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A Fast and Energy-Efficient Hybrid Cell Balancing Architecture for Series-Connected Lithium-Ion Battery Packs

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ABSTRACT
As the global transportation sector shifts toward electric vehicles, the performance and safety of high-voltage lithium-ion battery packs have become an important factor. It is critical to maintain same state of charge of all series connected cells to maximize the usable capacity and avoid catastrophic failures like thermal runaway. The balancing methods used traditionally have a significant trade-off: passive balancing is cost effective but highly inefficient, and active balancing is highly efficient, but is affected by an asymptotic tailing effect that significantly slows delays the final convergence.
This paper proposes a novel Hybrid Cell Balancing Topology that combines a single switched capacitor network with a switched resistor network based on a dual-mode control approach. The system utilizes a coarse-fine tuning approach: the active subsystem rapidly handles bulk energy transfer during high imbalances, while the passive subsystem executes precision equalization during the final settling phase.
Simulation results in MATLAB for a 4-cell series string shows that the hybrid balancing approach significantly reduces balancing time compared to standalone active methods. By limiting dissipative balancing to its final phase, the suggested topology considerably improves energy efficiency compared to independent passive balancing systems. This proposed hybrid architecture is the most effective in optimizing the operational envelope to give fast convergence required in dynamic EV applications without significant thermal limitations.
Keywords - Battery Management Systems (BMS), Cell Balancing, Hybrid Topology, Lithium-ion Batteries, SOC Equalization.

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I. INTRODUCTION

Electric Vehicles Overview.

The transportation industry of the world is currently in the paradigmatic shift as the use of internal combustion engine-powered vehicles is replaced with electric vehicles (EVs) due to the increasing environmental awareness and the exhaustion of fossil-fuel resources [1].The need to reduce greenhouse-gas emissions and improve the quality of urban air stimulates the accelerated introduction of EVs [2], [3].The global governments and manufacturers in the automotive industry are investing heavily in electrification technologies, and this puts EVs as the foundation of sustainable mobility in the future [4]. EVs use electricity to power electric motors, unlike the conventional vehicles that rely on mechanical propulsion based on the combustion of hydrocarbons, which present greater efficiency, instantaneous torque, and zero tailpipe emissions [5] .

1.2. The Lithium-Ion Battery: the EV Powerhouse.

Lithium-ion (Li-ion) batteries have become the most common source of power used in modern EVs out of the range of technologies available to store energy. They are predominant due to their high energy density, high power to weight ratio, low self-discharge rate and long cycle life as compared to lead acid or nickel metal hydride counterparts [6], [7]. However, the battery pack is the costliest and most important part of an EV. To meet the high-voltage and power needs of the vehicle drive train, hundreds or thousands of individual battery cells are needed to be connected both in series and in parallel arrangements [8], [9]. On the one hand, these high-capacity packs can increase the range of their driving capacity, but on the other hand, they create significant hazards in the areas of safety, reliability, and thermal control. Li-ion chemistries are sensitive to operating conditions such as operating beyond their safe voltage or temperature ranges can cause irreversible degradation or disastrous failure, such as thermal runaway [10], [11], [12].

1.3. Battery Management systems (BMS)

A Battery Management System (BMS) is an essential component to reduce the underlying risks and enhance the performance of Li -ion packs. The BMS is the brains of the battery pack and checks important parameters like voltage, current and temperature in real-time [13], [14]. The major functions of a good BMS are:

Safety Protection: Disconnection of load in the case of over-voltage, under-voltage or over temperature occurrences [15].

State Estimation: Calculation of the State of Charge (SOC) and State of Health (SOH) to forecast the driving range and the useful life remaining [10], [16].

Thermal Management: Control of cooling or heating processes to ensure that the battery pack is kept in its optimal thermal limits [17].

Cell Equalization: Active or passive equalization of the charge stored in series-connected cells [9], [18].

A Li-ion battery pack would go unsafe and virtually ineffective within a short time of operation without a functional BMS [14].

1.4. The necessity of Cell Balancing.

Ideally, the cells in a battery pack would be identical, and have exactly the same capacity, internal impedance, and self-discharge properties. Practically, however, the tolerances in manufacturing, non-uniform heat distribution in the pack and aging effects introduce some unavoidable variation between cells [19], [20]. These discrepancies cause a difference in the State of Charge of cells when the cells are operated in series. As shown in Fig.1, when charging, the weakest cell (i.e. the one with the smallest capacity or highest impedance) reaches the maximum voltage cutoff first, and the charging process of the whole pack ends prematurely. However, while discharging, the weakest cell will hit the lowest possible voltage threshold first, cutting off power input to the motor even when the other cells still have substantial energy [21], [22], [23].

This effect, popularly called imbalance, significantly reduces the usefulness of the battery pack. In addition to that, when the battery management system does not recognize such an imbalance, deficient cells can be overcharged or discharged, thus triggering an accelerated degenerative process and even safety hazards. Therefore, cell balancing is not just an extra feature, it is a crucial requirement to any multi-cell series battery setup.

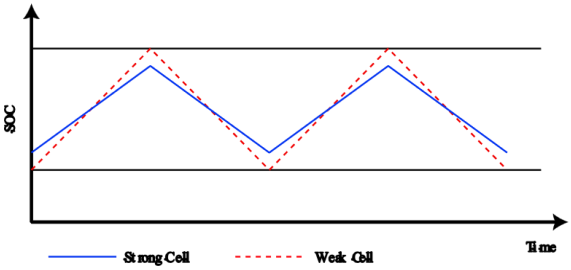

Fig. 1: Charging and discharging cycle of strong and week cells in series

1.5. Motivation and Research Objectives

The importance of the cell balancing is well established, but it has serious trade-offs when applied in practice. Dominating methodologies are generally categorized into passive (dissipative) and active (non -dissipative) topologies as further explained in the following chapters [3], [18].

Passive balancing is simple and cost-effective, but it dissipates energy as heat, and thus defeats the efficiency goals of electric vehicles [24], [25]. Compared to that, active balancing schemes based on capacitors or inductors are more efficient but tend to have slow equalization, especially at the end-stage of the process when the inter-cell voltage differences are small.

This suggests an obvious need of a balancing architecture which can integrate the speed and simplicity of passive approaches with the power efficiency of active ones. The proposed system aims to optimize both balancing speed and energy efficiency by including the single switched capacitor network to support bulk energy transfer and the switched resistor network for the final precision adjustment and will thus remedy the weaknesses of the existing standalone architectures.

II. REVIEW OF EXISTING CELL BALANCING TECHNIQUES

2.1. Introduction

The cell balancing methods can be traditionally distinguished into two main types, passive balancing and active balancing [26], [27]. This chapter will provide a detailed analysis of the theoretical functionality, equations of operation, performance limitation of the two simplest methods used in the literature, Switched Resistor (Passive) and Single Switched Capacitor (Active) balancing [28], [29].

2.2. Passive Cell Balancing: Switched Resistor Topology

2.2.1. Theory of Operation

The passive cell balancing is the most commonly used method of balance in commercial battery systems, mainly because of its simplicity and low cost. The basic operating principle involves the removal of excessive charge of the cells with a higher SOC to match the SOC of the cells with the minimum value in the string as shown in Fig.2. This goal is accomplished by placing a bleed resistor in parallel to every cell, whose connection is enabled by a controlled switch, usually a MOSFET. When a cell's voltage exceeds the balancing threshold, the switch closes, and the excess energy is dissipated as heat through the resistor [30], [31].

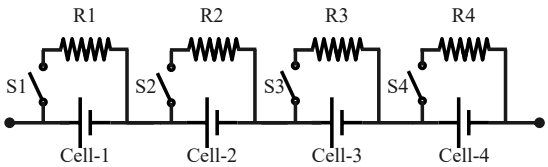

Fig. 2 Switched Shunt Resistor Balancing

2.2.2. Governing Equations

The operation of the passive balancing circuit is governed by Ohm's Law [32]. Assuming a cell voltage V_{cell} and a balancing resistor R_{bal}, the balancing current I_{bal} flowing through the resistor is given by:

$$I_{bal} = \frac{V_{cell}}{(R_{bal} + R_{on})} \quad (1)$$

Where R_{on} represents the on-state resistance of the MOSFET switch. Since R_{on} is typically negligible compared to R_{bal}, the equation simplifies to:

$$I_{bal} \approx \frac{V_{cell}}{R_{bal}} \quad (2)$$

The rate of energy dissipation, which dictates the thermal management requirements of the BMS, is calculated as the power loss P_{diss} [30][32].

$$P_{diss} = (I_{bal})^2 \cdot R_{bal} = \frac{(V_{cell})^2}{R_{bal}} \quad (3)$$

The total energy wasted (E_{loss}) during a balancing interval t is the integral of power over time:

$$E_{loss} = \int_0^t P_{diss}\, dt \quad (4)$$

While effective, this technique is inherently limited by the power rating of the resistors. To prevent overheating, R_{bal} must be kept relatively high, which inherently limits the balancing current I_bal and consequently slows down the equalization process. [30][31][32].

2.3. Active Cell Balancing: Single Switched Capacitor Topology

2.3.1. Theory of Operation

Active cell balancing aims to conserve energy by redistributing charge rather than dissipating it. The Single Switched Capacitor (SSC) topology is a widely researched active method that improves upon the component count of traditional multi-capacitor chains. Fig. 3 shows the circuit diagram of Single Switched Capacitor topology. Instead of using n-1 capacitors for n cells, this topology utilizes one single central capacitor shared among all cells via a switch matrix [28], [29], [33].

The operation follows a "Direct Energy Transfer" strategy:

Selection Phase: The controller identifies the cell with the highest SOC (SOC_{Max}) and the cell with the lowest SOC (SOC_{Min}) in the entire pack, regardless of their physical positions.

Charging Phase: The switch matrix connects the single capacitor in parallel to the SOC_{Max} cell, charging it.

Discharging Phase: The switches reconfigure to connect the capacitor in parallel to the SOC_{Min} cell, discharging the stored energy directly into the weakest cell.

This "Any-to-Any" transfer capability is a significant improvement over neighbour-to-neighbour methods, as it avoids the energy loss and delay associated with passing charge through multiple intermediate cells.

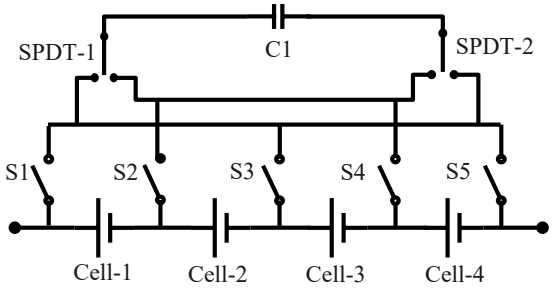

Fig. 3 Single Switched Capacitor Balancing

2.3.2. Governing Equations

The charge transfer capability of the SSC circuit depends on the voltage difference between the strongest and weakest cells ($\Delta V = V_{Max} - V_{Min}$), the capacitance value (C), and the switching frequency (f_{sw}) [28], [29].

The charge (Q) transferred in a single switching cycle is approximately:

$$Q = C \cdot (V_{Max} - V_{Min}) \tag{5}$$

The average balancing current (I_{avg}) delivered to the weak cell can be derived by multiplying the charge per cycle by the switching frequency:

$$I_{avg} = C \cdot (V_{Max} - V_{Min}) \cdot f_{sw} \tag{6}$$

Similar to the passive method, this can be modelled using an equivalent resistance (R_{eq}) representing the impedance of the switched capacitor network:

$$R_{eq} = \frac{1}{f_{sw} \cdot C} \tag{7}$$

Thus, the effective balancing current is:

$$I_{avg} = \frac{(V_{Max} - V_{Min})}{R_{eq}} \tag{8}$$

2.4. Comparative Analysis of Speed and Efficiency

The performance of the Switched Resistor and Single Switched Capacitor topologies is evaluated based on three primary metrics: Efficiency, Speed, and Convergence Behavior.

2.4.1. Efficiency Comparison

Switched Resistor: Possesses 0% energy efficiency regarding the equalized charge. It is a subtractive topology that wastes 100% of the differential energy as heat (P_{diss}), creating significant thermal management challenges. [34]

Single Switched Capacitor: Offers high energy efficiency (typically 85-95%). Energy is conserved and redistributed. Losses are limited to the internal Equivalent Series Resistance (ESR) of the capacitor and the conduction losses of the switches [27], [29].

2.4.2. Speed and Convergence Comparison

Resistive Balancing: Resistive balancing typically offers superior balancing speeds compared to switched-capacitor methods. The balancing current and thus the speed is primarily constrained by the thermal dissipation limits of the system. According to ($I \approx \frac{V_{cell}}{R_{bal}}$), the current remains relatively constant because V_{cell} only varies within a narrow operating range (e.g., 3.0V to 4.2V). This provides a predictable balancing rate that does not diminish as the cells get closer to equilibrium [32].

Single Switched Capacitor: The balancing speed is highly dynamic. As shown in Eq. (2.8), the balancing current is linearly proportional to the voltage difference ($I \propto \Delta V$).

Initial Phase: When imbalance is high ($large\ \Delta V$), the SSC method is fast and efficient.

Final Phase: As the cells become balanced ($\Delta V \to 0$), the balancing current drops asymptotically toward zero [34].

2.5. Conclusion: The Trade-off Dilemma

A critical comparison of Equations (2) and (8) reveals the fundamental limitation that motivates the research presented in Chapter 3. The Switched Resistor topology offers a fixed, deterministic balancing speed but suffers from excessive thermal waste. Conversely, the Single Switched Capacitor topology offers superior energy efficiency but is constrained by a severe "tailing effect" in its speed profile. As the voltage difference (ΔV) between the strongest and weakest cells decreases during the final stages of equalization, the effective balancing current in the SSC method approaches zero ($I_{avg} \to 0$), causing the equalization time to stretch asymptotically. This creates a dilemma: the passive method is too wasteful for handling large imbalances, while the active SSC method is too slow for precise, final convergence. This specific operational gap highlights the necessity for a Hybrid Topology that can synergize the high-efficiency bulk transfer capability of the SSC with the rapid, forced convergence of the resistor.

III. PROPOSED HYBRID CELL BALANCING TOPOLOGY AND PERFORMANCE ANALYSIS

3.1. Introduction

To address inherent trade-offs between speed and efficiency, this study proposes a novel **Hybrid Cell Balancing Technique** that synergizes the beneficial characteristics of both active and passive architectures. Specifically, the proposed topology integrates a Single Switched Capacitor (SSC) mechanism with a Switched Resistor (SR) network. This hybridization creates a "coarse-fine" tuning capability: the active switched capacitor stage rapidly handles bulk energy transfer during high imbalances, while the passive resistor stage executes precision equalization during the final settling phases. By leveraging the strengths of each method in their optimal operating regions, the proposed system achieves higher energy efficiency than standalone passive balancing and faster convergence speeds than standalone capacitive balancing.

3.2. Circuit Architecture and System Design

The schematic of the proposed hybrid circuit is presented in Fig. 4. The topology is designed around a modular cell structure comprising four series-connected cells (Cell-1 to Cell-4). The balancing network consists of two distinct subsystems sharing a common control interface:

The Active Subsystem: This utilizes a central energy storage element, capacitor C1, connected via a network of main switches (S1 through S5) and a pair of Single-Pole Double-Throw (SPDT) switches. This configuration allows C1 to shuttle charge between any two selected cells in the pack, regardless of their physical proximity. The SPDT arrangement significantly reduces the switch count compared to conventional cell-to-cell active topologies, reducing conduction losses and control complexity.

The Passive Subsystem: Parallel to each cell is a dissipative branch consisting of a bleed resistor and a dedicated control switch (SR1 through SR4). This layer provides independent, simultaneous discharging capabilities for individual cells.

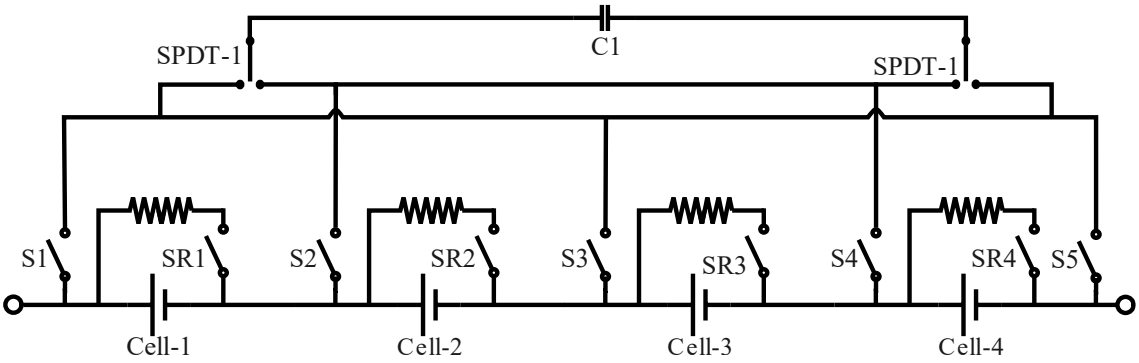

Fig. 4 Hybrid Cell Balancing Topology

3.3. Control Strategy and Operation

The operation of the hybrid topology is governed by the control algorithm illustrated in Fig. 6. The logic prioritizes operational speed and efficiency based on the instantaneous SOC spread ($\Delta\, SOC$) of the pack.

The process initiates with the measurement of SOC for all cells. The controller identifies the cells with the maximum (SOC_{Max}) and minimum (SOC_{Min}) charge levels. The equalization strategy is then determined by a predefined threshold hysteresis:

Phase I: Active Balancing (High Imbalance): If the difference between SOC_{Max} and SOC_{Min} exceeds the primary threshold value, the system engages the active capacitive mode. The SPDT switches and select main switches (S_x) connect the capacitor C1 in parallel with the highest energy cell to charge C1, and subsequently disconnect it to discharge into the lowest energy cell. This phase exploits the high voltage differential to drive significant current, achieving rapid "coarse" balancing without energy waste.

Phase II: Passive Balancing (Low Imbalance): As the cells converge and the $\Delta\, SOC$ drops below the threshold, the effectiveness of capacitive transfer diminishes due to the reduced voltage gradient. At this inflection point, the algorithm transitions to the resistive mode. Whenever a cell's SOC is higher than the minimum SOC, its corresponding switch SRx is closed, dissipating small amounts of excess energy through the resistors. This "fine" tuning phase eliminates the switching losses associated with the capacitor circuit and ensures precise voltage matching.

By strategically switching between these modes, the proposed hybrid method overcomes the "tailing" phenomenon often seen in capacitive balancing, where balancing slows down asymptotically, and

minimizes the thermal footprint associated with resistive balancing.

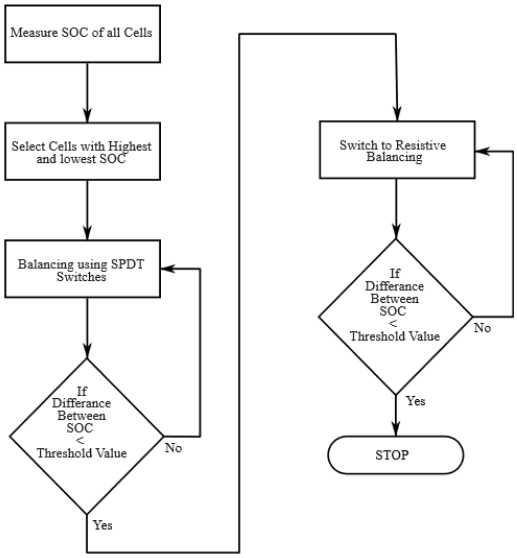

Fig. 6: Control algorithm of Hybrid Cell Balancing

3.4. Governing Equations of the Proposed Topology

The mathematical modelling of the proposed hybrid system is divided into two operational modes based on the state-of-charge difference ($\Delta\, SOC$) relative to the predefined threshold (ϵ).

3.4.1. Mode I: Active Capacitive Balancing ($\Delta\, SOC \geq \epsilon$)

In this high-imbalance phase, the energy transfer is governed by the switched capacitor dynamics. Let C_{bal} be the balancing capacitor and f_{sw} be the switching frequency. When the capacitor connects to the source cell (Cell i) with voltage V_i, and subsequently to the target cell (Cell j) with voltage V_j, the average balancing current I_{active} flowing from the source to the target is given by:

$$I_{active} = C_{bal} \cdot f_{sw} \cdot (V_i - V_j) \cdot \eta_{sys} \qquad (9)$$

Where η_{sys} represents the combined efficiency factor of the switch array and capacitor ESR.

The rate of change of SOC for the source cell (SOC_i) and target cell (SOC_j) during this interval is described by:

$$\frac{d(SOC_i)}{dt} = \frac{-I_{active}}{Q_{nom}} \qquad (10)$$

$$\frac{d(SOC_j)}{dt} = +\frac{I_{active}}{Q_{nom}} \qquad (11)$$

Where Q_{nom} is the nominal capacity of the battery cell in Ampere-seconds (As). This equation highlights that the balancing speed in Mode I is proportional to the voltage differential ($V_i - V_j$).

3.4.2. Mode II: Passive Resistive Balancing ($\Delta\, SOC < \epsilon$)

When the system transitions to the precision tuning phase, the active switching stops, and the bleed resistors are engaged. For any cell k where $SOC_k > SOC_{Min}$, the discharge current $I_{passive}$ flowing through the bleed resistor R_{bleed} is governed by Ohm's law:

$$I_{passive}, k = \frac{V_k}{(R_{bleed} + R_{on})} \qquad (12)$$

Where R_{on} is the on-state resistance of the MOSFET switch SR_k. Since $R_{on} \ll R_{bleed}$, the power dissipated (P_{diss}) as heat for that specific cell is:

$$P_{diss}, k \approx \frac{(V_k)^2}{R_{bleed}} \qquad (13)$$

The instantaneous rate of SOC reduction for the cell undergoing passive balancing is:

$$\frac{d(SOC_k)}{dt} = -\frac{V_k}{(R_{bleed} \cdot Q_{nom})} \qquad (14)$$

Unlike Mode I, this rate is independent of the neighbor cell voltages, ensuring a constant and deterministic convergence toward SOC_{Min}.

3.5. MATLAB Simulation Framework

To rigorously evaluate the performance characteristics and feasibility of the proposed hybrid balancing topology, a comprehensive discrete time-domain simulation was developed within the MATLAB environment. The primary objective of this simulation was to model the dynamic behavior of a lithium-ion battery string under hybrid equalization control and to quantify the efficiency gains of the hybrid architecture against traditional standalone balancing methods.

3.5.1. System Configuration and Initialization

The modelled battery pack consists of four lithium-ion cells connected in series (4S configuration). Each cell is assigned a nominal capacity of 2.5 Ah, representative of standard 18650 cylindrical cells used in automotive and industrial applications. To replicate a "worst-case" scenario of cell imbalance often caused by capacity fading, thermal gradients, or manufacturing inconsistencies over long-term cycling the simulation initializes the cells with a severe State of Charge (SOC) distribution. The initial SOC values were set to 90%, 80%, 70%, and 60%, respectively. This creates a maximum SOC deviation ($\Delta\, SOC_{Max}$) of 30% across the string, providing a robust testbed to analyse the system's convergence

speed and thermal performance under heavy equalization loads.

3.5.2. Hybrid Logic Implementation

The core of the simulation is a dual-mode control algorithm that dynamically switches between active and passive equalization topologies based on the real-time imbalance magnitude. A hysteresis switching threshold was established at $\Delta SOC = 5\%$ to optimize the trade-off between energy efficiency and balancing precision.

Active Equalization Phase ($\Delta SOC \geq 5\%$): During the initial phase, the system operates in "Active Mode" utilizing a Single Switched Capacitor topology. The simulation models a flying capacitor ($C_{fly} = 1\ mF$) switching at a frequency of $f_{sw} = 1\ kHz$. This process is modelled mathematically to conserve energy (neglecting switching losses for the ideal model), thereby reducing the bulk SOC disparity.

Passive Equalization Phase ($\Delta SOC < 5\%$): Once the imbalance falls below the 5% threshold, the controller transitions to "Passive Mode." In this phase, the system activates a switched resistor network with a balancing resistance of $R_{bal} = 3.3\ \Omega$. The logic identifies any cell voltage exceeding the minimum cell voltage and dissipates the residual excess energy as heat.

3.5.3. Simulation Execution

The simulation operates on a fixed time step ($dt = 1/f_{sw}$), iteratively updating the SOC of each cell using the Coulomb counting method. The simulation loop continues until the maximum SOC deviation across the entire string falls below a strict convergence target of 0.1%, ensuring the pack is perfectly balanced.

3.6. Results and Discussion

The efficacy of the proposed Hybrid Cell Balancing topology was evaluated against conventional standalone architectures through a rigorous analysis of transient State of Charge behavior, convergence speed, and energy efficiency.

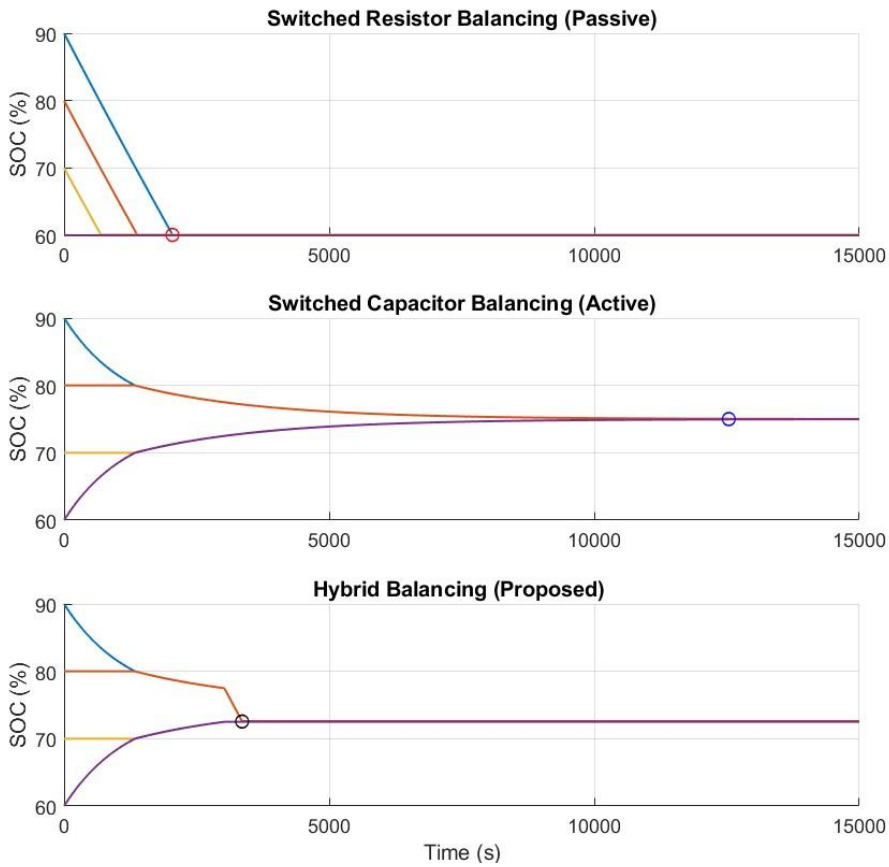

Fig. 7 Waveforms for cell balancing techniques

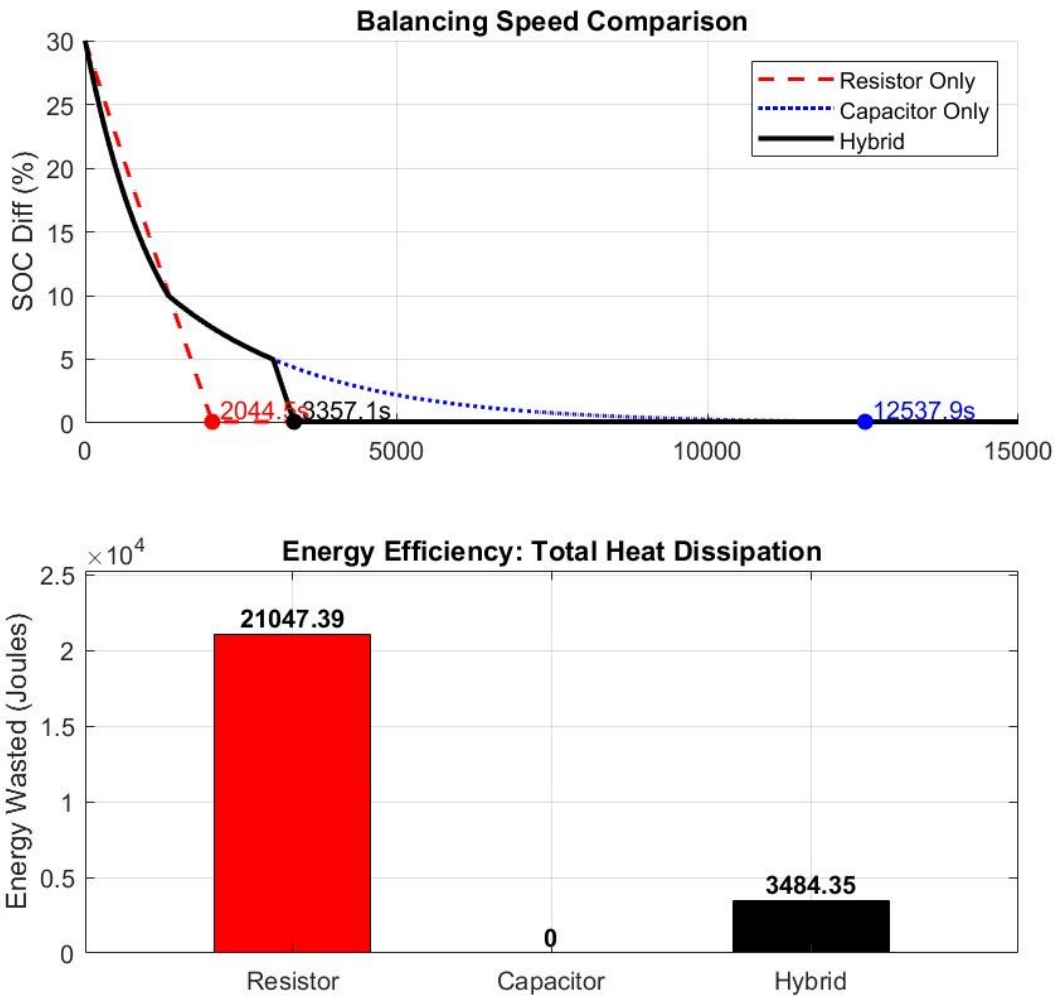

Fig. 9 Efficiency and Speed comparison of all cell balancing techniques

3.6.1. Transient SOC Behavior and Trajectory Analysis

The equalization trajectories for the three methodologies under an identical initial imbalance of 30% are presented in the simulation waveforms as show in Fig. 8.

Passive Balancing: The standalone passive method demonstrates a purely subtractive approach. The system achieves equilibrium solely by discharging the higher-energy cells to match the SOC of the weakest cell (i.e. 60%). This results in the highest capacity loss, effectively discarding useful energy from the healthier cells.

Active Balancing: The active method utilizing a single switched capacitor topology successfully redistributes energy, allowing the pack to converge toward an average SOC of approximately 75%. However, the waveform reveals a critical limitation: the rate of convergence decays exponentially over time. As the voltage difference (Δ V) between cells diminishes, the driving potential for charge transfer weakens, resulting in a "long tail" phenomenon where the system struggles to eliminate the final few percentage points of imbalance.

Hybrid Balancing: The proposed Hybrid method exhibits a distinct dual-slope trajectory. During the initial phase, the active circuit rapidly reduces the imbalance from 30% down to the 5% switching threshold. At this transition point, visible as a distinct "knee" in the waveform the control logic engages the resistive network. This change in topology forces a linear and rapid convergence for the final settling phase, avoiding the asymptotic delay associated with the capacitor method while maintaining a high final SOC of approximately 72.5%.

3.6.2. Quantitative Speed and Efficiency Evaluation

The performance trade-offs are further quantified in the comparative analysis charts.

Balancing Speed: The standalone Capacitor method required 12,537.9 s to achieve the 0.1% convergence target. This prolonged duration is a direct consequence of the diminishing current transfer capability at low SOC differentials. As shown in Fig. 8, the Hybrid method, by leveraging the resistor to "force" the final equalization, completed the process in 3,357.1 s. This corresponds to a substantial 73.2% reduction in balancing time compared to the purely active approach, proving that the hybrid architecture effectively resolves the "slow finishing" characteristic of capacitor-based circuits.

Energy Efficiency: From an efficiency perspective, the standalone Resistor method dissipated a massive 21,047.39 J of energy as waste heat. This thermal load presents significant challenges for Battery Management System (BMS) design. Conversely, the Hybrid method dissipated only 3,484.35 J. By restricting the resistive bleeding to only the final fine-tuning phase (after the bulk 25% gap was bridged without losses), the proposed topology achieved an 83.4% improvement in energy efficiency.

3.7. Conclusion

These results confirm that the hybrid technique effectively optimizes the operational envelope, delivering the speed required for dynamic applications without the excessive thermal penalties of passive balancing.

IV. CONCLUSION

This paper presented a novel hybrid cell balancing topology that combines a single switched capacitor (SSC) based active balancing stage with a switched resistor (SR) based passive balancing stage to address the fundamental trade-off between balancing speed and energy efficiency in series-connected lithium-ion battery packs. Conventional passive balancing methods, while simple and fast, suffer from excessive energy dissipation and thermal stress, whereas active capacitive methods, although energy efficient, exhibit slow convergence during the final stages of equalization due to the diminishing voltage differential between cells.

The proposed hybrid architecture exploits the strengths of both approaches through a dual-mode control strategy. In the presence of large SOC imbalance, the system operates in active mode, enabling rapid and efficient bulk energy transfer between the strongest and weakest cells. As the imbalance reduces below a predefined threshold, the system transitions to passive mode, where resistive bleeding ensures deterministic and fast final convergence, effectively eliminating the “tailing” effect inherent to capacitive balancing methods.

A comprehensive MATLAB simulation of a four-cell lithium-ion battery pack with an initial SOC spread of 30% was carried out to validate the proposed concept. The results demonstrate that the hybrid method achieves a 73.2% reduction in balancing time compared to standalone switched capacitor balancing, while simultaneously reducing energy dissipation by 83.4% compared to purely resistive balancing. Moreover, the hybrid approach maintains a higher final pack SOC than the passive method, confirming its superior energy utilization.

These findings confirm that the proposed hybrid balancing technique successfully optimizes the operational envelope of cell equalization by delivering both high speed and high efficiency. The simplicity of the architecture, combined with its significant performance gains, makes it a strong candidate for practical implementation in advanced Battery Management Systems for electric vehicles and other high-energy battery storage applications. Future work will focus on hardware implementation, experimental validation, and optimization of the control thresholds under real-world operating conditions.

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