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RESEARCH ARTICLE

Electrical and Electronic Engineering

Advanced cell balancing strategies for scalable lithium-ion battery management in electric vehicles

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Abstract: The growing demand for efficient and reliable energy storage in electric vehicles has led to significant advancements in battery management systems (BMS), particularly in cell balancing. While existing research has primarily focused on balancing techniques using a small number of cells (typically 2 to 4), or lead-acid batteries, and employed algorithms like Kalman filters and state of charge (SoC)-based estimations for passive resistor-based or simple inductor/capacitor-based balancing, these approaches often face limitations in energy efficiency and scalability. In contrast, this study presents a comprehensive analysis of 13 lithium-ion cells using both passive and active balancing, as well as an advanced active staggered cell balancing strategy. The proposed system re-allocates the charge more efficiently among cells, minimizing thermal loss and improving overall energy utilization. Using MATLAB®/Simulink® simulations, we evaluate and compare the simultaneous start and staggered start methods under various load conditions. Results show that active balancing methods can reduce energy loss from 15–25 W (typical in passive systems) to 3–7 W and decrease balancing time from 120–180 minutes to 45–80 minutes. Notably, the staggered start method delivers superior thermal management and extended battery life, confirming its suitability for high-performance and scalable BMS in electric vehicles.

Keywords: Fast charging battery management systems, hybrid cell balancing techniques, electric vehicles, lithium-ion batteries, next-generation electric vehicles, energy efficiency.

INTRODUCTION

Efficient battery management is significant for keeping electric vehicle (EV) batteries safe, reliable, and long-lasting. Batteries are the core of EVs, storing energy to run the vehicle's motor and other systems (Chavan et al., 2024). The lithium-ion cells are connected to form the battery pack, but how well the pack performs affects key factors such as how far the car can go, how long it takes to charge, and how long the vehicle will last (Fichtner, 2022). These cells can have voltage, capacity, and resistance differences because of how they are made, how old they are, and how they are used. A big challenge is to ensure each cell in a battery pack has the same charge level (Zhang et al., 2023). If the cells are not balanced, some might get overcharged or undercharged, reduce the battery's life, or even make it unsafe. Overcharging speeds up aging and can lead to overheating, while undercharging reduces how much energy the battery can store and use (Khan et al., 2024). To address these challenges, cell balancing methods are employed to equalize the voltages or state-of-charge (SOC) of cells within a pack, ensuring optimal performance and safety (Sharma et al., 2024).

Traditional passive cell balancing methods dissipate excess energy from high-voltage cells as heat using resistors. Although passive balancing is simple and worthwhile, they are naturally inefficient due to power dissipation and slow response times (Ali et al., 2024). On the contrary, active cell balancing methods dynamically transfer charge between cells. This process distributes energy from the high-voltage cell to the low-voltage cell. This saves energy and achieves balance more quickly (Sugumaran & Prabha, 2022). Active balancing is

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especially useful for applications that require high energy efficiency and fast response for EVs (Thiruvonasundari & Deepa, 2023). Lithium-ion batteries are needed for EVs, due to the density of stored energy, long service life, and low loss rates. However, the chemicals of lithium-ion cells make them too sensitive to charging and depth (Rahman & Alharbi, 2024). Therefore, a strong battery management system (BMS) must check and control its work. They can balance the longevity of consumer concerns during the construction of infrastructure. The cost of charging the battery is important in the development of the latest technological progress, such as a DC-DC converter in two directions, the prediction and learning of the machine have given new opportunities for balanced system innovation (Wongdet et al., 2023). But the cells are enabled, inspecting, and controlling the dynamic conditions to be appropriate and confident that the best performance utilization is achieved from the software, MATLAB®/Simulink® (Farooq et al., 2024).

This study is positioned within ongoing efforts to improve scalable and energy-efficient battery management systems for EVs. While recent literature has explored passive dissipation-based techniques, converter-based active balancing, and algorithmic estimation strategies, many investigations remain limited to small cell configurations or focus primarily on hardware topology optimization. The present work extends these studies by evaluating balancing performance in a 13-cell lithium-ion configuration representative of practical EV battery modules. Furthermore, it introduces a staggered-start active balancing strategy that complements existing simultaneous transfer approaches by improving thermal behaviour, reducing switching stress, and enhancing energy utilization. By providing a unified comparative simulation framework and quantitative benchmarking, this work contributes system-level insights that support scalable BMS design.

A comparative analysis of active and passive cell balancing techniques was conducted by Rout & Samal (2024) using a two-cell lithium-ion battery pack for maintaining the battery performance and prolonging battery life in electric vehicles. A novel approach for active cell balancing was proposed by Sharma et al. (2024), utilizing the Kalman filter algorithm to estimate the state of each battery cell and determine the optimal charging and discharging currents, thereby improving the efficiency of BMS, and extending the battery lifespan. The bidirectional active balancing solution was developed by Qi (2024) for the transit of power bidirectionally between the vehicle's 12V bus and the high-voltage bus for the addition and removal of charges to any cell in the energy storage system. This also acts as a charger for the 12V lead acid battery. A single inductor-based active cell balancing topology was explored by Kaushik et al. (2024) for a series of connected four-cell batteries to address the state of charge imbalance among the cells. It employed a min-max state of charge (SoC) control algorithm to balance the cells effectively during static, charging, and discharging modes. The novel two-layer multi-inductor and single-layer multi-inductor active cell balancing was developed by Venkatasatish & Dhanamjayulu (2024) with a SoC controller for 52V battery systems, and tested with the OPAL-RT 5700 simulator for effectiveness. This paper studied the implementation and simulation of an active balancing technique in a 13-cell lithium-ion battery pack, a configuration commonly used in EVs, by comparing three common methods: passive balancing, staggered active balancing (upon initiation), and active balancing (simultaneous start). Studying the principles, efficiency, and practical meaning provides a comprehensive understanding. The goal is to identify an efficient and scalable balancing solution. This is in line with the increasing demand for sustainable and high-performance EV technology. This study developed a simulation model to assess the effectiveness of different balancing techniques, providing valuable in-depth information for researchers and engineers in EVs.

From the reviewed literature, it is evident that prior studies predominantly investigate topology-level innovations or estimation-based control applied to limited cell counts. However, fewer works examine scalability-oriented comparative strategy evaluation under unified simulation environments representative of EV battery modules. Addressing this gap, the present study complements existing research by integrating passive and two active balancing strategies within a single modeling platform and extending analysis to a larger cell configuration. This enables direct benchmarking of efficiency, thermal impact, and balancing duration, thereby advancing understanding of practical deployment trade-offs in scalable BMS architectures.

MATERIALS AND METHODS

The proposed method analyzes the simulated operations of a 13-cell lithium-ion battery pack using passive, active simultaneous start, and active staggered start configurations. The study explores different methods for achieving balanced voltage distribution and deals with real-life situations in battery cells regarding response time, ease of use, and operational efficiency. Table 1 indicates the notations used in the proposed system.

Figure 1: Flowchart of the proposed system

Table 1: Notations of the proposed system

Symbol	Description	Unit
P_{loss}	Power loss due to passive balancing	W
$V_{Cell, max}$	Maximum Cell Voltage	V
$V_{Cell, min}$	Minimum Cell Voltage	V
R_{bal}	Balancing Resistor	Ω
$E_{transferred}$	Energy transferred during balancing	J
C_{bal}	Capacitance	F
I_{ind}	Inductor Current	A
L	Inductance for energy transfer	H
t	Time step for charge transfer	s

The flowchart in Figure 1 shows the battery cell balancing strategy selection between passive balancing and active simultaneous balancing, followed by active staggered balancing.

- The method starts by creating an initial phase, includes measuring cell voltage levels and setting voltage balance limits.
- The balancing method selection occurs by considering voltage discrepancies together with available power outputs.
- The procedure of passive balancing allows energy dissipation into resistors, yet it creates power wastage.
- Active simultaneous balancing requires a large amount of power for its operation because it distributes energy to all cells at the same time.
- Active staggered balancing controls the delay timing of energy flow operations to enhance the distribution of energy while minimizing power spikes.
- All cells require equalization through the balancing process before carrying out performance evaluations.
- Step four examines and declares the best balancing method by measuring efficiency results, temperature regulation, and time requirements.

The structured method enables researchers to select the battery balancing method with maximum efficiency, thermal performance, and energy utilization benefits.

Simulation setup

The simulation setup using MATLAB®/Simulink® software for the cell balancing method of 13 lithium-ion cells in Figure 2 shows the Simulink model of the proposed balancing system, in that all three balancing methods have been incorporated using balancing logic. Table 2 provides the simulation parameters used in the proposed system.

Once the simulation has been started with switches, the balancing happens in three levels and the balancing methods are explained as follows. The balancing techniques consist of some equations and their notations are given in Table 3.

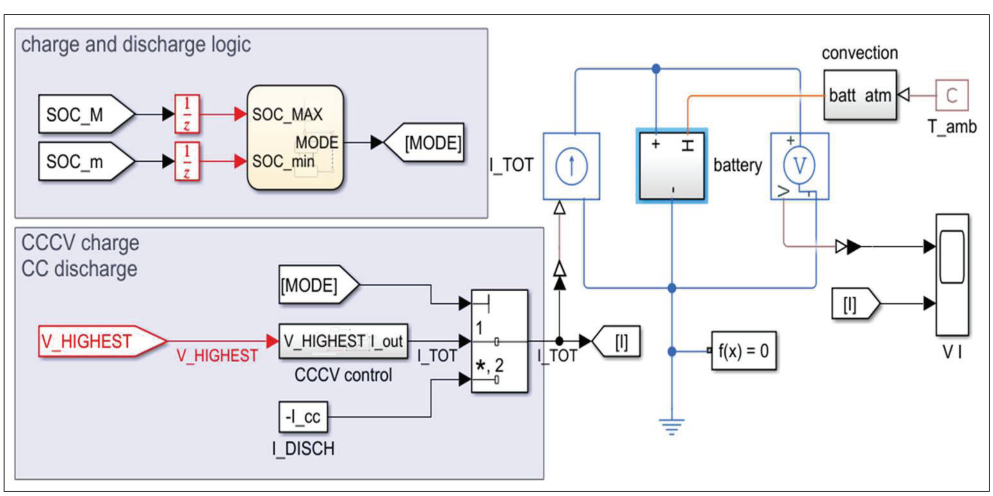

Figure 2: Simulation model of the Lithium-ion battery cell

Table 2: Simulation components and description

Serial No.	Components	Description
1.	Battery	Represents the lithium-ion battery with a nominal voltage of 3.7V per cell.
2.	Load Resistor	Simulates the battery discharge process by providing a resistive load.
3.	Passive Balancing Resistors	Used for passive balancing, ensuring equal charge distribution among cells.
4.	DC-DC Converter	Implements active balancing by transferring energy between cells to maintain voltage balance.
5.	Voltage Measurement Sensor	Measures the voltage across different battery cells for monitoring and control.
6.	Current Sensor	Measures the current flow in the system to analyze energy distribution.
7.	Scope	Displays real-time voltage and current waveforms for system performance analysis.
8.	Simulink-PS Converter	Converts Simulink signals to physical signals for interaction with Simscape blocks.
9.	PS-Simulink Converter	Converts physical signals from Simscape back into Simulink signals for data analysis.
10.	Display	To display the values during the simulation.

Table 3: Notations of the proposed system

Serial No.	Notation	Description
1.	I_{bal}	Balancing Current
2.	$V_{cell,\max}$	Highest voltage cell
3.	$V_{cell,\min}$	Lowest voltage cell
4.	R_{bal}	Balancing Resistor Value
5.	P	Power dissipated in the resistor
6.	I	Current Value
7.	R	Resistance value
8.	P_{loss}	Power loss during balancing
9.	E_{loss}	Energy loss during balancing
10.	Δt	Time interval
11.	Q_{bal}	Total charge transferred during balancing
12.	t_{bal}	Balancing time
13.	C_{cell}	Cells Capacitance
14.	E	Energy stored in the cell
15.	V	Cell voltage
16.	$E_{\max}$	Total energy stored in the highest voltage cell before balancing
17.	$E_{\min}$	Total energy stored in the lowest voltage cell before balancing

Passive balancing

Passive balancing as in Figure 3 is performed by resistors through the process of energy surplus dissipation. The passive cell balancing circuit discharges energy from higher-voltage cells to resistors for distributing charge evenly across the battery pack. A control system utilizes voltage sensors to collect continuous data about every cellular level. The control system identifies high-voltage cells after which the control method activates specific switches that enable the cells to connect to resistors so excess energy can turn into heat. This basic approach succeeds through simplicity and low cost, yet produces inefficient operation because energy conversion into heat uses power, resulting in poor performance in high-power situations. Unfortunately, passive balancing has its constraints, but it functions to stop battery overcharging and increases the life span by keeping all cells at uniform voltage levels.

To calculate the power loss during passive balancing, the fundamental things related to power loss are current flow, energy dissipation, and power transfer in the resistors. When a switch is closed for passive balancing, the excess charge flows through the balancing resistor R_{bal}. The following equations are used to derive the power loss. Ohm's law is used for balancing circuits and is represented in equation (1) because if a switch is closed for passive balancing, the excess charge flows through the balancing resistor $R_{bal.}$

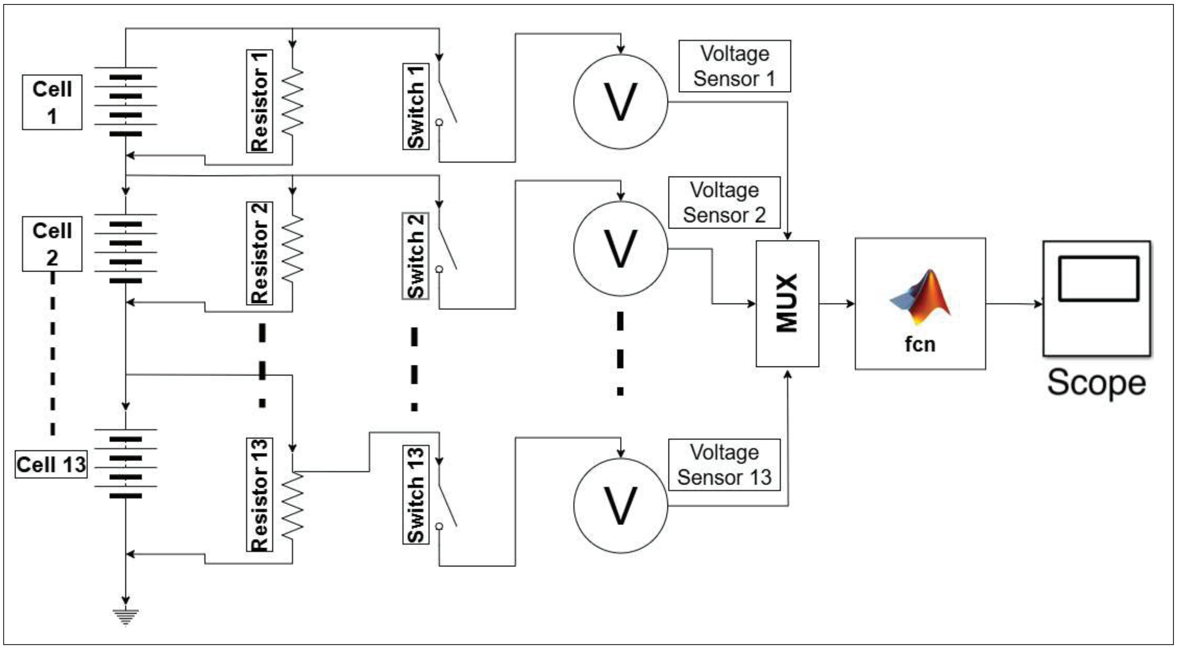

Figure 3: Proposed simulation circuit for passive balancing

$$I_{bal} = \frac{V_{cell,\max} - V_{cell,\min}}{R_{bal}} \quad ...(01)$$

The next step is to derive the power dissipation in the resistor through equation (2)

$$P = I^2 R \quad ...(02)$$

By substituting I_{bal} from equation (1), we get equation (3)

$$P_{loss} = \frac{\left(V_{cell,\max} - V_{cell,\min}\right)^2}{R_{bal}} \quad ...(03)$$

The energy dissipation over time due to balancing is given by equation (4)

$$E_{loss} = \int P_{loss} dt \quad ...(04)$$

By assuming a constant power loss over a small-time interval Δt in equation (5), and it is shown that the energy wasted as heat is directly proportional to time

$$E_{loss} = \frac{\left(V_{cell,\max} - V_{cell,\min}\right)^2}{R_{bal}} .\Delta t \quad ...(05)$$

The steps to find out the total charge transferred during balancing are derived by following equation (6) and (7). The charge Q_{bal} removed from a higher voltage cell during balancing is expressed as:

$$Q_{bal} = I_{bal} .\Delta t \quad ...(06)$$

By substituting I_{bal}:

$$Q_{bal} = \frac{V_{cell,\max} - V_{cell,\min}}{R_{bal}} .\Delta t \quad ...(07)$$

This indicates that the charge transfer depends on the voltage difference, resistor value, and balancing time.

Since balancing follows an exponential discharge behaviour, the time required to equalize the voltages can be approximated using the equation (8)

$$t_{bal} \approx R_{bal} C_{cell} \ln\left(\frac{V_{cell,\max}}{V_{cell,\min}}\right) \quad ...(08)$$

The technique of passive balancing releases higher-voltage cell energy as heat through resistors. It is a simple implementation at a reasonable cost, but major energy loss and slow balancing rates are important disadvantages. The time it takes for balancing depends on both the chosen resistor value and the cell capacitance, which determines overall efficiency. The technique functions for minor cell imbalances, although it proves unfit for commercial applications because of its excessive power usage and thermal defects. The basic hardware limitations restrict this method because the dissipated heat energy goes to waste instead of supplying cells with redistributed power. This technique requires better equipment to operate effectively for battery energy management, therefore it fails to meet the requirements of fast rebalancing and long battery life in specific applications.

In the MATLAB®/Simulink® implementation, these analytical expressions are directly used to evaluate power loss during simulation. Cell voltages and balancing currents are measured through voltage and current sensor blocks, and the instantaneous power dissipation is computed using embedded mathematical function blocks based on the derived relations. The cumulative energy loss is then obtained by numerical integration over time. This approach ensures consistency between theoretical formulation and simulation-based performance evaluation, enabling direct comparison of balancing strategies under identical operating conditions.

Active balancing (simulation start)

DC-DC bidirectional converters and MOSFETs are the power electronics components of active balancing systems that can perform multiple simultaneous operations by relocating electronic charges between cells. At the very first step, each cell separately starts the balancing process with the rest of the cells at the very same moment. By targeting individual cells, the charge within the neighboring cells dynamically alters voltages. They aim to attain an equal charge in all the cells with minimal energy loss. The proposed simulation circuit for the active balancing using simultaneous start is shown in Figure 4.

The active cell balancing circuit performs an important function through its mechanism, transferring extra power from cells with higher voltage to those with lower voltage thereby maintaining a balanced distribution of energy throughout the battery pack. The controlled switching mechanism along with a DC-DC converter enables this method to efficiently transfer energy instead of heat-based dissipation found in passive balancing techniques. The battery pack maintains continuous voltage sensor input which leads the control algorithm to determine ideal balancing operations. The active balancing uses adaptable charging management capabilities to cut down power loss, decrease heat effects and extend battery life. Active cell balancing demonstrates remarkable advantages within power systems that need high operational efficiency and extended battery usage, like EVs, alongside energy storage systems.

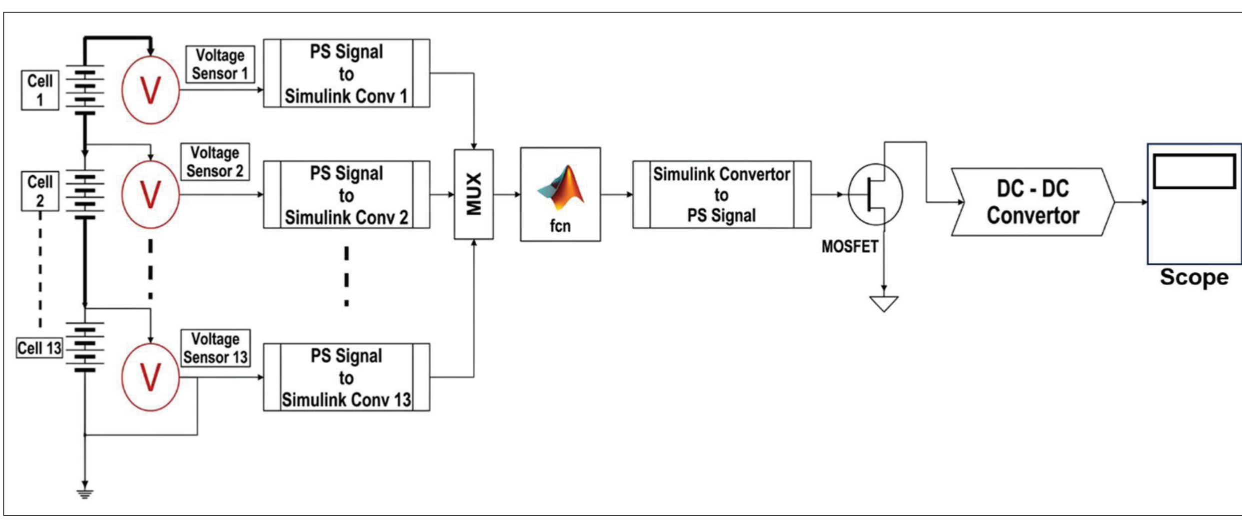

Figure 4: Proposed simulation circuit for active balancing

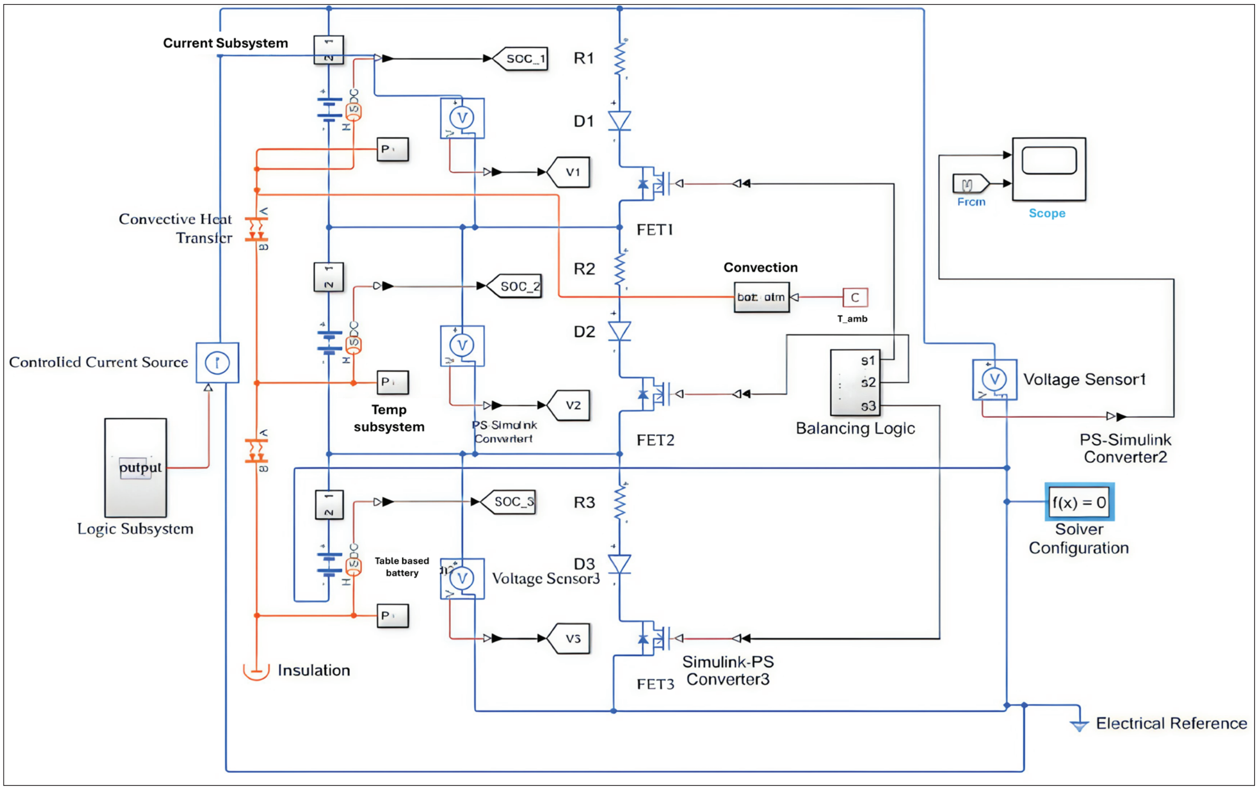

Figure 5: ACB circuit with MOSFET transistor

Figure 5 illustrates the MOSFET-based ACB sub-circuit implemented in MATLAB®/Simulink®. Each lithium-ion cell is modeled with associated sensing and switching elements enabling controlled energy redistribution. The balancing structure consists of:

- MOSFET switches (FET1–FET3):
  This act as controllable bidirectional current paths driven by the balancing logic. When activated, they enable charge transfer from higher-voltage cells toward lower-voltage cells through the balancing network.
- Balancing resistors (R1–R3):
  These components regulate current magnitude and limit transient surges during switching events, ensuring numerical stability and realistic dissipation modeling.
- Protection diodes (D1–D3):
  These are included to prevent reverse current flow and protect switching devices from voltage transients during charge redistribution.
- Voltage sensing blocks:
  Cell voltages are continuously monitored and forwarded to the balancing control logic, enabling adaptive switching decisions based on imbalance thresholds.
- Logic control subsystem:
  This implements the decision algorithm that determines MOSFET gating signals using SOC and voltage deviation metrics. This ensures selective activation of simultaneous or staggered balancing modes.
- Isolation and interfacing elements:
  Converter blocks and electrical references ensure compatibility between physical-domain signals and Simulink control signals, maintaining simulation integrity.

Overall, the circuit models realistic switching-based energy equalization where MOSFET activation dynamically redistributes charge across cells, enabling performance evaluation of balancing strategies under controlled simulation conditions.

In this method, we define each lithium-ion battery cell as a capacitor because the charge stored in a cell is proportional to its voltage. Therefore, the energy stored in a capacitor is given by equation (9):

$$E = \frac{1}{2} C_{bal} V^2 \qquad \text{...(09)}$$

If the battery pack is imbalanced, some cells have high voltage, other cells remain with a lower voltage. To transfer the excess energy from the higher voltage cell to the lower voltage cell is the important objective. The total energy stored in the highest voltage before balancing is given in equation (10)

$$E_{\max} = \frac{1}{2} C_{bal} V_{cell,\max}^2 \qquad \text{...(10)}$$

Likewise, the total energy stored in the lowest voltage cell before balancing is given in equation (11):

$$E_{\min} = \frac{1}{2} C_{bal} V_{cell,\min}^2 \qquad \text{...(11)}$$

By substituting the energy expressions, we obtain equation (12):

$$E_{transferred} = \frac{1}{2} C_{bal} (V_{cell,\max}^2 - V_{cell,\min}^2) \qquad \text{...(12)}$$

The calculated formula demonstrates that capacitance along with squared voltage differences controls the energy movement between voltage extremities. Power electronics utilized for active balancing allow efficient energy charge redistribution thus outperforming the regressive heat dissipation method of passive balancing. The continuous dissipation method in passive balancing produces large energy wastage yet active balancing accomplishes fast convergence along with maximal energy efficiency. This approach restores equal cell charging levels through its method and enhances both battery efficiency and operational life extensions. The active balancing method stands as the best solution for high-performance electric vehicles since it offers automatic speed-efficient cell rebalancing, optimizes the usable energy and ensures long-term battery system reliability.

For active balancing configurations, power loss is calculated from converter current flow and switching behaviour rather than resistive dissipation alone. Sensor outputs capturing current transfer and voltage differences are processed using equivalent energy-transfer formulations implemented within the Simulink model. These measurements allow estimation of energy redistribution efficiency and residual losses associated with switching and component resistance. Consequently, the reported loss values represent simulation-derived metrics grounded in the same analytical framework used for passive balancing.

Active balancing (staggered start)

The active balancing method employs an additional practicality with the staggered start technique consisting of the same circuit diagram as in Figure 3 but only the MATLAB® code is modified according to the staggered start. Active balancing using staggered start improves efficiency together with redistributing battery cell charges at increased speed. The method enables a step-by-step charge movement instead of simultaneous transfers thus minimizing the circuit peak load while improving thermal control capacities. A controlled switching sequence dictates the balancing process which moves energy from the most elevated cell voltage through an inductor until reaching the smallest voltage cell. The developed equation shows how cells create current flux through the inductor as a function of their differential tension and the balance integration speed. Staggered activation within this model reduces power switching losses, distributes energy evenly, and grows battery lifetime. Such a control system brings exceptional benefits to platforms combining electric vehicles with large-scale energy storage because it provides exact management and efficiency.

RESULTS AND DISCUSSION

For each technique, the voltages of all 13 cells are recorded at each time step over a simulated duration of 2 hours. The results are visualized as separate plots in Figure 6 for each technique, showing how cell voltages evolve and eventually converge to the target voltage. The x-axis represents time, while the y-axis displays cell voltages, providing a clear comparison of the dynamics and efficiency of each method.

Although the results are generated through MATLAB®/Simulink® simulation, the performance trends reflect realistic operational conditions due to hardware-representative component modeling and practical parameter selection. Metrics such as voltage convergence rate, power loss, and balancing duration correspond to observable characteristics in experimental battery pack testing. Consequently, the simulation outcomes serve as a reliable indicator of comparative strategy effectiveness. However, absolute numerical values may vary in physical deployment due to temperature effects, manufacturing variability, and electrochemical aging, which are beyond the scope of the present system-level study.

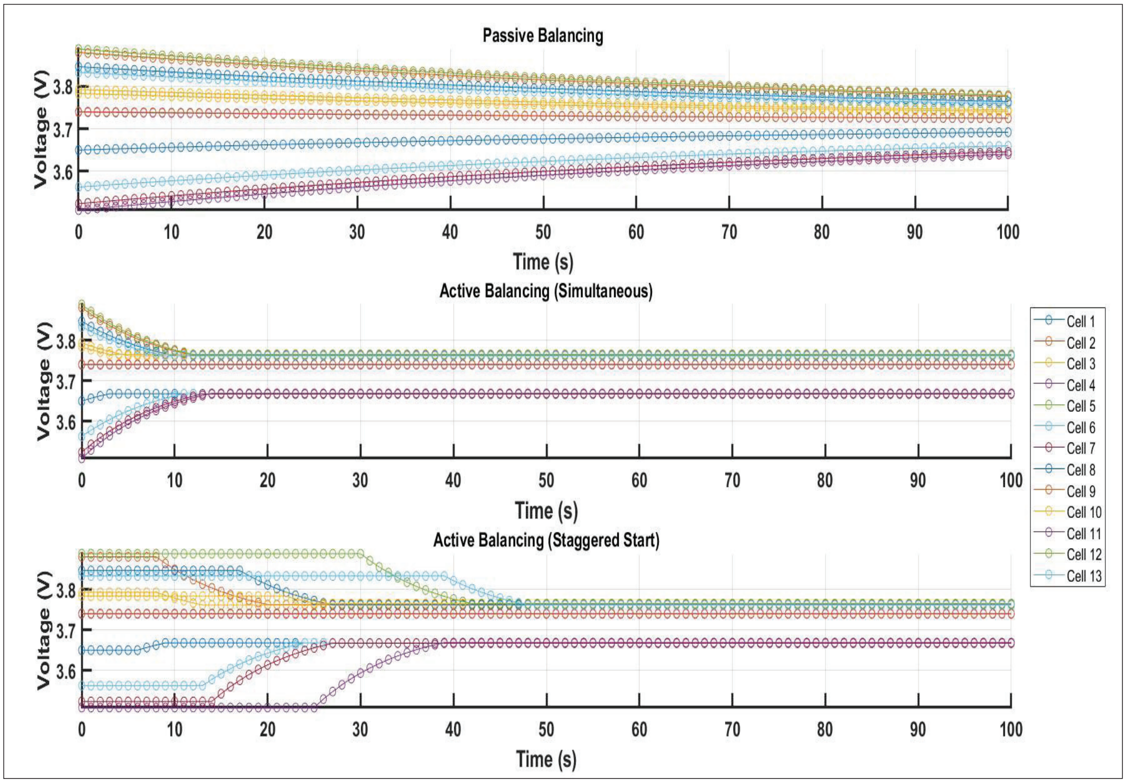

Figure 6: Simulation output of the proposed balancing techniques

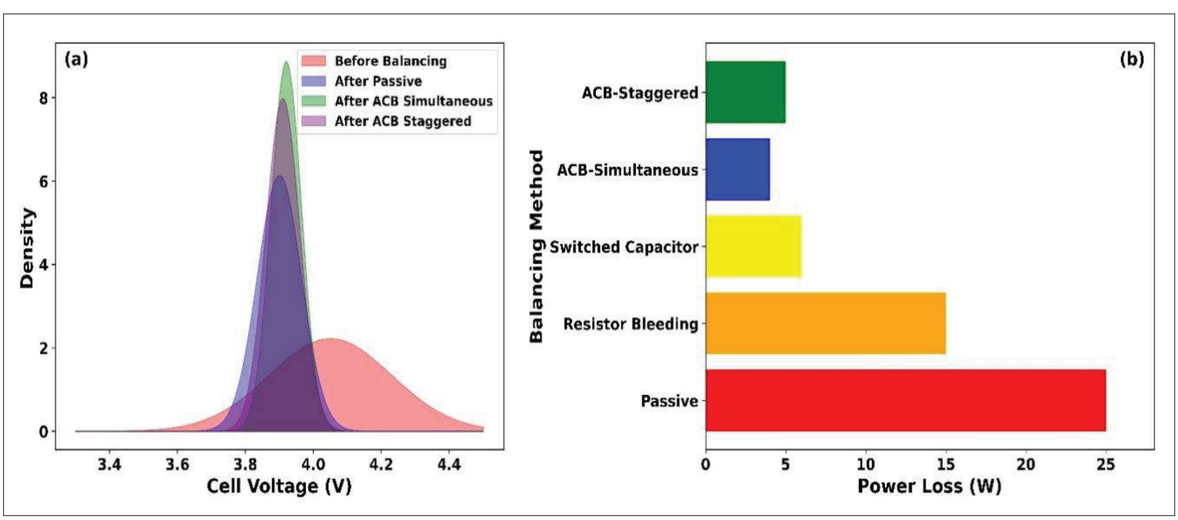

Figure 7: (a)Voltage distribution before and after balancing; (b)Power loss comparison

The analysis presents three cell balancing approaches: passive balancing and active balancing via the simultaneous method along with the staggered start method. The process of passive balancing (top graph) produces heat through resistors to dissipate excess energy from higher voltage cells, thus causing cells to become equalized at a slow and inefficient rate over time. Through a capacitor system, simultaneous active balancing (middle graph) enables direct voltage exchanges from high-voltage to low-voltage cells which results in a rapid equilibrium that stabilizes quickly. The charge transfer within staggered start active balancing (bottom graph) is distributed sequentially between cells at different intervals during the balancing operation. This approach enables better control of the balancing process to minimize energy waste, while preventing sudden current surges, resulting in enhanced voltage equalization between cells.

The red distribution in Figure 7 (a) reveals how the voltage ranges from high to low before balancing occurs because different cells possess various voltage levels. The difference in cell voltage levels destabilizes battery performance while shortening its overall operational time. Different balancing methods cause voltages to move toward proximity with each other. Passive balancing (green) works under a system where voltage differences are reduced through time yet it maintains heat dissipation as a side effect.

The active balancing method (blue) transfers energy between cells instantaneously which produces rapid and even voltage spread throughout the system. Staggered active balancing through the purple sequence provides a methodical balance process that controls the performance while maintaining consistent current flow. All balancing approaches together drive the voltages of cells toward equilibrium yet active methods provide more efficient and effective results than passive methods.

Different battery balancing techniques appear in Figure 7 (b) showing their power loss measurements. Red in the graph indicates passive balancing which results in the maximum power consumption totaling almost 25W. The production of heat through resistors results in energy waste in passive balancing since it extracts energy from higher voltage cells to balance of their voltage. The power loss for resistor bleeding (orange) stands out since this method performs energy dissipation like its counterpart. The yellow method of switched capacitor balancing performs better than passive balancing in terms of power loss because it can redirect cell charge between cells yet it does lose some energy through operation. The implementation of ACB Simultaneous (blue) decreases power waste and uses active components to move energy between cells without requiring heat dissipation (under dynamic conditions, it may slightly increase and exceed up to 6 W). The ACB Staggered approach (green) proves to be the most power-efficient method among all the

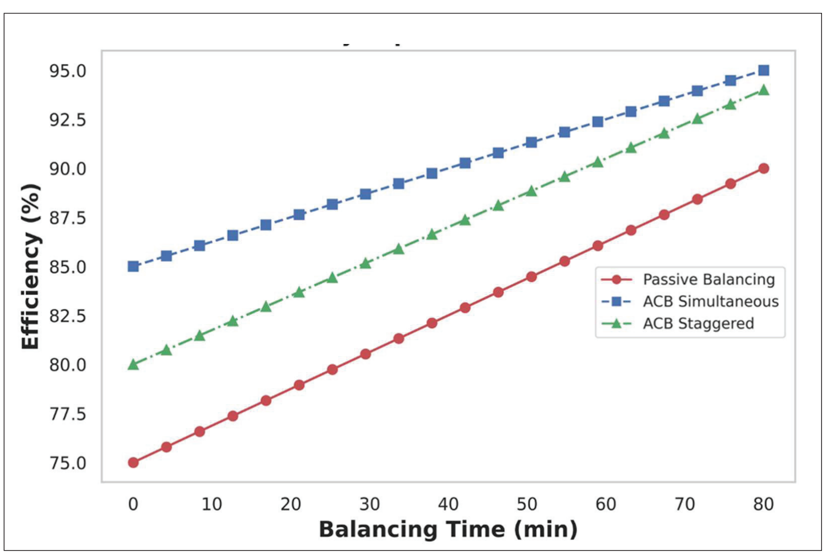

Figure 8: Efficiency improvement over time

solutions. Series connection of MOSFETs occurs in a timed sequence to stop momentary high currents and reduce the production of heat. The technique increases total energy efficiency but maintains balanced cell operations.

The power-loss values illustrated in Figure 7(b) are derived from simulation measurements processed through the analytical formulations presented in the methodology sections. Real-time voltage and current data obtained during balancing are applied to the loss equations to compute instantaneous dissipation and aggregate energy loss over the balancing period. This integration of theoretical equations with sensor-based simulation outputs ensures that reported performance metrics are not solely graphical observations but quantitatively grounded calculations.

Figure 8 shows how efficiency improves over time for different balancing methods. Initially, efficiency is lower (around 75-85%), but as balancing progresses, it gradually increases to nearly 95%. ACB Staggered achieves the highest efficiency by optimizing energy flow and minimizing unnecessary energy loss.

ACB Simultaneous balances the cells quickly but loses more energy in the process. Passive Balancing, on the other hand, improves efficiency at a much slower rate due to continuous minor energy losses. Overall, ACB Staggered provides the best balance between speed and energy efficiency, making it the most effective method over time.

Figure 9 compares the switching patterns of MOSFETs for different balancing methods. Passive balancing enables frequent switching of its switches (every 5 minutes) which results in substantial energy losses. ACB Simultaneous operates all MOSFETs as a complete group at 10-minute intervals while using increased energy.

ACB Staggered presents the most efficient configuration which applies power to MOSFETs in sequential order at 20-minute intervals to minimize power waste and extend battery life. ACB staggered delivers the optimal solution for long-lasting battery performance as well as reliability.

Here is Table 4 summarizing the design and implementation of the three balancing techniques:

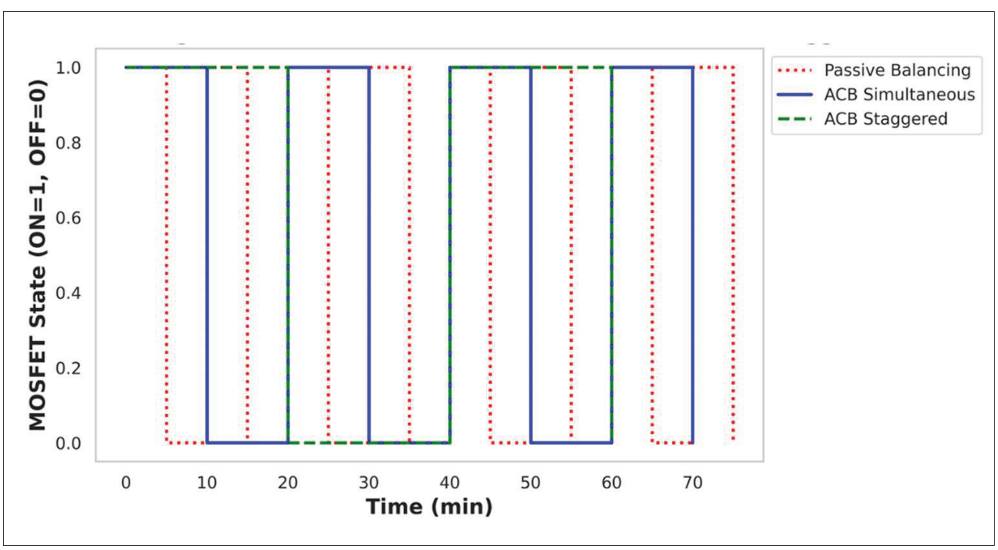

Figure 9: MOSFET switching pattern- passive vs simultaneous vs staggered

Table 4: Features of balancing techniques

Feature	Passive balancing	Active balancing (simultaneous start)	Active balancing (staggered start)
Balancing principle	Excess energy is dissipated as heat through resistors.	Charge is redistributed among cells using DC-DC converters.	Charge redistribution is like simultaneous balancing but starts at different times for each cell.
Energy efficiency	Low (energy is wasted as heat).	High (minimal energy loss).	High (like simultaneous balancing).
Balancing speed	Slow, due to energy dissipation rate.	Fast, as all cells start balancing at the same time.	Gradual, as each cell starts balancing at staggered intervals.
Control logic	Simple: proportional dissipation based on voltage.	Uses a control block to balance voltage differences actively.	Adds staggered start times to the active balancing logic.
Simulation components	- Battery blocks - Resistor blocks - Scope blocks	- Battery blocks - DC-DC converters - MATLAB® Function for logic - Scope blocks	- Battery blocks - DC-DC converters - MATLAB® Function for staggered start logic - Scope blocks
Key parameters	Resistance factor for energy dissipation.	Voltage threshold and balancing step size.	Voltage threshold, balancing step size, and staggered start times.
Expected output	Gradual convergence of voltages, with energy loss as heat.	The rapid convergence of all voltages with minimal energy loss.	Gradual convergence, with delayed balancing for specific cells.
Visualization	Voltage profiles of all cells over time.	Voltage profiles show fast convergence of all cells.	Voltage profiles show staggered convergence of cells.

Table 5: Comparison with existing systems

Balancing type	Power level (W)	Energy loss (W)	Balancing time (min)	Efficiency (%)	Complicity	Source
Switched capacitor	5	6-10	70-90	85-90	Medium	(Sun *et al.*, 2021)
Inductor capacitor	5	2-4	50-70	92-97	High	(Guo *et al.*, 2023)
Resistor bleeding	5	20-30	150-200	50-60	Very low	(Duraisamy & Deepa, 2021)
Passive balancing	5	15-25	120-180	60-70	Low	Proposed
Active balancing (Simultaneous start)	5	3-5	45-60	90-95	High	Proposed
Active balancing (Staggered start)	5	4-7	60-80	88-92	Medium	Proposed

Comparison with the existing systems

Table 5 compares different battery balancing techniques based on energy loss, balancing time, efficiency, and complexity. Passive methods, such as resistor bleeding, have high energy loss and longer balancing times but are simpler. In contrast, active balancing methods, especially inductor-capacitor and simultaneous start approaches, offer higher efficiency with lower energy loss, though they require more complex circuitry. Now, let us analyze these results in detail.

The comparative evaluation of balancing techniques using a normalized reference power level was used to ensure fair benchmarking against previously reported studies. The proposed strategies were simulated under identical electrical conditions corresponding to a representative 5 W cell-level balancing transfer capability. The resulting loss values reflect system-level dissipation that includes converter switching losses, sensing overhead, and control interactions rather than idealized transfer-only losses. Consequently, absolute magnitudes exceed theoretical converter efficiency estimates but remain consistent in relative ranking across methods.

Passive techniques exhibit substantially higher dissipation due to resistive energy dumping, whereas active simultaneous balancing achieves the lowest loss and highest efficiency. Staggered balancing shows moderate overhead attributable to sequential control coordination. This normalized evaluation framework ensures that performance improvements observed for the proposed methods arise from architectural advantages rather than differing operating scales, thereby strengthening the validity of cross-study comparison.

Observations

Figure 10 shows the comparison with the existing systems, and the key findings are:

- Efficiency is marginalized with passive balancing owing to energy dissipation.
- The performance obtained by active balancing (simultaneous start) can significantly reduce the balancing time and the internal drive voltage deviation.
- Staggered start active balancing provides a balance with moderate performance improvements.

The complexity scale illustrated in Figure 8 is intended to provide a qualitative comparison of implementation efforts across different balancing strategies. The classification is established based on three technical considerations: (i) circuit topology requirements, including the number of passive and active components, magnetic elements, and switching devices; (ii) control and sensing requirements, representing the level of monitoring, synchronization, and algorithmic coordination involved; and (iii) implementation overhead, encompassing driver circuitry, design effort, and integration challenges within a battery management system environment. Using these criteria, methods employing minimal circuitry and straightforward control logic are categorized as low complexity, whereas approaches requiring additional switching coordination or energy-transfer components are designated as moderate complexity. Techniques incorporating magnetic elements or tightly coordinated switching control are classified as high complexity. This normalized qualitative framework facilitates comparison of design trade-offs alongside efficiency and loss metrics without implying a hardware-specific cost or precise numerical measure.

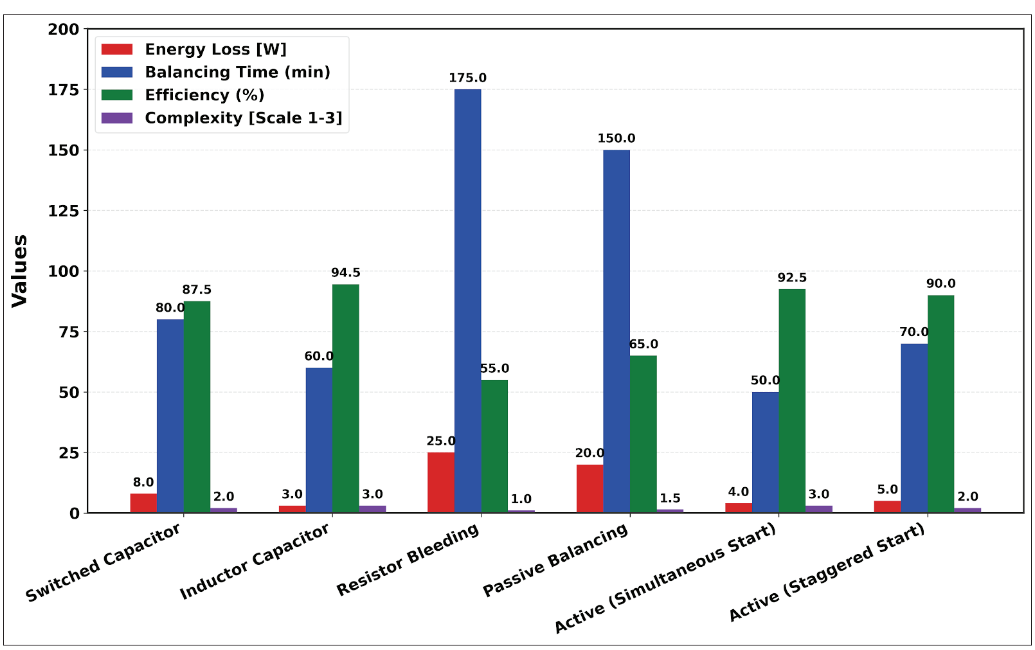

Figure 10: Comparison of the proposed system with existing methods

A three-level ordinal scale (1–3) is adopted to represent these categories, as implementation complexity is not directly quantifiable through physical measurement. Employing a limited number of levels avoids artificial numerical precision while preserving interpretability in graphical representation. The selected structure provides adequate differentiation among balancing architectures and aligns with qualitative benchmarking practices commonly used in BMS research.

From a practical EV deployment perspective, the most critical performance metric highlighted in Figure 8 is energy efficiency, represented by reduced power loss during balancing. In real-world EV battery packs, minimizing dissipative losses directly preserves usable stored energy, thereby extending driving range and reducing charging frequency. Additionally, lower energy dissipation mitigates thermal buildup, which is strongly linked to accelerated battery aging, safety risks, and cooling system burden. Although balancing time influences responsiveness and circuit complexity affects implementation cost, efficiency remains the dominant system-level priority because it simultaneously impacts operational safety, lifetime reliability, and energy utilization. The superior loss characteristics observed in the staggered active balancing strategy therefore indicate strong practical suitability for scalable EV BMS.

The possible ways to further develop the current work and improve the performance of battery management systems based on innovative methods and new technologies are:

Integration with advanced BMS: Active cell balancing has the potential to be integrated into next-generation BMS for EVs, electric bikes, and energy storage systems (ESS). With improvements in BMS algorithms, active balancing can be modified to work under real-time load and charging conditions of the system to enhance performance.

Machine learning and AI for predictive balancing: Introducing machine learning algorithms can facilitate predictive cell balancing by flagging potential imbalances before they happen. AI can use historical data to enhance the efficiency of balancing and minimize energy waste.

Compatibility with solid-state batteries: As solid-state batteries become more mainstream, methods of active cell balancing can be altered for smooth control of solid electrolytes, higher energy density, and a broader operating voltage range.

Scalability for large battery packs: Future work can be chosen to increase the scope of active balancing techniques for heterogeneous battery systems, like grid-level energy storage, where thousands of cells must be optimized.

CONCLUSIONS

The research investigates passive and active balancing technologies for EV battery packs, evaluating their advantages and disadvantages. The findings reveal that active balancing techniques, specifically the simultaneous start and staggered start methods, excel in performance by reducing energy waste, shortening balancing periods, and enhancing operational efficiency. Active battery balancing reduces energy loss to between 3 and 7 watts, with balancing durations typically ranging from 45 to 80 minutes. In comparison, traditional passive balancing results in higher losses of 15 to 25W and extended balancing periods of 120 to 180 minutes. The staggered start method facilitates automated energy distribution, minimizing cell temperature variations and extending battery life expectancy. This study establishes that advanced active balancing techniques significantly improve lithium-ion battery packs in EVs compared to traditional methods such as switched capacitors and resistor bleeding techniques. Moreover, it highlights that intelligent battery management strategies enhance performance in sustainable battery control systems. Future efforts will concentrate on hardware-in-the-loop testing or experimental validation to verify the simulation results in real-world operating conditions. Future work incorporating machine learning is aimed at creating predictive balancing techniques, which will improve energy efficiency, extend battery life, and increase system reliability in EVs.

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