Enhanced Modular Battery Management System Based on Active Balancing Technique for Electrified Systems

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Abstract—*The growing deployment of electrified transportation and renewable energy systems has increased the demand for scalable, cost-effective, and reliable battery management solutions, particularly for systems utilizing recyclable lithium-ion cells. The recyclable battery cells often suffer from voltage inconsistency, capacity mismatch, and nonuniform aging, which significantly degrade battery performance and reliability. This paper presents a modular battery management system (BMS) incorporating an active balancing technique specifically designed to address the challenges of using recyclable battery cells. The proposed architecture follows a hierarchical structure consisting of a main control module and multiple branch modules, enabling flexible scalability for various electrified applications. Comprehensive simulation and experimental investigations are conducted to evaluate suitable battery package configurations that are based on recyclable battery cells. with a comparative analysis between series–parallel and parallel–series arrangements. Additionally, active and passive balancing strategies are assessed using detailed modeling and state-of-charge (SoC) estimation techniques. The simulation and experimental results demonstrate that the series–parallel configuration exhibits superior stability and robustness when operating with degraded cells. Moreover, the proposed active balancing approach significantly improves voltage alignment, reduces energy losses, and enhances SoC uniformity compared to passive balancing. Experimental results confirm that the novel modular BMS maintains battery cell voltage deviation within 50 mV and extends the usable battery capacity by approximately 10%. These findings highlight the effectiveness of the proposed system as a practical, low-cost solution for managing recyclable lithium-ion batteries in electrified and sustainable energy applications.*

I. INTRODUCTION

The rapid electrification of transportation and energy sectors is driven by the urgent need to reduce greenhouse gas emissions and dependence on fossil fuels. Battery energy storage systems play a pivotal role in this transition, enabling electric mobility (e-mobility), renewable energy integration, and a wide range of portable electronic applications. A critical component ensuring the safe and reliable operation of battery packages is the battery management system (BMS) [1-3]. The BMS supervises key parameters such as voltage, current, and temperature, thereby preventing abnormal operating conditions that may lead to performance degradation or safety hazards [2]. However, conventional BMS architectures particularly centralized designs often suffer from limited scalability and flexibility when applied to systems with many battery cells [3]. There are different types of the battery, such as Lithium-ion, lead acid, etc. The Lithium-ion batteries are widely adopted in electrified systems due to their high energy density, favorable power characteristics, and long cycle life [1-2]. Traditional battery systems show significant environmental challenges, including resource consumption, recycling, and toxic waste generation, whereas using recyclable battery cells shows limitations with respect to the performance. The target and goal of using recyclable batteries are to solve these challenges by enabling the extraction and re-use of valuable materials, which conserves natural resources and minimizes waste, contributing to a greener and more sustainable tomorrow in the real-world. Nevertheless, the increasing interest in recyclable and repurposed lithium-ion cells introduces additional challenges. Such battery cells typically exhibit nonuniform aging, capacity mismatch, and increased internal resistance because of prior usage, which can significantly degrade battery pack performance if not properly managed. Despite these challenges, recyclable lithium-ion cells play an important role in enhancing sustainability by enabling the recovery of critical materials and reducing the environmental impact associated with battery disposal [4-7]. These recyclable battery systems could be integrated with power converters for electrified system applications [7-11]. In addition to the benefits of the recyclable battery systems and BMS, different battery configurations are studied and analyzed with respect to optimized performance, where the proposed BMS manages the recyclable battery systems.

Consequently, advanced BMS strategies are required to ensure safe operation and reliable performance when integrating these recyclable battery cells into new battery packages. To address these challenges, this paper presents a novel design of a modular BMS specifically designed for employing recyclable lithium-ion battery cells. The proposed architecture is organized into independent and scalable modules, where each module can manage up to seven battery cells at a nominal voltage of 28 V under fully charged conditions. This modular structure enhances flexibility, simplifies system expansion, and provides precise charge control compared to conventional monolithic

BMS designs. A key focus of this work is the evaluation of battery package configurations suitable for recyclable lithium-ion cells, which are particularly sensitive to imbalance effects caused by aging and degradation. Simulation and experimental studies are conducted to compare series–parallel and parallel–series arrangements in terms of stability, efficiency, and charge uniformity. Advanced modeling tools are employed to support the design and validation of the modular BMS incorporating active balancing techniques.

This paper is organized as follows. Section I explains the benefits of the BMS and battery systems. Section II describes the proposed methodology of the recyclable battery configurations and novel BMS. Section III presents the simulation works of the recyclable battery configurations and proposed novel BMS. Section IV illustrates the proposed BMS architecture. Section V shows the experimental setup and results of the battery configurations and proposed BMS. Finally, Section IV concludes the paper and outlines potential directions for future work.

II.   METHODOLOGY

This research employs a comprehensive approach combining simulation and experimental investigations to develop and validate the novel modular BMS tailored for recyclable lithium-ion battery cells. The methodology includes studying different battery package configurations to identify the most suitable setup for recyclable battery cells, which are typically characterized by capacity mismatch and nonuniform aging. The proposed novel BMS is designed to be scalable, where a single main control module supervises up to six branch modules, each managing four cells connected in series, allowing the system to handle up to 28 cells. Battery cell balancing is an essential requirement in BMS design. Existing balancing techniques are commonly categorized into passive, active, and hybrid schemes, each with different trade-offs in terms of efficiency, complexity, and cost [2-3]. These general concepts form the background of balancing strategies without imposing constraints on the proposed system architecture, where the balancing schemes are simulated and analyzed, as described in Section III. In addition to the design of the modular BMS and battery configurations using recyclable battery cells are investigated with respect to efficiency and reliability performance.

The adopted methodology integrates two complementary stages. First, simulation and experimental studies are conducted to model the electrical behavior of recyclable battery cells for the battery packages under different configurations and operating conditions. The simulation studies are used to evaluate voltage stability, current distribution, and state-of-charge characteristics of recyclable lithium-ion cells. Experiments are conducted to validate the battery package configurations. Second, simulation and experimental setups are performed to study and analyze the proposed modular BMS, including the balancing technique. The proposed balancing scheme is based on an active energy redistribution approach implemented at the battery cell level and coordinated at the module level to optimize power distribution among cells while maintaining a low-cost

system design. Measurement, decision-making, and balancing operations are integrated within a unified modular structure, enabling precise control and scalable system expansion. Fig. 1 illustrates the block diagram of the proposed active balancing system. The architecture incorporates a closed-loop Flyback converter that draws energy from the overall battery package and redirects it to the weakest battery cell, as identified by the measurement circuit and controlled through a microcontroller unit (MCU). This structure enables controlled energy transfer while preserving electrical isolation and minimizing energy losses.
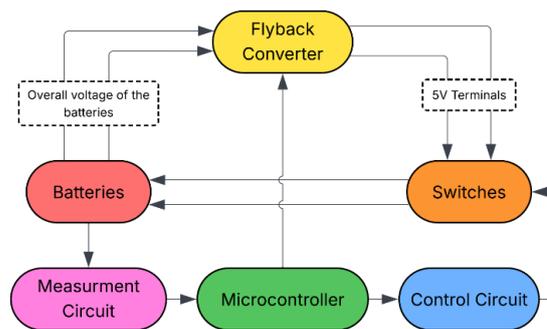

Fig. 1. Block diagram of proposed BMS.

The simulation phase is used to evaluate multiple battery package configurations and balancing strategies, enabling the identification of the most effective arrangement for recyclable lithium-ion cells. In parallel, experimental work involves assembling and testing prototype modules to verify system behavior under real operating conditions. The modular architecture, comprising a main control module and multiple branch modules, is implemented to evaluate scalability, measurement accuracy, and active balancing capability. Detailed simulation results, experimental validation, and comparative performance analysis are presented in the following sections.

III.   SIMULATION WORKS

This section illustrates the simulation results and analysis of the different battery package configurations using recyclable battery cells and the different balancing techniques.

A. Simulations of Recyclable Battery Configurations

The simulation studies are carried out using MATLAB/SIMULINK tool to evaluate the performance of different battery package configurations under controlled operating conditions and the novel modular BMS. The simulations focus on modeling series and parallel arrangements of recyclable lithium-ion cells, which are known to exhibit capacity inconsistency because of prior usage cycles [7]. Two battery configurations are investigated in detail. The first configuration is a series–parallel arrangement, where four battery cells are connected in series within two branch modules that are connected in parallel (4S2P). The second configuration is a parallel–series arrangement, where two cells are connected in parallel and four such groups are connected in series (2P4S). The simulation framework is designed to assess key performance indicators, including voltage stability across the battery package, charge uniformity among individual

cells, and overall efficiency during charge–discharge cycles. Both configurations are simulated at a 1C rate, corresponding to a full charge or discharge within one hour, to reflect realistic operating conditions. To represent the variability commonly observed in recyclable lithium-ion battery cells, whereas the battery cell capacities are modeled with deviations of up to 20% from their nominal values.

Both battery configurations are simulated, analyzed, and tested under no-load conditions for 3600 seconds to evaluate voltage stability, current distribution, and State of Charge (SoC) uniformity, particularly in the presence of degraded battery cells [6]. The simulation results, including voltage levels and internal resistance values, are summarized in Table I, highlighting the behavior of individual cells before and after configuration. Eight recyclable battery cells, labeled A–H, are considered in the analysis, where the voltage values of each cell are recorded before and after assembling the battery configurations, which indicate the impact of balancing of the battery cells with respect to the configuration and internal resistance values. Figures 2–7 illustrate the voltage, current, and SoC profiles for both configurations, providing visual insight into their dynamic behavior. In the 2P4S configuration, the voltage profile shown in Figure 2 demonstrates apparent voltage stabilization over time, while the current profile in Figure 3 indicates a relatively high current demand caused by degraded battery cells. This behavior leads to a noticeable deterioration in SoC uniformity, as illustrated in Figure 4. Although, the 2P4S configuration exhibits self-balancing behavior under no-load conditions, this effect does not persist when a load is applied. In such cases, degraded cells (C, F, and H) adversely affect healthier cells due to the parallel connection at the module level, resulting in a reduction in the overall output voltage of the battery package. The voltage values of the eight battery cells are balanced at 4V without any external resource in the expense of the output voltage and current of the battery package when parallel-series configuration is used as listed in Table I. In contrast, the 4S2P configuration demonstrates improved robustness against the impact of degraded cells. The voltage, current, and SoC profiles shown in Figures 5–7 indicate better isolation of degraded cells, acceptable balancing current levels, and a limited effect on SoC uniformity. While the current in the 4S2P configuration reaches zero at approximately 2200 seconds, the voltage and SoC values of all cells remain relatively stable, exhibiting only minor variations over nearly 50 minutes. This behavior is attributed to the series connection of battery cells at the module level, which mitigates the influence of degraded cells. Overall, the simulation results confirm that the series–parallel configuration (4S2P) provides superior performance compared to the parallel–series configuration (2P4S) when recyclable lithium-ion cells are employed. The reduced sensitivity to degraded cells and improved charge uniformity makes the 4S2P configuration more suitable for modular BMS applications targeting recycled battery systems. The simulation analysis of different battery package configurations confirms that the series–parallel battery arrangement is more suitable than the parallel–series configuration when recyclable lithium-ion cells are employed. Based on this outcome, the series–parallel

configuration (4S2P) is selected for further investigation of battery balancing techniques through the proposed modular BMS. The low SoC/voltage of battery cell(s) are balanced from the energy storage through the magnetic components, as described in the system architecture of the BMS (Section IV).
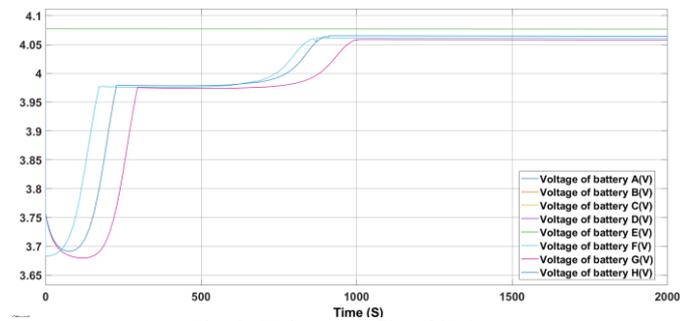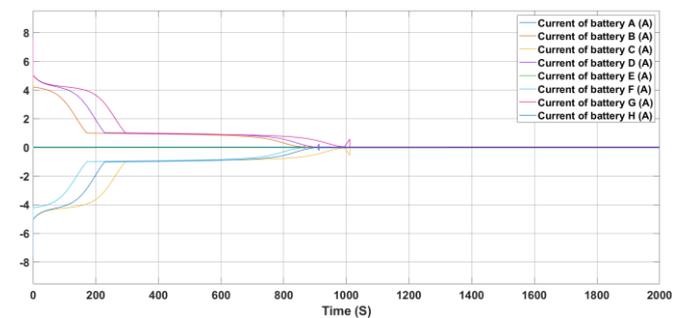

Fig. 2. Voltage profile of 2P4S

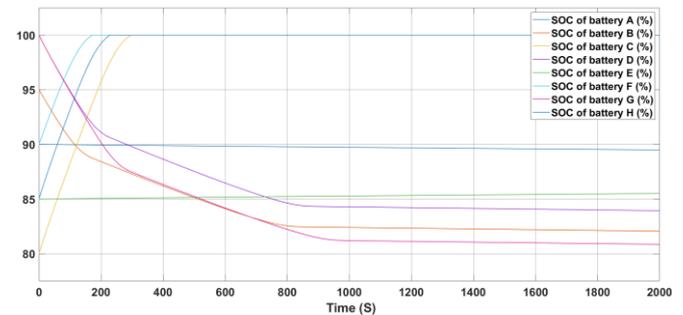Fig. 3. Current profile of 2P4S
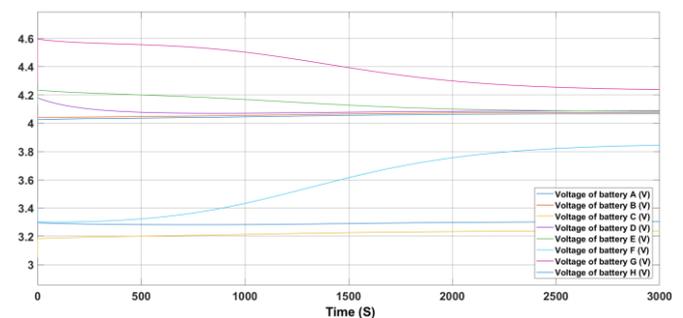

Fig. 4: SoC profile of 2P4S
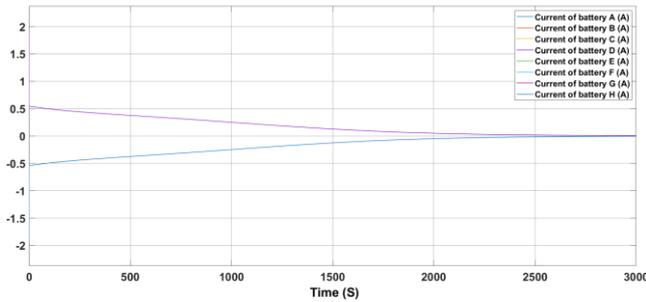

Fig. 5. Voltage profile of 4S2P
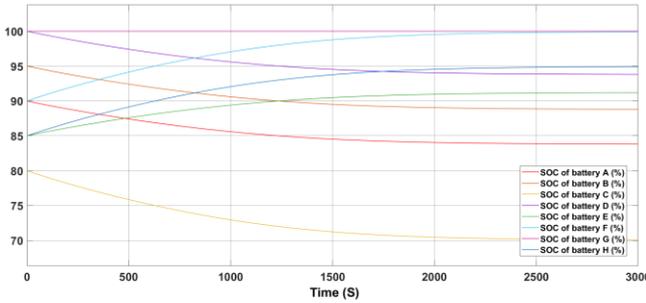
Fig. 6. Current profile of 4S2P

Fig. 7. SoC profile of 4S2P

TABLE I
SIMULATION RESULTS OF 2P4S & 4S2P

Battery	Voltage (V) before configuration	Voltage (V) after 4S2P	Voltage (V) after 2P4S	Internal Resistance (Ω)
A	4.023	4.0673	4.077	0.03
B	4.035	4.078	4.06	0.03
C	3.048	3.23	4.055	0.1
D	4.173	4.09	4.06	0.03
E	4.127	4.081	4.076	0.03
F	3.436	3.85	4.05	0.1
G	4.28	4.23	4.06	0.03
H	3.43	3.3	4.06	0.1

B. Simulations of Battery Balaning and SoC Techniques

This section therefore presents also the simulation analysis of both passive and active balancing approaches applied to the 4S2P configuration, in addition to the SoC estimation methods utilized within the proposed active balancing framework. Three SoC estimation techniques are considered in this study: coulomb counting (CC), the voltage-based method, and the Kalman filter method. The CC approach estimates the SoC by integrating the charging and discharging current over time, while the voltage-based method relies on the voltage–SoC characteristic curve to infer the battery SoC from terminal voltage measurements. The Kalman filter method employs a model-based estimation algorithm that incorporates battery parameters such as internal resistance and temperature to enhance estimation accuracy under dynamic conditions [1-3, 6-7]. Accordingly, three SoC estimation schemes are implemented for comparison: the built-in SoC estimation provided by MATLAB/SIMULINK, the CC method, and the Kalman filter method. Figures 8–9 illustrate the voltage, current, and SoC profiles of the 4S2P configuration when passive balancing is applied. The results show that the voltage and SoC profiles of the two battery modules converge and stabilize at approximately 15.8 V and 75%, respectively. This behavior indicates that passive balancing can achieve voltage equalization at the module level;

however, the associated energy dissipation and slower balancing dynamics motivate further evaluation of active balancing techniques, which are addressed in Section IV. The active balancing approach ensures efficient energy utilization while maintaining the SoC uniformity across the battery package. A Flyback converter is employed as the core balancing mechanism, as it enables electrical isolation and controlled power transfer between modules [4]. Each battery module is connected to the Flyback converter through a dedicated switching network, allowing precise regulation of the energy flow during the balancing process.
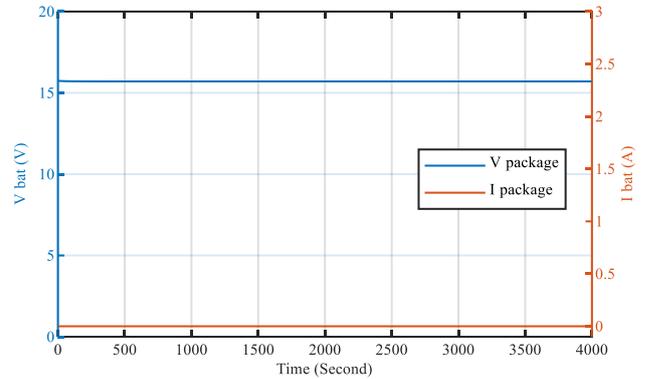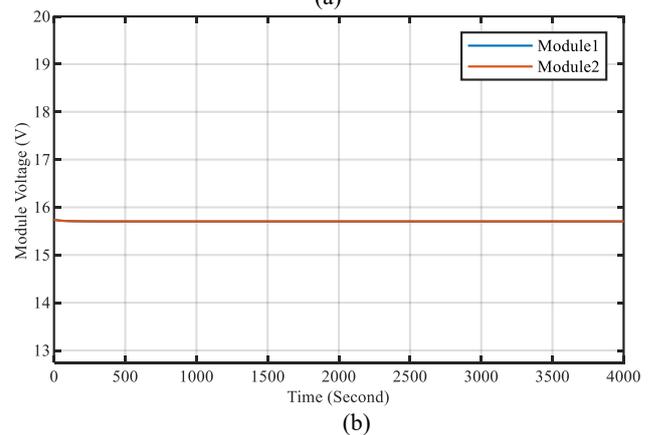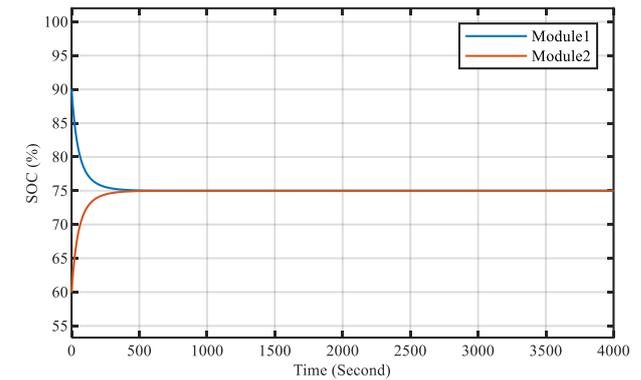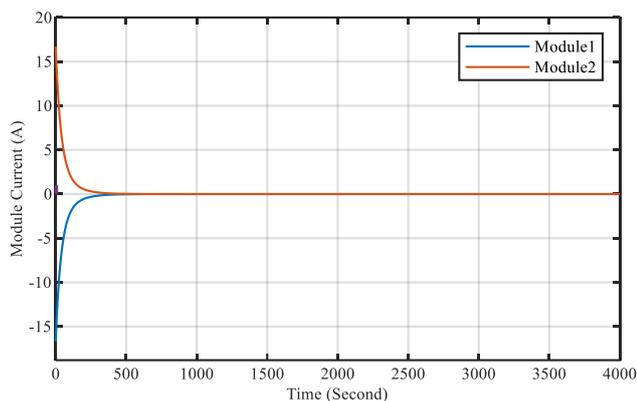

Fig. 8. Voltage and current waveform for 4S2P package using passive balancing method.

(a)

(b)

(c)

Fig. 9. Module performance of 4S2P using passive balancing method; (a) SoC, (b) voltage, and (c) current.

The SoC of all battery modules is continuously monitored using real-time estimation techniques. Based on these measurements, the system identifies modules with lower SoC that require additional energy and modules with higher SoC from which energy can be redistributed. The Flyback converter actively transfers energy from higher SoC modules to lower SoC modules through its primary and secondary windings. This control strategy minimizes power losses and prevents both overcharging and undercharging conditions at the module level. The performance of the 4S2P battery package and its associated modules is illustrated in Figures 10–11, where the current waveforms clearly demonstrate the directional flow of energy facilitated by the Flyback converter. The observed current direction confirms the active transfer of power between modules. In addition, the voltage profiles of individual modules before and after balancing are presented. Modules with higher SoC exhibit a gradual decrease in voltage as energy is transferred out, while modules with lower initial SoC show a corresponding voltage increase. The transient response during this process reflects the operational efficiency of the Flyback-based balancing strategy in redistributing energy across the battery pack. Table II presents a comparative analysis of active and passive balancing methods used in BMS applications. The comparison highlights key differences in terms of implementation complexity, cost, balancing precision, energy efficiency, and suitability for various applications.

TABLE II

COMPARISON BETWEEN ACTIVE AND PASSIVE BALANCING TECHNIQUE

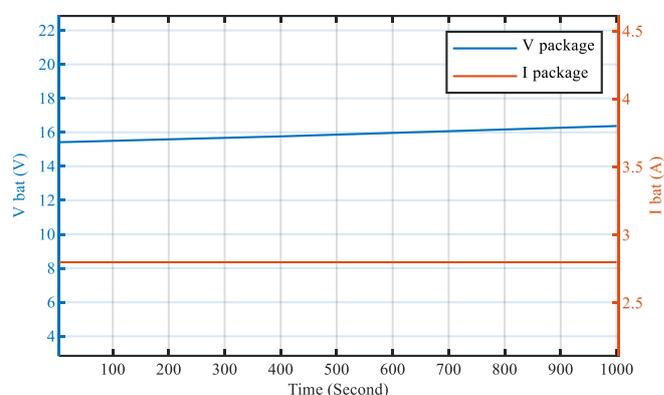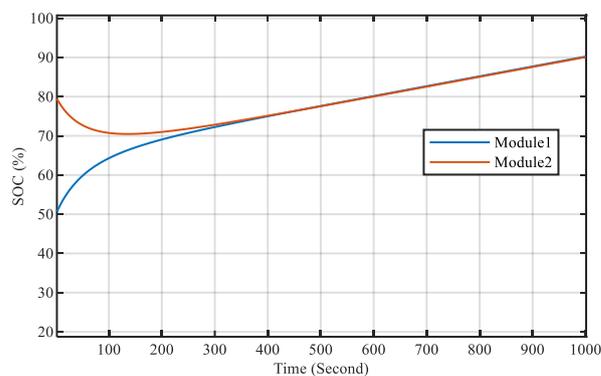| Aspect	Active Balancing	Passive Balancing
Implementation Complexity	More complex, involving active electronics	Simpler, using passive components
Cost	Higher due to the complexity of electronic components	Lower as it relies on passive components, making it more cost-effective
Precision	Highly precise in balancing individual cell voltages	Less precise compared to active balancing
Speed of Balancing	Faster at redistributing energy and balancing cells	Slower in equalizing cell voltages
Efficiency	More efficient in redistributing energy with less energy loss	Less efficient, dissipating excess energy as heat
Handling Large Voltage Differences	Effective in managing large voltage disparities between cells	May not be as effective when dealing with significant voltage differences
Application Suitability	Suitable for applications with strict balancing requirements	Suitable for applications with relatively balanced cells or cost-sensitive applications
Impact on Battery Life	Can extend the overall battery pack's life and improve performance	May have a limited impact on battery life improvement

Fig. 10. Voltage and current waveform for 4S2P package using active balancing method.

(a)

(b)

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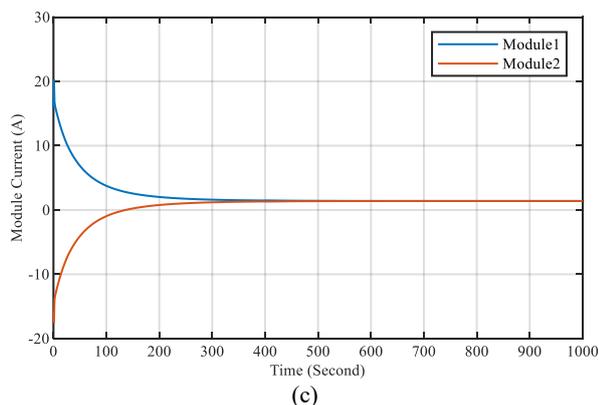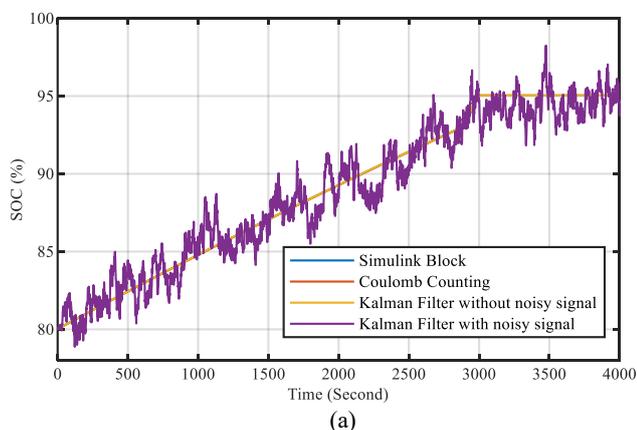
(c)

Fig. 11. Module performance of 4S2P using active balancing
method; (a) SoC, (b) voltage, and (c) current.

(b)

Fig. 12. SoC estimation using (a) passive balancing method and (b)
active balancing method.

IV. BMS ARCHITECTUE

The simulation analysis confirms that the series–parallel battery configuration exhibits superior performance compared to the parallel–series arrangement when recyclable lithium-ion cells are employed. Furthermore, the proposed BMS adopts a hierarchical modular structure consisting of one main module and a scalable number of branch modules, each capable of managing up to seven lithium-ion cells connected in series. This architecture enables flexible scalability, making the system suitable for applications ranging from residential energy storage to large-scale electric mobility systems. Figure 13 illustrates the schematic diagram of the proposed active balancing system. The main module acts as the central controller, coordinating the operation of all branch modules and managing communication with external systems, such as the battery charger. Each branch module accommodates four lithium-ion cells connected in series, while the main module is responsible for all measurement, control, and balancing operations, as shown in Figure 14. This hierarchical structure enables precise control and supports system scalability within a coordinated modular framework. The main module integrates the MCU, such as an Arduino Uno, to coordinate voltage measurement, decision-making, and balancing tasks. Four multiplexers are employed in the system architecture: two multiplexers are dedicated to the measurement phase, and two multiplexers are allocated for the balancing phase. These multiplexers operate in a single-stage configuration, allowing independent and flexible access to individual battery cells. Each branch module relies on the main module for coordination, ensuring consistent operation across the entire battery package. Voltage measurement is performed using a voltage divider feedback network, which provides an indirect indication of the SoC of individual battery cells [2-3, 14-17]. This measurement process is sequentially applied to all cells in the system, enabling safe and accurate monitoring without excessive hardware complexity. During the balancing phase, the system identifies the battery cell with the lowest voltage and applies controlled charging through the Flyback converter, which generates a regulated 5 V output to charge the selected cell. The balancing-phase multiplexers maintain the connection to the selected low-voltage cell until its voltage reaches alignment with the remaining cells, after which the

Accurate SoC estimation is essential for the effective operation of both passive and active balancing methods. In this study, a multi-pronged approach is adopted for SoC estimation, utilizing three different techniques: direct simulation-based SoC measurement, CC, and the Kalman filter method. Direct simulation measurements are first used to obtain SoC values directly from the simulation environment, providing a baseline reference for comparison and validation. The CC method estimates the SoC by integrating the battery current over time, considering the initial SoC and the nominal capacity of the battery. Although this approach is simple to implement, it is inherently sensitive to measurement errors and may suffer from cumulative drift if periodic recalibration is not applied. The Kalman filter method combines voltage and current measurements with a mathematical battery model to estimate the SoC more robustly. By accounting for noise measurement and model uncertainties, this method provides improved estimation accuracy under dynamic operating conditions [2, 12-13]. To assess the robustness and accuracy of the implemented SoC estimation techniques, artificial noise is introduced into the voltage and current measurements, as illustrated in Figure 12. This evaluation ensures that the proposed estimation can tolerate realistic sensor inaccuracies and external disturbances while maintaining reliable SoC tracking.
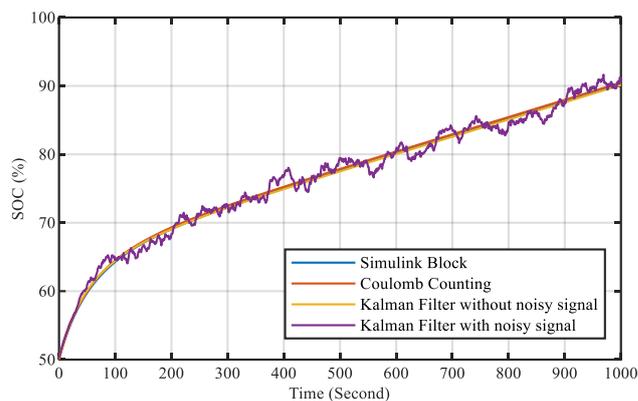

(a)

balancing cycle proceeds to the next identified imbalance. While the measurement phase continuously scans all battery cells, the balancing phase can operate simultaneously, allowing real-time correction of voltage deviations. This separation between measurement and balancing operations enhances overall efficiency and reduces system latency. The flowchart describing the proposed module-level active balancing process is presented in Figure 15.
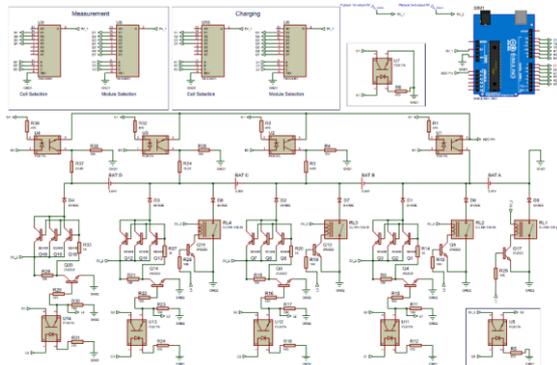

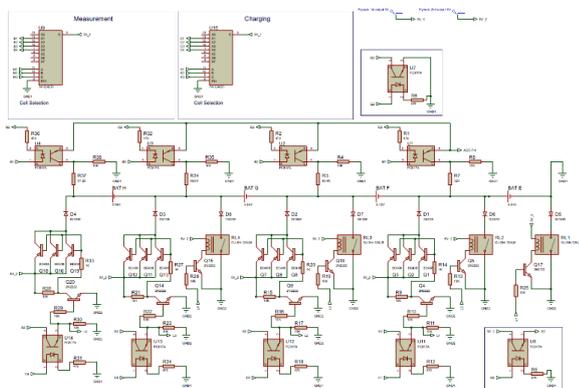Fig. 13. Main module of the proposed novel active balancing BMS

Fig. 14. Branch module of the proposed active balancing BMS

I.   RESULTS AND DISCUSSION

This section describes the experiment setup and results of the battery package configurations and proposed modular active balancing technique. The voltage levels and internal resistances of the eight battery cells (A–H) are analyzed before and after configuring the cells into 2P4S and 4S2P battery packages under no-load conditions for 20 minutes. The initial cell voltages range from 1.912 V to 4.077 V, while the internal resistances vary between 0.792 Ω and 3.872 Ω, as summarized in Table III. These values reflect the significant variability typically observed in recyclable lithium-ion cells. After configuration, notable changes in cell voltages are observed. The voltage of cell G, identified as a degraded cell, increases significantly from 1.912 V to 3.391 V, indicating a strong balancing interaction within the battery package. Other cells exhibit smaller adjustments, where some voltages decrease slightly (e.g., cell C from 4.039 V to 4.000 V) and others increase (e.g., cell F from 4.065 V to 4.174 V). This behavior reflects dynamic energy redistribution among cells during the configuration process. The results indicate that the 2P4S configuration can mitigate voltage imbalance among cells under no-load conditions.
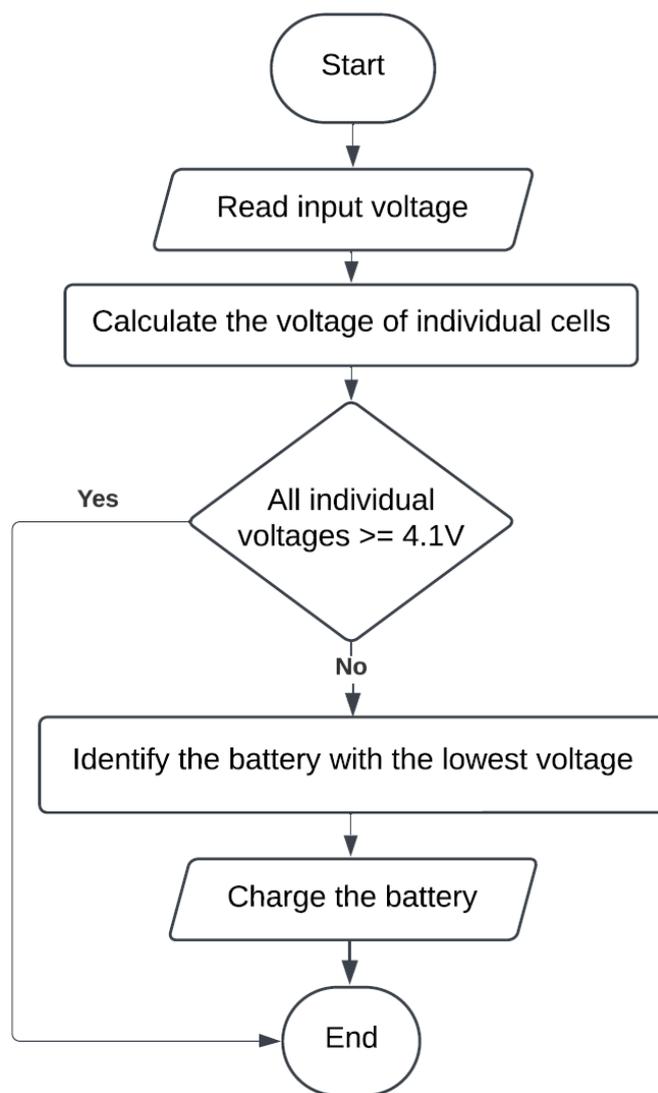

Fig. 15. Flowchart of proposed BMS.

However, this comes at the expense of reduced total output voltage and current, as degraded cells consume a portion of the available energy during the balancing process. In contrast, the 4S2P configuration demonstrates voltage and current levels that remain close to their rated values. In this arrangement, healthier cells dominate the overall behavior of the battery package due to the series connection at the module level, thereby reducing the impact of degraded cells. Although an external balancing mechanism is generally required to redistribute energy among mismatched cells, the proposed active balancing approach enables energy transfer through magnetic components rather than dissipative elements, thereby improving energy utilization efficiency [15-18].

TABLE III

BATTERY CONFIGURATIONS MEASUREMENTS

Battery cell	Voltage (before) [V]	Voltage (after) [V]	Internal Resistance (before) [Ω]
A	3.769	3.767	0.811
B	3.988	3.987	0.935
C	4.039	4.000	0.792

D	4.077	4.082	0.8123
E	4.035	3.991	0.989
F	4.065	4.174	0.870
G	1.912	3.391	3.872
H	4.013	3.996	0.961

The active balancing algorithm is incorporated into the simulation environment to evaluate its impact on system performance. The algorithm redistributes energy from higher-voltage cells to lower-voltage ones using a Flyback converter model to emulate controlled energy transfer. This approach allows the influence of active balancing on voltage alignment and charge uniformity to be examined without introducing dissipative losses in the simulation model. The adopted methodology integrates both simulation and experimental investigations to develop and validate the proposed modular BMS. Two battery modules are employed to experimentally validate the proposed active balancing technique, where each battery module consists of four lithium-ion cells connected in series (4S). Figure 16 illustrates the experimental setup of the modular BMS used to verify the proposed balancing approach. The setup is equipped with an Arduino Uno microcontroller for system coordination and control, along with four multiplexers, where two are dedicated to voltage measurement and the remaining two are allocated for balancing operations. A Flyback converter, powered by the battery pack voltage and providing a regulated 5 V output, is utilized to perform the balancing process. The experimental architecture supports scalability through the implementation of multiple branch modules, with up to six modules, each managing four series-connected cells. During operation, the active balancing process involves identifying the battery cell with the lowest voltage and selectively charging it using the Flyback converter. This experimental configuration enables validation of the proposed balancing strategy under practical conditions and demonstrates its applicability for modular and scalable battery management systems [17-18].
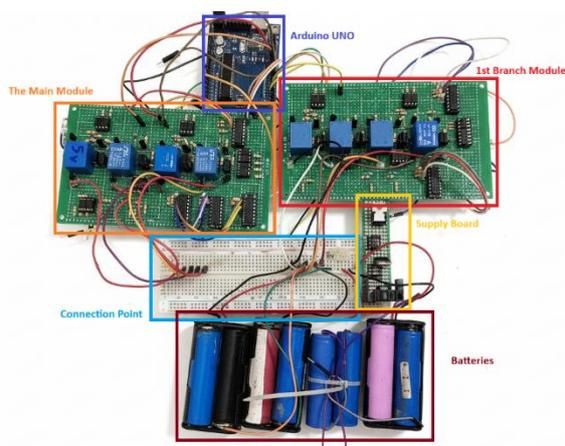

Fig. 16. The active balancing BMS prototype

The main module, equipped with an Arduino Uno microcontroller and multiplexers, serves as the central processing unit of the proposed system, coordinating communication and control across all branch modules. Each branch module is responsible for managing a group of four lithium-ion cells connected in series (4S). The branch modules are connected to the main module through a custom-designed communication bus that facilitates both voltage measurement and active balancing operations. This architecture provides voltage measurements with an accuracy of ±5 mV, which is verified using a calibrated multimeter. For active balancing, a Flyback converter is deployed at each branch module and draws power from the entire 4S battery package, with a nominal voltage of 14.8 V for lithium-ion cells. The converter selectively charges the battery cell with the lowest voltage, as identified in real time by the main module. The Flyback converter operates at a switching frequency of 50 kHz, with a duty cycle dynamically adjusted between 20% and 80% to regulate energy transfer. Cell voltages are continuously monitored through a serial communication interface, and the balancing algorithms are tuned to maintain voltage differences within 50 mV across all cells. The experimental results confirm the simulation outcomes, demonstrating that the active balancing system effectively mitigates voltage imbalance even when recyclable cells exhibit capacity variations of 15–20%. Over a 10-cycle test, the proposed system maintains battery package uniformity and extends the usable capacity by approximately 10% compared to a passive balancing baseline, highlighting the robustness and scalability of the proposed approach. Figure 17 presents the experimental monitoring of the balancing process during the charging of a battery pack consisting of eight cells connected in series (two modules). The voltage values of the battery cells are recorded over approximately 140 minutes, with measurements sampled every three minutes. The initial voltages of the eight cells are 3.97, 3.94, 3.95, 3.94, 4.01, 4.12, 4.04, and 3.94 V, respectively. All cells are balanced at approximately 4.1 V within 60 minutes using a balancing current of 650 mA. The balancing duration can be reduced by increasing the charging current; however, lower balancing currents are generally recommended to preserve battery lifetime [4]. The voltage profile shown in Figure 17 provides a proof-of-concept for the proposed active balancing technique, demonstrating effective balancing without the need for external excitation sources. Practical challenges related to multiplexer complexity and measurement accuracy are mitigated through careful calibration and synchronization. These results highlight the potential of the proposed BMS for electrified systems applications, particularly for cost-effective management of recyclable lithium-ion cells.
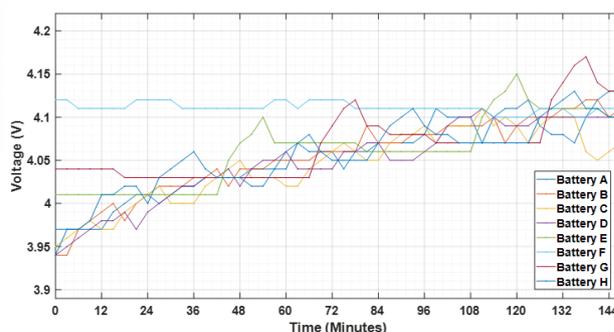

Figure 17. Voltage profile of one module using proposed active balancing technique.

II. CONCLUSION AND FUTURE WORKS

This paper presented a systematic methodology for identifying the most suitable battery package configuration for recyclable lithium-ion battery cells. Both simulation and experimental investigations were conducted to evaluate different configurations, where the results consistently confirmed that the series–parallel arrangement offered the most stable and reliable performance when recycled cells are employed, as demonstrated in Tables I and III. The modular BMS architecture incorporating an active balancing technique was introduced for electrified systems utilizing repurposed battery cells. Comprehensive simulation studies were performed to assess both passive and active balancing approaches. The simulation results demonstrated that active balancing outperformed passive balancing by enabling controlled energy redistribution rather than dissipative equalization. This leads to reduced thermal stress and improved voltage alignment among cells, even when initial capacity variations reach 15–20%. Furthermore, the SoC estimation results verified that active balancing preserves SoC uniformity more effectively, minimizing estimation drift and maintaining consistent performance across operating cycles and noises. In contrast, passive balancing exhibited slower convergence, higher energy losses, and increased sensitivity to noise measurement, particularly under degraded cell conditions. Simulation and experimental results obtained from the series–parallel configuration (4S2P) with active balancing showed superior performance, maintaining voltage deviations within 50 mV across cells and achieving improved charge uniformity during operation. Although the parallel–series configuration (2P4S) demonstrated voltage equalization under no-load conditions, it exhibited notable limitations when recyclable cells were used, including reduced efficiency and performance degradation due to uneven current distribution across parallel branches. These findings confirmed that the combination of a series–parallel configuration with active balancing is the most suitable choice for the proposed BMS architecture and directly informed the experimental validation phase. The proposed hierarchical BMS architecture, was capable of managing up to 28 cells through one main module and six branch modules, provided a scalable, cost-effective, and flexible solution for applications ranging from residential energy storage systems to e-mobility systems.

Future works would focus on further optimizing the balancing algorithm to achieve shorter balancing times and higher energy efficiency. In addition, integrating advanced fault detection techniques, such as machine learning–based approaches, may enhance the system's capability to handle cell inconsistencies and degradation effects. Expanding the system to support wireless communication for remote monitoring and diagnostics also represents a promising direction for future development.

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