it is simple and low-cost, passive balancing is inherently inefficient because it wastes energy rather than redistributing it. This method is often used in low-cost or low-power applications where efficiency is not a major concern.

Active balancing, on the other hand, transfers excess charge from higher SOC cells to lower SOC cells using components like capacitors, inductors, or transformers. This method conserves energy and allows for faster and more efficient equalization. Active balancing is more complex to design and implement, requiring additional circuitry and control algorithms, but it offers significant advantages in terms of energy efficiency, particularly in high-capacity EV battery packs.

In this study, both passive and active balancing techniques are implemented and evaluated using MATLAB/Simulink. The comparison focuses on several performance metrics, including energy loss, balancing time, voltage uniformity, and system complexity as illustrated in Fig. 3. The results help determine which strategy is more suitable for electric vehicle applications under different usage conditions and design priorities [8]

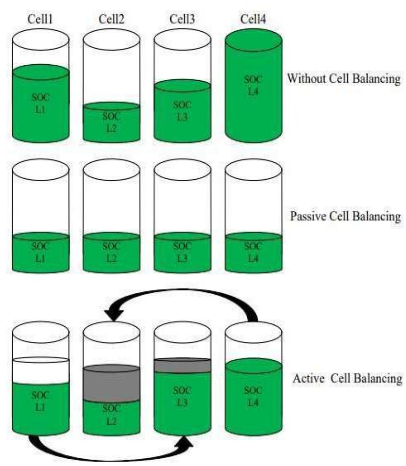

Fig. 3. Pictorial comparison between passive and active cell balancing

A. Passive Cell Balancing

Passive cell balancing is the most commonly used method due to its simplicity, low cost, and ease of integration into battery management systems (BMS). In this approach, excess energy from higher-voltage cells is dissipated in the form of heat using resistors. Each cell in the battery pack is connected to a parallel resistive circuit, typically controlled by switches or transistors. When the BMS detects a cell voltage above a predefined threshold, it activates the resistor

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circuit, allowing the excess charge to be drained until it matches the lower-voltage cells. This method is particularly suitable for systems where cost, simplicity, and reliability are prioritized over efficiency. However, passive balancing is inherently inefficient because the energy is wasted rather than reused. Moreover, continuous dissipation may lead to thermal buildup, requiring careful thermal management, especially in high-capacity packs. Passive balancing is more effective when the imbalance is small and occurs infrequently, such as during slow charging or storage conditions as illustrated in Fig. 4.

In MATLAB/Simulink, the passive balancing circuit is modeled using resistive loads connected in parallel with each cell and controlled through switching logic based on cell voltage levels. Simulation helps to observe the heat dissipation, energy loss, and balancing speed, providing insights into the limitations and performance of this method in EV applications.

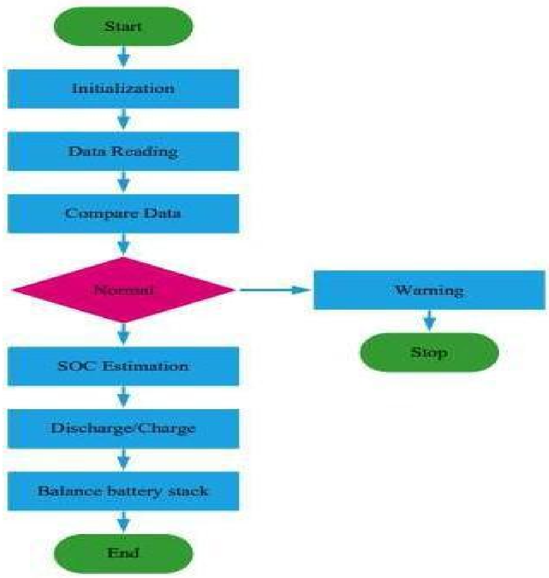

Fig.4.Flowchart of the algorithm

Fixed Shunting Resistor

The **Fixed Shunting Resistor** method is the most basic form of passive cell balancing. In this approach, a resistor is permanently connected in parallel with each cell in the battery pack. As the cells charge, the excess energy from higher-voltage cells is continuously dissipated through these resistors in the form of heat. This constant energy loss helps to reduce the voltage of stronger cells, allowing weaker cells to catch up over timeas illustrated in Fig. 5.

While this method is simple and requires no active control circuitry, it is highly inefficient. The continuous energy drain leads to unnecessary power loss even when the cells are already balanced or not charging. Additionally, the fixed resistor value must be carefully chosen to avoid excessive current flow, which could generate heat and damage the battery. Due to its lack of control and energy inefficiency, fixed shunting is rarely used in modern electric vehicles but may still be found in low-cost or low-power applications [9].

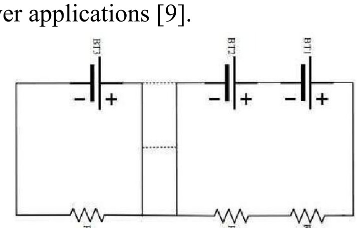

Fig.5.Fixed shunt resistor.

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Switched Shunting Resistor

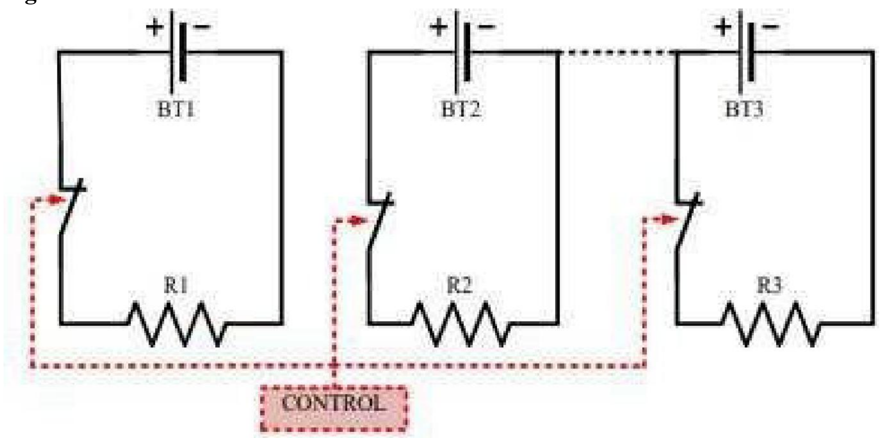

Fig.6. Switched shunt resistor.

The Switched Shunting Resistor method is a more controlled and widely used version of passive balancing. In this approach, resistors are placed in parallel with each cell, but instead of being permanently connected, they are controlled by electronic switches—typically MOSFETs. The Battery Management System (BMS) monitors each cell's voltage and activates the switch when a cell exceeds the voltage threshold as illustrated in Fig. 6. The resistor then dissipates the excess

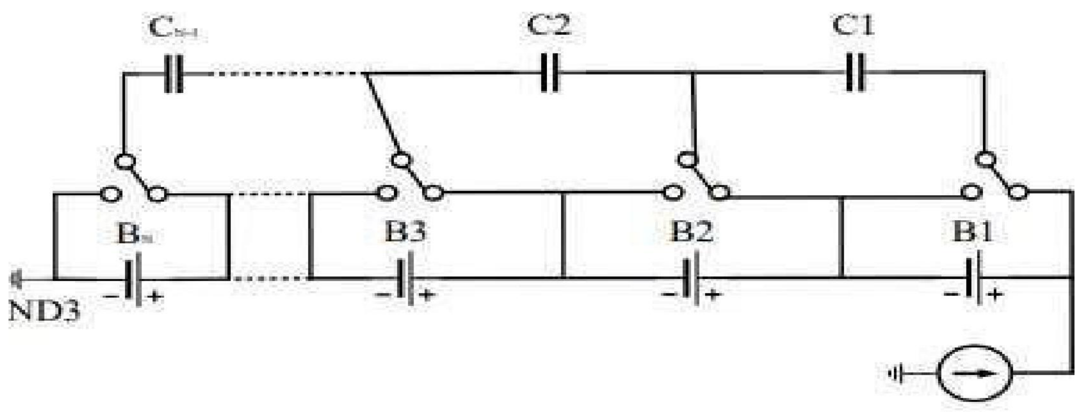

Fig. 7. Switched capacitor balancing topology

This method offers better control and efficiency compared to fixed resistors, as energy is only dissipated when necessary. It also reduces unnecessary heat generation and prolongs thelife of the balancing circuit components. Although still inefficient compared to active methods—since energy is lost as heat—switched shunting provides a cost-effective and reliable solution for moderate-performance EV battery systems.

In MATLAB/Simulink simulations, this method is modeled by integrating resistors with controlled switching blocks that respond to voltage sensors. The switching logic ensures that only the overcharged cells are discharged, making the balancing process more targeted and manageable [10].

B. Active cell balancing method

This Active cell balancing is a more advanced and efficient technique in which energy from cells with higher voltage is transferred directly to those with lower voltage. Unlike passive methods, active balancing conserves energy by redistributing it within the battery pack, resulting in improved overall efficiency and prolonged battery life. This method is especially useful in electric vehicles, where battery energy is valuable and must be used optimally.

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There are several topologies used in active balancing, including capacitor-based, inductor-based, and transformer-based designs. In capacitor-based balancing, a flying capacitor alternately connects to overcharged and undercharged cells, transferring charge through controlled switching. Inductor-based designs use energy storage in a magnetic field to transfer charge between cells. These methods require more complex circuitry and control algorithms but offer faster and more precise balancing with significantly lower energy loss.

In the MATLAB simulation environment, active balancing is implemented using dynamic charge transfer circuits with control logic that monitors the voltage of each cell and regulates the switching sequence. The simulation tracks energy redistribution, voltage equalization, balancing time, and component stress. The results highlight the performance advantages of active balancing over passive methods, particularly in terms of energy retention and responsiveness under varying load conditions.

However, this approach results in energy loss because of the high current flowing through the resistors and switches during the balancing process, as illustrated in Fig. 7.

a) Single Switched Capacitor

The Single Switched Capacitor method is a simple and efficient form of active cell balancing that transfers charge between adjacent cells using a capacitor and controlled switches. In this method, a flying capacitor is alternately connected acrosspairs of cells — first to a higher-voltage cell to store energy, and then to a lower-voltage cell to release that energy. This process continues cyclically, allowing gradual redistribution of charge among neighboring cells.

The system requires minimal components: one capacitor and two electronic switches per cell pair. Control logic is used to monitor cell voltages and time the switching operations appropriately. Although the method is relatively straightforward and has low implementation cost, it is limited by the fact that it only balances charge between adjacent cells. As a result, balancing speed may be slower for packs with wide voltage disparities or non-adjacent imbalance.

In MATLAB/Simulink, the single switched capacitor circuit is modeled using sequential switch control and voltage sensing blocks. This allows evaluation of energy transfer efficiency, balancing speed, and current stresses on the capacitor [11].

b) Double-Tiered Capacitor

The Double-Tiered Capacitor method is a more advanced version of the switched capacitor approach, designed to overcome the adjacency limitation of the single-tier configuration. It involves two levels (or tiers) of capacitor balancing: the first tier operates between neighboring cells, while the second tier can transfer charge across non-adjacent cells by using intermediary connections as illustrated in Fig. 8. This configuration greatly enhances the flexibility and efficiency of the balancing process. By allowing energy transfer beyond adjacent cells, double-tiered capacitor balancing can more quickly correct large imbalances in SOC, especially inhigh-voltageorhigh-capacitybatterypacksusedinelectricvehicles.However,thisincreased performance comes with added complexity, requiring more capacitors, switches, and a more sophisticated control algorithm to prevent switching conflicts and ensure safe operation.

In the MATLAB simulation environment, the double-tiered configuration is implemented using layered capacitor-switch networks controlled by a central balancing logic unit. The performance is assessed based on how quickly and evenly it can restore cell balance under varying load and initial imbalance conditions as illustrated in Fig. 9.

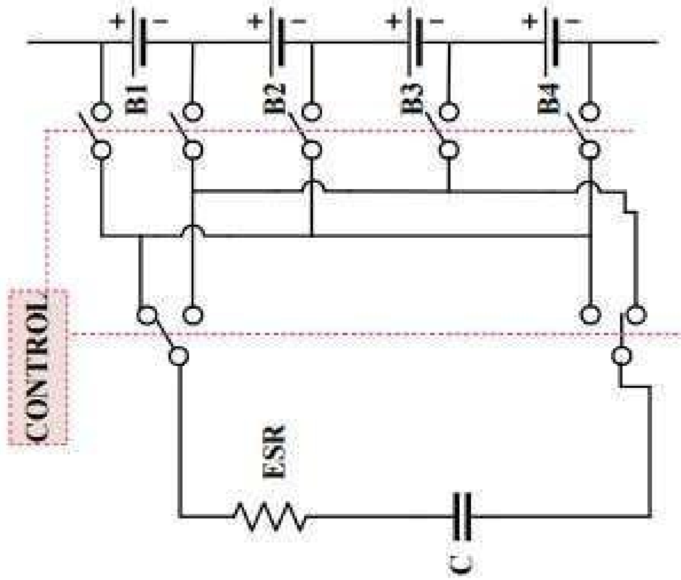

Fig. 8. Single switched capacitor cell balancing topology

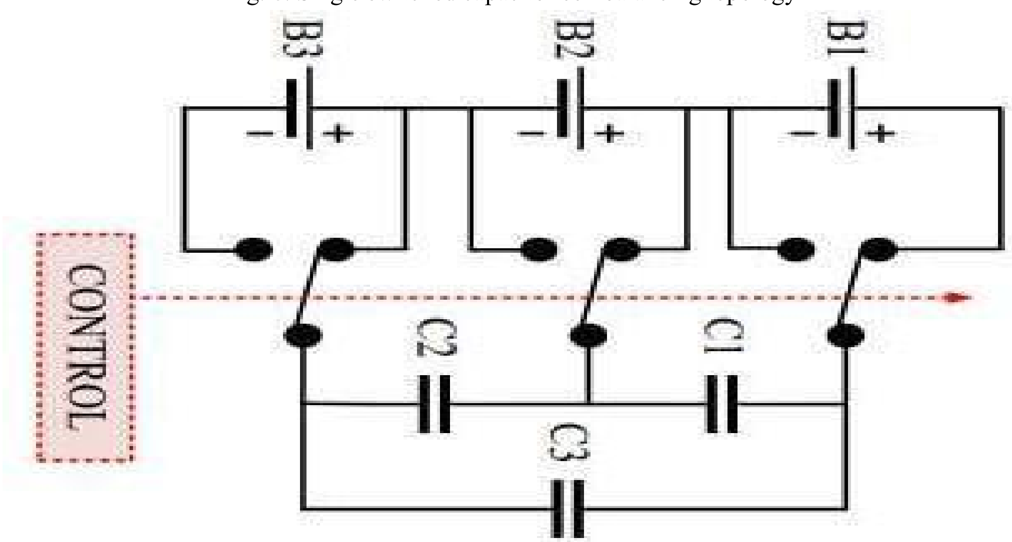

Fig. 9. Double-tiered switched capacitor cell balancing topology

2) Inductors/transformers-based topology

In Inductor- and transformer-based topologies are among the most energy-efficient active balancing methods for lithium-ion battery systems, especially in electric vehicles where power conservation is critical. These techniques use magnetic energy storage components — inductors or transformers — to temporarily store energy from higher-voltage cells and then release it to lower-voltage cells. The energy transfer is achieved through precisely timed switching operations, which minimize energy loss and enhance the overall balance of the battery pack.

These topologies are particularly suitable for high-capacity EV batteries because they can handle higher currents and allow balancing over longer distances within the pack — including non-adjacent cells. Although they provide excellent performance in terms of energy efficiency and balancing speed, the complexity of control circuits and switching mechanisms is significantly higher compared to capacitor-based methods. Moreover, electromagnetic interference (EMI) and component sizing must be carefully managed during design and implementation.

Inductor-based methods are categorized mainly into Single Inductor and Multi-Inductor configurations, each with unique characteristics and trade-offs.

IV. CONCLUSION

The simulation results clearly demonstrate that active cell balancing techniques outperform passive methods, especially in terms of energy conservation and long-term battery health — factors that are critical in electric vehicle (EV) applications. Active balancing efficiently redistributes charge from higher-voltage cells to those with lower voltages, minimizing energy loss through heat dissipation and improving overall system performance and battery lifespan. In this study, a switched resistor-based passive balancing circuit was also developed and tested. To enhance its performance, a diode was integrated in series with each resistor. This addition helped suppress reverse current flow, reduced voltage instability, and improved the reliability of the balancing process. While passive balancing is inherently less efficient due to the conversion of excess energy into heat, it continues to be widely adopted in lithium-ion NMC battery systems due to its simplicity, lower cost, and minimal control requirements.

One of the key advantages of passive systems lies in their compact design and reduced component count, which translates into lower manufacturing costs and simpler maintenance. These systems are particularly suitable for applications where minor SOC imbalances are acceptable, and cost-effectiveness is a higher priority than absolute energy optimization. In contrast, active balancing offers higher energy utilization efficiency, but its greater circuit complexity, higher component count, and increased cost may limit its feasibility for budget-constrained or small-scale systems.

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