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Design and Experimental Validation of an Active Cell-Balancing Battery Management System for Lithium-Ion Energy Storage Applications

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Abstract. Lithium-ion battery–based energy storage systems are a key enabler for renewable energy integration, electric mobility, and portable electronic applications. Their performance and lifetime critically depend on the proper management of individual cells within the battery pack. Battery Management Systems (BMS) are therefore essential to ensure reliable operation and mitigate cell imbalance effects. This paper presents the design, development, and experimental validation of a Battery Management System focused on individual lithium-ion cell voltage monitoring and active cell balancing. The proposed BMS implements a switched-capacitor active balancing strategy combined with a simple rule-based control algorithm, enabling energy redistribution between cells during normal battery operation. Experimental validation is carried out on a two-cell lithium-ion battery module supplying an external load, demonstrating effective reduction of voltage imbalance and stable operation under discharge conditions. The results confirm the suitability of the proposed approach for low-complexity and scalable battery management solutions in both stationary and mobile energy storage applications.

Key words. Battery Management System, Lithium-ion batteries, Energy storage systems, Cell balancing.

1. Introduction

Energy storage based on lithium-ion batteries has become a key element for the efficient integration of renewable energy sources, the improvement of power supply quality, and the development of electric mobility applications and portable electronic devices. Their high energy density, high efficiency, and progressive cost reduction have driven their deployment in both grid-connected stationary systems—such as self-consumption installations, microgrids, and backup systems—as well as in electric traction and consumer electronics applications [1]. Nevertheless, the performance, safety, and lifetime of these systems critically depend on the proper management of the cells that make up the battery.

In this context, Battery Management Systems (BMS) play a fundamental role not only as protection elements against out-of-range operating conditions, but also as active monitoring and control systems capable of maximizing the overall energy efficiency of the storage system [2]. Inadequate management can lead to cell imbalances, energy losses, accelerated aging effects, and, in extreme cases, safety hazards.

Lithium-ion batteries are composed of cells with slight differences in their electrical and electrochemical characteristics, arising from both manufacturing tolerances and progressive aging during operation. These differences are exacerbated over charge–discharge cycles, leading to imbalances in voltage, capacity, and internal resistance that limit the usable energy of the battery pack and reduce its effective lifetime [3], [4]. For this reason, individual cell voltage monitoring becomes an essential aspect to ensure homogeneous and reliable operation of the energy storage system.

Modern BMS architectures are evolving toward advanced monitoring platforms that can support the estimation of key internal states—such as state of charge (SoC), state of health (SoH), and other relevant parameters—during normal system operation [2], [5]. These capabilities provide the basis for advanced control strategies and maintenance-oriented functionalities, while already contributing to improved operational awareness and informed decision-making. In grid-connected applications, such features contribute to enhanced energy efficiency and power quality, whereas in electric mobility and portable electronic applications they enable improved autonomy and operational robustness [1], [6].

Among the critical functions of a BMS, cell balancing is of particular importance. Inefficient balancing limits the available capacity of the system and accelerates aging mechanisms. Compared to passive strategies, active balancing methods allow energy redistribution among cells, improving energy efficiency and reducing electrochemical stress, which is especially beneficial in energy storage systems subjected to frequent cycling and variable operating conditions [7].

Within this framework, the present work addresses the design, development, and experimental evaluation of a Battery Management System focused on individual lithium-ion cell voltage monitoring and active cell balancing. The proposed approach is applicable to both grid-connected stationary energy storage systems and mobile applications, providing a flexible and scalable architecture that improves voltage uniformity, supports efficient energy utilization, and contributes to a more reliable operation of lithium-ion battery systems.

2. Battery Management System Architecture

This section describes the architecture of the proposed Battery Management System (BMS), including the monitored battery module, the hardware structure, the sensing strategy, and the control platform adopted for experimental validation.

A. System Overview

The proposed BMS has been designed to monitor and manage a lithium-ion battery module composed of cells connected in series, with a focus on individual cell supervision, active balancing capability, and low-cost experimental implementation. The architecture follows a modular approach, integrating sensing, control, and balancing stages into a compact system suitable for laboratory validation and scalable to larger battery packs. Figure 1 shows the overall hardware architecture of the proposed BMS, highlighting the measurement stage, control unit, gate driving circuitry, and active balancing stage.

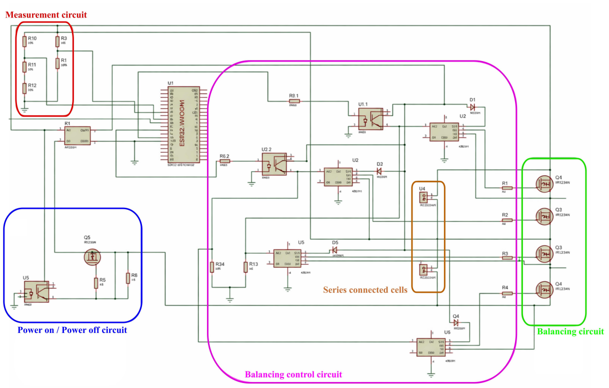

Fig. 1. General architecture of the BMS.

The main functions of the BMS include individual cell voltage acquisition, control of the active balancing circuitry, and execution of balancing strategies based on real-time measurements. The system is conceived to operate autonomously during normal battery operation, providing the basis for future integration of advanced diagnostic and degradation-aware control strategies.

B. Battery Module Description

The experimental setup is based on a lithium-ion battery module composed of two cylindrical NCR18650 cells connected in series. Each cell has a nominal voltage of approximately 3.6 V and a maximum voltage of 4.2 V. Although the module is limited in size and power, it represents a suitable test platform to validate the proposed BMS architecture and balancing strategy under realistic operating conditions.

Series-connected lithium-ion cells are particularly sensitive to voltage imbalances caused by manufacturing tolerances and aging effects. Even small deviations between cells can significantly reduce the usable capacity of the battery pack, justifying the need for individual cell monitoring and balancing mechanisms.

C. Hardware Architecture and Measurement Strategy

The hardware architecture of the proposed BMS is designed to enable individual cell monitoring and active balancing while ensuring safe operation and low implementation cost. The system integrates sensing, control, and power stages, with appropriate isolation between the control electronics and the battery power circuitry.

A key requirement of the architecture is the accurate measurement of individual cell voltages during normal operation and balancing processes. Since the control unit operates with a maximum input voltage of 3.3 V, resistive voltage dividers are employed to scale both individual cell voltages and the total module voltage to safe levels for analog-to-digital conversion. High-value resistors are selected to minimize current draw and reduce the impact of the measurement circuitry on the battery behaviour.

This measurement strategy enables continuous voltage monitoring of each cell, which is essential for detecting imbalance conditions and for driving the balancing control logic.

D. Active Cell Balancing Hardware

The proposed BMS incorporates an active cell balancing circuit based on a switched-capacitor topology to mitigate voltage imbalances between series-connected lithium-ion cells. Unlike passive balancing approaches, which dissipate excess energy as heat, the selected topology enables energy transfer between adjacent cells, improving balancing efficiency and reducing energy losses.

The balancing circuit consists of a capacitor and a set of MOSFETs arranged to alternately connect the capacitor to different cells according to a predefined switching sequence. During operation, the capacitor is charged from the cell with higher voltage and subsequently discharged into the cell with lower voltage, progressively equalizing the cell voltages. The switched-capacitor active balancing topology implemented in the proposed BMS is depicted in Fig. 2.

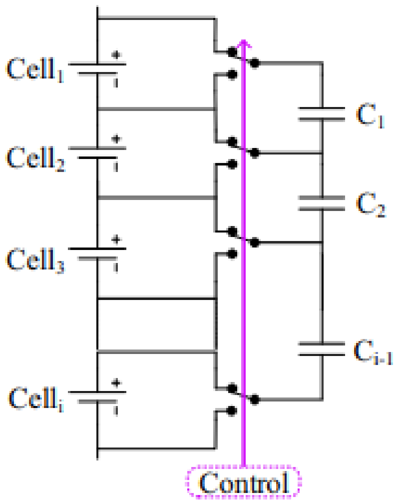

Fig. 2. Switched-capacitor balancing topology

This topology was selected due to its favourable balance between efficiency, circuit simplicity, cost, and scalability, making it well suited for experimental validation and future extension to larger battery packs.

E. Gate Driving and Electrical Isolation

Reliable and safe operation of the balancing circuit requires proper control of the MOSFET switching elements. To this end, dedicated gate driver circuits are used to ensure appropriate driving of both low-side and high-side MOSFETs.
Galvanic isolation between the control unit and the power stage is achieved through optocouplers, which protect the microcontroller from voltage transients and potential fault conditions originating in the battery or balancing circuitry. This isolation improves system robustness and enhances operational safety, particularly during experimental testing.

The combined use of optocouplers and gate drivers allows flexible and precise control of the switching sequence required by the active balancing strategy.

F. Control Unit and Processing Platform

The central control unit of the BMS is based on an ESP32 microcontroller, selected for its low cost, adequate processing capabilities, and integrated analog-to-digital converters. The ESP32 is responsible for acquiring cell voltage measurements, executing the balancing control algorithm, and generating the control signals for the gate driver circuitry.

The control firmware is developed using the Arduino programming environment, enabling rapid prototyping and straightforward modification of control strategies. This platform provides sufficient flexibility to implement rule-based balancing algorithms and serves as a foundation for future extensions toward more advanced monitoring, diagnostic, or degradation-aware control approaches.

Table I. - Main hardware components of the BMS prototype

Component	Model	Function
Microcontroller	ESP32	Control unit and data acquisition
MOSFET	IRLZ34N	Switching element for balancing
Gate driver	IR2101	High-side and low-side MOSFET driving
Optocoupler	4N35	Galvanic isolation
Balancing capacitor	470 µF, 25 V	Energy transfer between cells
Voltage dividers	High-value resistors	Cell voltage measurement
DC–DC converter	XL6009E1	Auxiliary power supply

3. Active Cell Balancing Strategy and Control Algorithm

Voltage imbalance between series-connected lithium-ion cells is an inherent issue arising from manufacturing tolerances, operating conditions, and aging effects. If not properly managed, these imbalances lead to reduced usable capacity, increased stress on weaker cells, and accelerated degradation of the battery pack. To address this problem, the proposed Battery Management System implements an active cell balancing strategy based on a switched-capacitor topology.

A. Switched-Capacitor Balancing Principle

The energy transfer process between cells is performed through a cyclic switching sequence. Fig. 3 illustrates an example of the operating sequence of the switched-capacitor active balancing strategy applied to a two-cell lithium-ion system.

The capacitor voltage evolves over time, either increasing or decreasing until it matches the voltage of the cell to which it is connected. This change cannot occur instantaneously; instead, it takes place gradually. If the initial voltages, the equivalent resistance of the circuit, the capacitance of the capacitor, and the time it has been connected to the cell are known, the capacitor voltage can be determined at any instant. Its evolution can be described by (1) or (2), depending on whether the capacitor is initially more or less charged than the connected cell, respectively.

$$V_c(t) = V_{BL} + (V_{BL} - V_{CH}) \cdot e^{-t/\tau} \quad (1)$$

$$V_c(t) = V_{BH} + (V_{BH} - V_{CL}) \cdot e^{-t/\tau} \quad (2)$$

where:

$V_c(t)$ is the capacitor voltage as a function of time.
V_{BH} is the voltage of the higher-voltage cell.
V_{BL} is the voltage of the lower-voltage cell.
V_{CL} is the capacitor voltage just before being connected to the higher-voltage cell.
V_{CH} is the capacitor voltage just before being connected to the lower-voltage cell.
t is the elapsed time since connection.
τ is the time constant of the circuit.

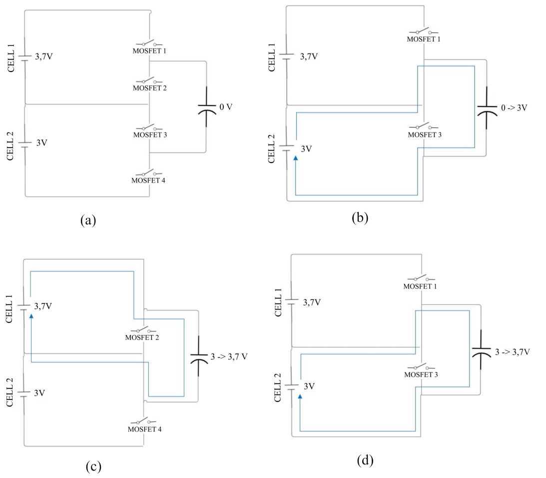

Fig. 3. Balancing operating sequence.

The initial condition corresponds to an imbalanced state, where Cell 1 presents a voltage of 3.7 V while Cell 2 is at 3.0 V, resulting in a voltage difference of 0.7 V. In this situation, the balancing algorithm identifies Cell 1 as the higher-voltage cell and initiates the energy transfer process. In the first stage (Fig. 3-a), the balancing capacitor is connected to Cell 1 by turning on the corresponding MOSFETs, allowing the capacitor to charge up to approximately the voltage of the higher cell. Once the capacitor is charged, the switching elements associated with Cell 1 are turned off, electrically isolating the capacitor from the battery pack (Fig. 3-b). In the subsequent stage (Fig. 3-c), the MOSFETs associated with Cell 2 are activated, connecting the capacitor to the lower-voltage cell and enabling the partial discharge of the stored energy into Cell 2. Finally, the capacitor is disconnected again (Fig. 3-d), completing one balancing cycle.

This sequence is repeatedly executed until the voltage difference between cells is reduced below the predefined balancing threshold, progressively equalizing cell voltages while minimizing energy losses and electrochemical stress.

Compared to passive balancing methods, the switched-capacitor approach offers improved energy efficiency and lower thermal stress, while maintaining relatively low circuit complexity and cost. These characteristics make it suitable for experimental implementation and scalable extension to larger battery packs.

B. *Balancing Control Logic*

The balancing control algorithm is executed by the central control unit based on real-time measurements of individual cell voltages. At each control cycle, the measured voltages are compared to identify imbalance conditions between cells. When the voltage difference exceeds a predefined threshold, the balancing process is enabled. Fig. 4 summarizes the control flow of the proposed BMS algorithm, illustrating the voltage measurement, imbalance detection, and active balancing decision process.

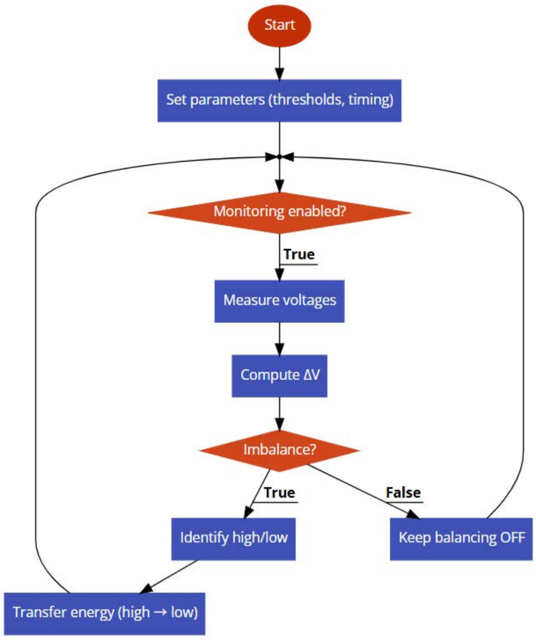

Fig. 4. Control flow of the proposed BMS algorithm.

The control logic determines the appropriate switching sequence to connect the balancing capacitor alternately to the selected cells. Switching signals are generated by the microcontroller and transmitted to the power stage through isolated gate drivers, ensuring safe operation. The balancing process is maintained until the voltage difference is reduced below the defined threshold or a maximum balancing time is reached.

This rule-based control approach allows reliable and deterministic operation, while keeping computational requirements low. The algorithm can be easily adapted to different balancing criteria, thresholds, or operating conditions.

C. *Safety and Operational Considerations*

To prevent undesired operating conditions, the balancing strategy incorporates basic safety constraints, such as avoiding simultaneous conduction paths and limiting switching frequency to prevent excessive current peaks in the balancing capacitor. In addition, balancing is inhibited when cell voltages fall outside predefined safe limits.

The proposed strategy is designed to operate during normal battery operation and can be extended to support more advanced degradation-aware or state-based balancing approaches. As such, it provides a solid foundation for future enhancements toward predictive maintenance and adaptive battery management.

4. Experimental Setup and Validation

This section presents the experimental test bench developed for the experimental validation of the proposed BMS, together with the main results obtained from the active balancing operation tests.

A. *Experimental Setup*

The experimental validation of the proposed BMS has been carried out using a laboratory-scale test bench assembled in a modular manner on solderless breadboards, as shown in Fig. 5. This approach allows rapid prototyping and flexible interconnection of the different functional blocks of the system, facilitating signal access, debugging, and verification of the control logic and active balancing operation prior to the implementation of a dedicated final PCB (Fig. 6).

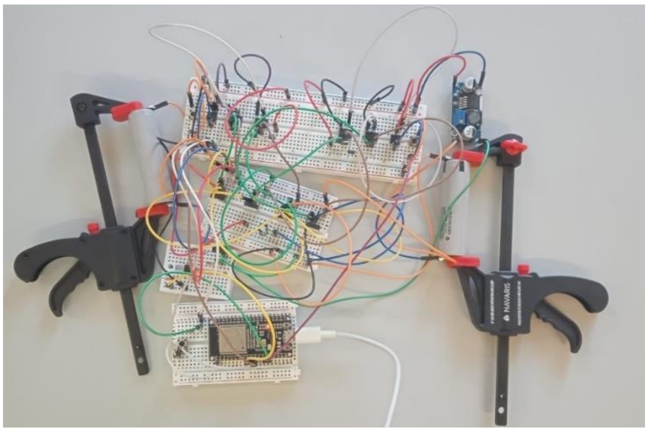

Fig. 5. Experimental setup.

The setup is based on a lithium-ion battery module composed of two series-connected cylindrical cells of type Panasonic NCR18650BD, whose main characteristics are summarized in Table II.

Table II. - Main characteristics of the cell NCR18650BD

Parameter	Value
Nominal voltage	3.6 V
Nominal capacity	2,910 mAh
Rated capacity	3,080 mAh
Standard charge	0.5C – 4.15 V
Maximum continuous discharge current	8 A
End-of-discharge voltage	2.5 V
Internal resistance	44 mΩ

Each cell voltage is measured individually through the sensing circuitry described in Section 2, enabling real-time acquisition during both idle and balancing operation. The BMS control unit executes the balancing algorithm described in Section 3 and generates the corresponding control signals for the switched-capacitor balancing circuit through isolated gate drivers.

To emulate realistic imbalance scenarios, the cells are initially charged to different voltage levels, creating a controlled voltage difference between them. This approach allows direct observation of the balancing process and its effect on the evolution of cell voltages over time. All measurements are acquired during operation to assess the behaviour of the system under dynamic conditions.

The experimental platform is powered and monitored using standard laboratory equipment, ensuring safe operation and repeatability of the tests. This setup provides a reliable framework for evaluating the effectiveness of the proposed BMS architecture and control strategy.

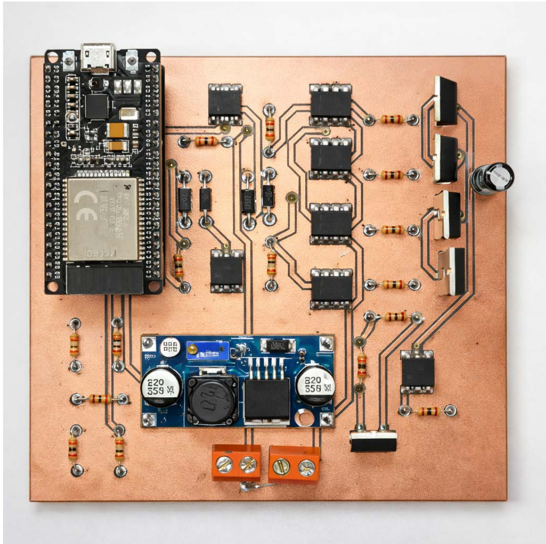

Fig. 6. Final PCB with components implemented.

B. *Balancing Operation and Validation Results*

Experimental tests have been conducted to evaluate the performance of the active balancing strategy under an initial voltage imbalance condition while the battery module is connected to an external load. In this test, the battery module composed of two series-connected cells supplies the load during the entire experiment, and the balancing process is carried out simultaneously with the battery discharge. At the beginning of the test, Cell 1 and Cell 2 present initial voltages of 3.87 V and 3.96 V, respectively, representing a realistic imbalance scenario that may arise due to aging effects or non-uniform operating conditions.

Once the voltage imbalance exceeds the predefined activation threshold, the balancing algorithm is enabled, and the switched-capacitor circuit starts transferring energy from the higher-voltage cell to the lower-voltage one while the module continues delivering power to the load. As a result, the system progressively prioritizes the discharge of the more charged cell and redirects part of the transferred energy to the less charged cell, achieving simultaneous load supply and cell equalization. The capacitor charging and discharging phases follow the operating sequence described in Section 3, leading to a gradual reduction of the voltage difference between cells.

As shown in Fig. 7, the experimental results reveal a clear convergence of the individual cell voltages as the balancing process evolves. The voltage of Cell 2 exhibits a steeper decreasing slope due to the combined effect of load discharge and energy transfer, while the voltage of Cell 1 decreases more slowly. After approximately 16 hours of operation, both cell voltages converge until reaching a difference of approximately 2 mV, which corresponds to the predefined minimum voltage difference threshold set as an input parameter in the control algorithm, below which the balancing circuit ceases operation. This confirms the effectiveness of the proposed balancing strategy under load conditions.

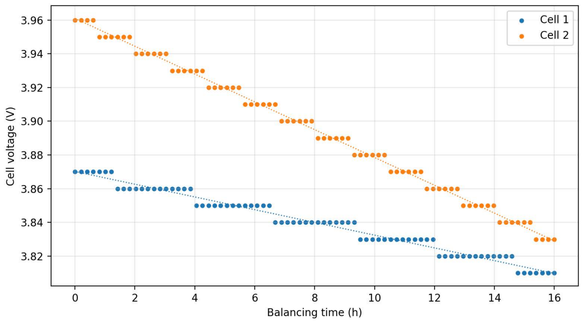

Fig. 7. Cell voltage evolution during active balancing

Fig. 8 illustrates a detailed view of the current through the balancing capacitor and the corresponding capacitor voltage with respect to ground during active balancing operation.

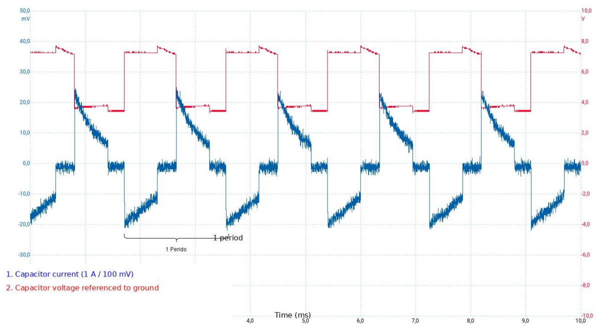

Fig. 8. Detail of capacitor current and capacitor voltage referenced to ground during active balancing operation.

The blue waveform represents the capacitor current, while the red waveform shows the capacitor voltage referenced to ground. This voltage represents the capacitor voltage referenced to ground, whose variation reflects the voltage difference between the cells as the capacitor is alternately connected to the higher-voltage and lower-voltage cell.

During the balancing process, the capacitor is alternately connected to the higher- and lower-voltage cells, producing successive charging and discharging phases. Each commutation lasts 600 µs and is followed by a 300 µs dead-time, during which all MOSFETs remain open to prevent shoot-through currents and ensure safe operation.

As shown in Fig. 8, the capacitor current exhibits a transient response in each phase, confirming controlled energy transfer and the periodic behavior of the balancing process.

These results validate the correct operation of both the hardware and control algorithm, demonstrating the ability of the proposed BMS to reduce cell voltage imbalance and improve voltage uniformity during discharge.

5. Conclusion

This paper has presented the design, development, and experimental validation of a Battery Management System focused on individual cell monitoring and active voltage balancing for lithium-ion battery applications. The proposed architecture combines a switched-capacitor balancing circuit with a simple and effective control algorithm, enabling energy transfer between cells when voltage imbalance conditions are detected.

Experimental results obtained using a laboratory-scale test bench demonstrate the correct operation of the proposed system. Under controlled initial imbalance conditions, the active balancing strategy successfully reduces the voltage difference between cells, leading to a clear convergence of individual cell voltages. The experimental observations confirm stable operation of both the hardware and control logic throughout the balancing process.

The results validate the suitability of the proposed approach for battery storage applications, where efficient cell-level management is essential to maximize usable capacity, contribute to improved voltage uniformity and potentially extend battery lifetime. Despite being validated on a two-cell configuration, the proposed architecture and control strategy can be extended to larger battery modules, maintaining low complexity and scalability.

Future work will focus on extending the system to higher cell counts and incorporating additional monitoring and control functionalities to further enhance performance and applicability in real-world energy storage systems.

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