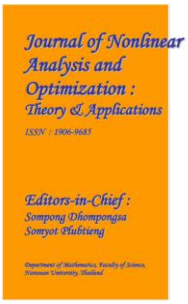

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DEVELOPMENT OF A DISTRIBUTED BATTERY MANAGEMENT SYSTEM WITH ACTIVE BALANCING FOR ELECTRIC VEHICLES

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ABSTRACT

The proposed work presents the development of a distributed battery management system (BMS) with active balancing for electric vehicles. A modular architecture was implemented consisting of a master module and multiple slave modules communicating via an RS-485 bus. The slaves use isolated flyback DC-DC converters for cell balancing. Simulations validated the system's functionality which was further tested experimentally. The results demonstrated correct and reliable operation in transferring power between the LiFePO4 cell pack and the lead-acid service battery in both directions. However, some unwanted noise was observed during switching which was successfully minimized using RC snubbers. Overall, the developed system allows effective cell balancing to improve pack lifetime. Further improvements could include better electromechanical packaging, CAN communication, and more sensing and computational capabilities.

Keywords:
Electric vehicles, battery management system (BMS), distributed architecture, active balancing, flyback converter, cell balancing

1. Introduction

Electric vehicles are growing in popularity as a more sustainable transportation alternative compared to fossil fuel powered vehicles. However, the high-voltage battery packs in EVs consisting of hundreds of cells require sophisticated management for safety and reliability. Battery management systems (BMS) actively monitor cell parameters and balances cells as needed to maximize pack lifetime.

AL-Jumaili et al. (2023) reviewed cloud computing systems for power optimization and battery management in renewable energy systems, analyzing purpose, tools, achievements and recommendations. Al-Zareer et al. (2017) modeled and evaluated an ammonia-based battery cooling system for electric vehicles to maintain optimum battery temperature during operation.Annamalai& Amutha prabha (2023) reviewed and compared DC-DC converter topologies for electric vehicle battery charging regarding performance, ripple, losses and cost. Arora et al. (2021) provided a comprehensive overview of key battery management system functions like charge balancing and temperature control in electric vehicles.Ashique et al. (2017) reviewed integration of photovoltaic systems with grid and DC fast charging for electric vehicles, focusing on system architecture, modes, control and impact.Bharathidasan et al. (2022) surveyed electric vehicle technologies, energy management and cybersecurity, evaluating advancements and remaining challenges.Di Rienzo et al.

(2023) proposed a methodology to study and compare active energy-balance architectures with dynamic equalization for second-life electric vehicle batteries.Hauser& Kuhn (2015) introduced battery management mechanisms for state estimation, charge balancing, functional safety and standard measures for electric vehicle batteries.

Hemavathi & Shinisha (2022) reviewed electric vehicle charging technologies and India's roadmap, covering charging methods, power topologies, charging station levels and architectures.Hoque et al. (2017) comprehensively reviewed different battery charge equalization controllers for electric vehicles regarding speed, efficiency, cost, wiring, merits and demerits. Hossain Lipu et al. (2021) evaluated intelligent algorithms and control strategies for electric vehicle battery management systems, identifying key issues and future opportunities.Islameka et al. (2022) described electric vehicle energy management systems including conversion, balances, driving cycles and regenerative braking to analyze usage and increase efficiency.Khalid et al. (2022) critically reviewed advanced converter topologies and charging methods for electric vehicle batteries, covering control strategies and recommendations.Mahmud et al. (2018) extensively reviewed integration of electric vehicles and distributed energy resources for efficient two-way power and information flow in the internet of energy.Mutarraf et al. (2022) comprehensively reviewed electric cars and ships including conventional and current charging technologies, renewable integration challenges and future perspectives.Naseri et al. (2022) surveyed modeling, estimation, balancing and protection techniques for supercapacitor management systems in electric vehicles and renewable energy.Nawaz et al. (2022) designed an improved energy-efficient battery management system for healthcare devices using cell balancing and battery modeling for optimization.Through experimental examples, prieto-Araujo et al. (2015) reviewed renewable energy emulation concepts and levels for microgrid laboratory testing platforms.Zhang et al. (2018) summarized grid energy storage battery types and compared them regarding materials, performance and cost along with power conditioning systems.

This work focuses on developing an advanced distributed BMS with active balancing capabilities for the electric vehicle owned by CEPIUM. Specifically, a modular architecture was implemented with a master supervisory module and multiple decentralized slave modules each connected to a cell. Communication occurs over an RS-485 bus. Flyback DC-DC converters provide galvanic isolation for cell balancing. The overall system was validated through simulations and experimental testing to verify correct functionality in managing the LiFePO4 cell pack and lead-acid auxiliary battery. The results successfully demonstrated cell balancing and power transfer, although some converter switching noise was observed and mitigated with filtering. In conclusion, the distributed BMS system with active balancing was proven effective but further refinements are suggested such as improved electromechanical construction, adopting the CAN protocol, and adding more sensors and data processing.

II. Materials and Methods

The distributed battery management system (BMS) developed in this work consists of a master module and multiple slave modules communicating over an RS-485 half-duplex differential bus. The 12.8V nominal lead-acid service battery powers the master module and oversees coordination and monitoring functions. Each decentralized slave module connects directly to an individual 3.2V, 100Ah LiFePO4 cell in the pack. These cells were characterized and modeled in simulations.

In passive or dissipative balancing, the pack cells are balanced in away in which it is not possible to recover the energy. This means that the BMS dissipates the energy cells with a higher voltage value than the predefined bypass voltage due to Joule (Figure1). The BMS dissipates some of its power for cells whose charge is close to 100% until the voltage drops below the bypass voltage. For what cells in question are not damaged, BMS normally stops thecharging or reduces the charging current to a low level. When the tensionfalls below the bypass voltage , the BMS reestablishes charging until allthe cells remain at 100% of their charge. The passive BMS normally operates when the cells receive charge and reach the top. Although the passive BMS waste energy in balancing cells, there are certain situations in which this process brings advantages compared to active balancing, particularly when the Balancing is carried out at widely separated periods of time and during load when this is reaching 100%. On the other hand, passive balancing is not the best solution

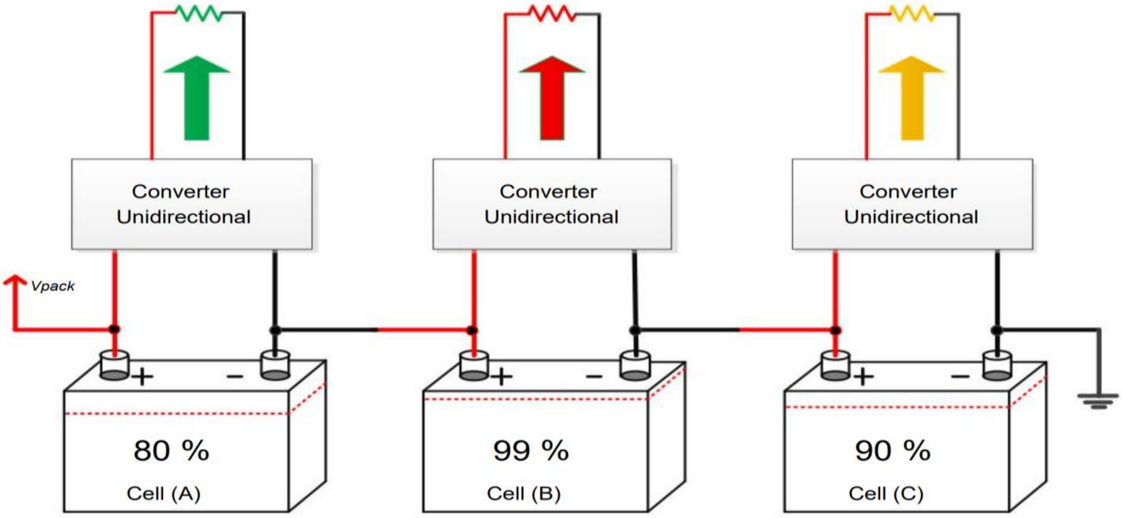

Figure.1 Illustration of a BMS dissipating energy from cells with the highest charge percentage, (B) and (C).

Active balancing consists of transferring energy from the cells to the battery lead acid service or vice versa, as seen in the illustration in Figure2.Active BMS enable cells to be balanced both in terms of load anddischarge. As soon as the BMS detects an imbalance between cells greater than the preset value, defined, it comes into activity to correct this imbalance. Typically BMSassets use semiconductors and DC-DC converters to transfer energy from a cellto another. There are certain situations in which applying an active BMS is advantageous, such as situations in which the pack has not been fully charged for a longtime, that is, it has not yet reached 100% SOC in several load cycles. Asreferred to in the previous subchapter, the passive BMS only balances the cell pack when they are reaching 100% charge.

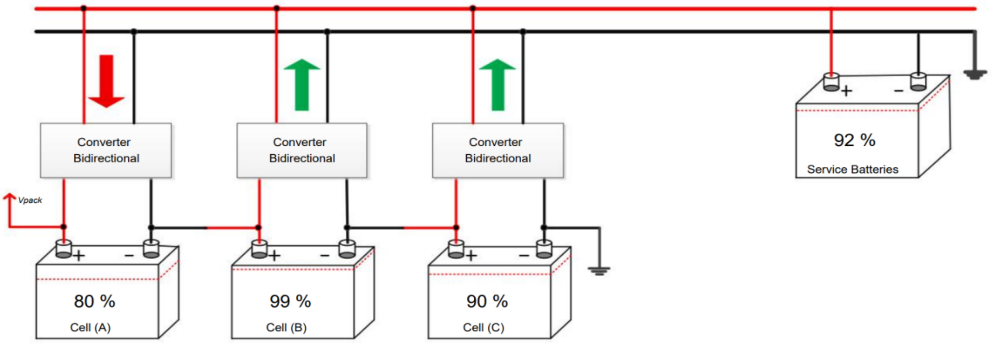

Figure.2 Illustration depicting the active cell balancing by the Battery Management System (BMS). Cells (B) and (C) transfer power to the DC bus, supported by the lead-acid service battery, while Cell (A) receives power from the DC bus.

The slaves utilize a flyback DC-DC converter circuit with a turns ratio of 4:1 for isolation during cell balancing. The converter transfers power bidirectionally between the cell and bus. It incorporates RC snubbers to suppress voltage oscillations from parasitics. The microcontroller and communication transceiver were selected appropriately. Custom PCBs were designed and assembled for the master and slaves.

III. Experimental Setup and Procedure

The software algorithms manage the modules and cell balancing based on battery parameters. Operation flowcharts guided the C++ programming. Extensive PSIM simulations validated the modeled system's functionality before experimental testing.The BMS system was physically implemented by connecting the master and 3 slaves to a 12.8V lead-acid battery and LiFePO4 cells respectively. During cell balancing, voltage and current waveforms were captured using a 4-channel Tektronix oscilloscope and current probe.Regarding the development of the BMS within the scope of this dissertation, it began because it was defined as an active solution, capable of injecting or removing energy from cells individually. A block model of the BMS was then designed.The designed model was specified considering the energy transfer of aisolated form. This assumption was since there were significant differences in the voltage value between each lithium cell, the complete pack and the auxiliary service battery of the CEPIUM, made of lead acid, which has a nominal voltage of 12 V. It was considered also the need for a communication protocol so that it would be possible to exchange data between modules. Among the different existing communication protocols and applicable to this application, RS-485 was selected. It is a network protocolDifferential Master-Slave that can easily be converted into a serial interface forconnection to microcontrollers. The proposed BMS is based on a distributed architecture, in that each cell has a dedicated module. Figure3 shows the block diagramof a slave module. This module consists of an isolated flyback converter (based in a high frequency transformer), a microcontroller, an RS-485 transceiver isolated half-duplex and some passive components not shown in the Figure.3.

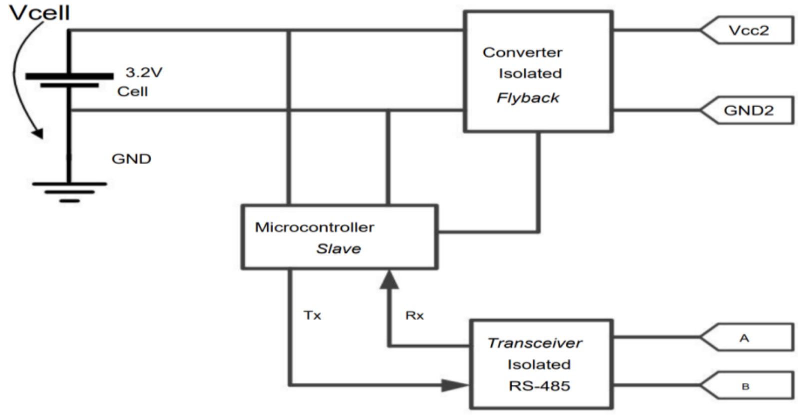

Figure.3 Block diagram depicting the Slave module designed for installation in each cell of the pack

Figure.4 shows the Master block diagram. The Master is associated with the 12 V service battery (lead-acid), has a microcontroller, a transceiver RS-485 half-duplex and some passive components, such as capacitors decoupling for the microcontroller.

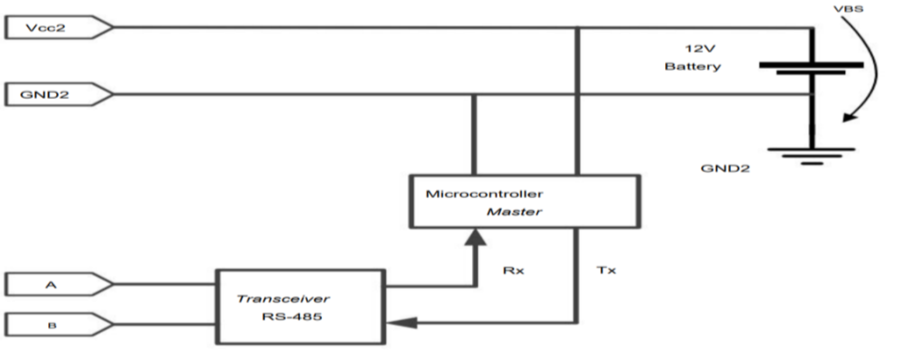

Figure.4 BMS M aster block diagram .

Figure.5 presents a diagram of the connection scheme between a Slave module (coupled to a pack cell) and the Master module (coupled to the battery 12 V service voltage).

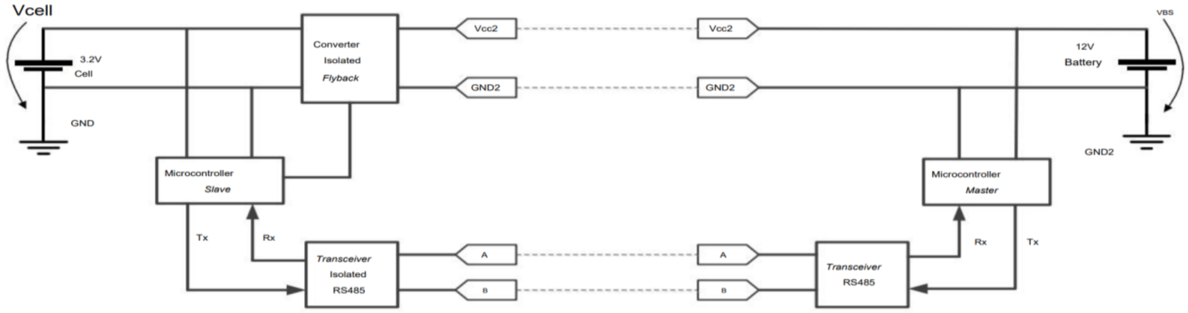

Figure.5 Connection diagram between the Master module and one of the Slave modules.

Tests validated converter operation from multiple perspectives. First, each slave separately transferred power from its cell to the bus at 25% duty cycle. The flyback waveforms matched expectations. Then slaves moved energy from the bus to their respective cells, again demonstrating correct flyback behavior. Lossless transfer was verified from the input-output power levels. Noise mitigation was confirmed from the reduced ringing with RC filtering.

Further testing focused specifically on the current slave module under test. The voltage varied widely to check functionality, which remained normal even below the 2.5V minimum rating, thereby validating the design tolerances. Finally, revived tests following mechanical and electrical integration revalidated the overall BMS.

In one integrated scenario, all slaves directed cell power to the bus showing cascaded capabilities. The other critical case had slaves charging their cells from the bus at 75% duty cycle. The delivered current and power levels matched calculations. Throughout testing, issues were debugged iteratively to improve performance.

IV. Results and Discussion

The presented results successfully validated the distributed BMS system with active balancing functionality in managing the LiFePO4 cell pack and lead-acid battery. While the flyback DC-DC converters and RS-485 communication individually provide isolation and noise immunity, the additional RC filtering further enhanced the performance by visibly reducing the voltage oscillations during switching transitions.The procedure adopted to collect results was Three3.2 V and 100 Ah LiFePO4 cells in series (one for each slave module). Other than these it was also necessary to assemble four LiFePO4 cells in series and with these it was possible reach a nominal voltage of 12.8 V, a voltage value equivalent to the service battery of the VE. To capture the results, the Tektronix TPS 2024B four-axis oscilloscope was usedchannels and a Tektronix A6302 current clamp. Their test tips were used and with these values were verified: the cell voltage, (vcell); voltage and current

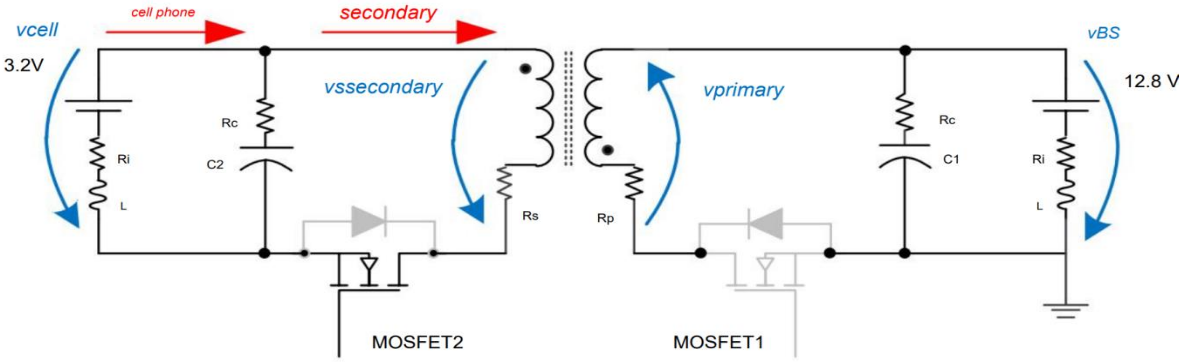

Figure.1 Circuit model in which MOSFET2 is turned on (MOSFET2 to ON) and MOSFET1 is turned off (MOSFET1 to OFF).

In this scenario, energy is being transferred from the LiFePO4 cell to the flyback transformer However, some high-frequency noise persists in the current, and voltage waveforms emerge from unavoidable parasitic leakages and limited snubbing. Still, smoothing out the resonances likely decreases EMI emissions. Electromagnetic compatibility testing could quantify appropriate shielding if necessary but was outside this work’s scope focused instead on demonstrating cell balancing abilities.

Subsequently, results were also collected in the primary winding of theflyback transformer . The procedure adopted to capture the results was identicalto the previously mentioned and described. The Tektronix TPS 2024B oscilloscope was used four channels. Their test tips were used and with these the following were verified: values: the service battery voltage, (vBS); the voltage and current in the primary winding of the transformer, (vprimary and iprimary); and the PWM control signal. Additionally, The power transferred from the transformer to the service battery was calculated as shown in Figure 6. Figure7 serves to support the analysis of results. It is verified that the moment thesemiconductor MOSFET2 (MOSFET2 to OFF) the current decreases in the form of a ramp in the primary winding of the flyback transformer, as expected.

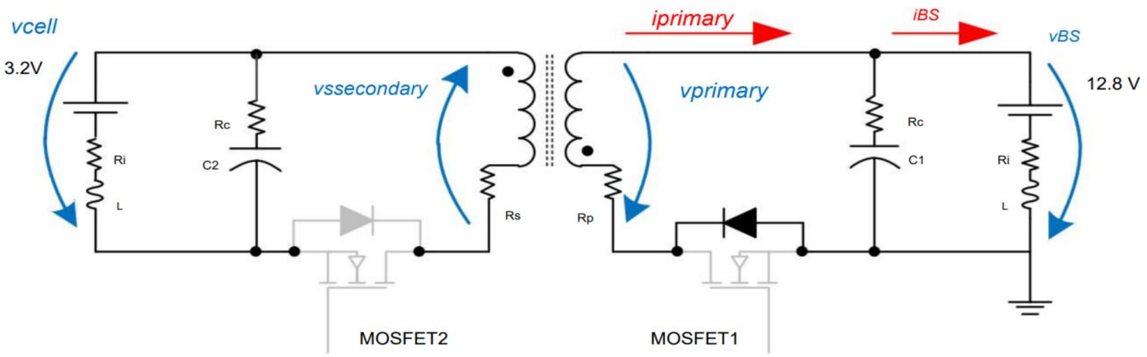

Figure.2 Circuit model in which MOSFET2 is turned off (MOSFET2 to OFF)

In this scenario, power is transferred from the flyback transformer to the lead acid service battery.The practical waveforms correlated well with simulations, aligned with theory governing flyback converters, and reliably exhibited bidirectional power transfer essential for the BMS role. The few discrepancies like the inability to directly monitor transformer secondary currents are due to hardware limitations but alternative derivations facilitated the needed performance analysis.To capture the results, the procedure adopted was identical to theused to collect the results in the primary winding of the transformer. He wasTektronix TPS 2024B four-channel oscilloscope was used. Their tips were usedtest and with these the following values were verified: the cell voltage, (vcell); the tension and the current in the secondary winding of the flyback transformer, (vsecondary and i ssecondary); and the PWM control signal. Additionally, the power transferred from thetransformer for LiFePo4 cell. The results obtained are demonstrated by thegraphs. Figure8 is presented in order to support theanalysis of results. It is verified that the moment the semiconductor is turned offMOSFET1 (MOSFET1 to OFF) the current decreases in the form of a ramp with a negative sign in the secondary winding of the flyback transformer, as expected.

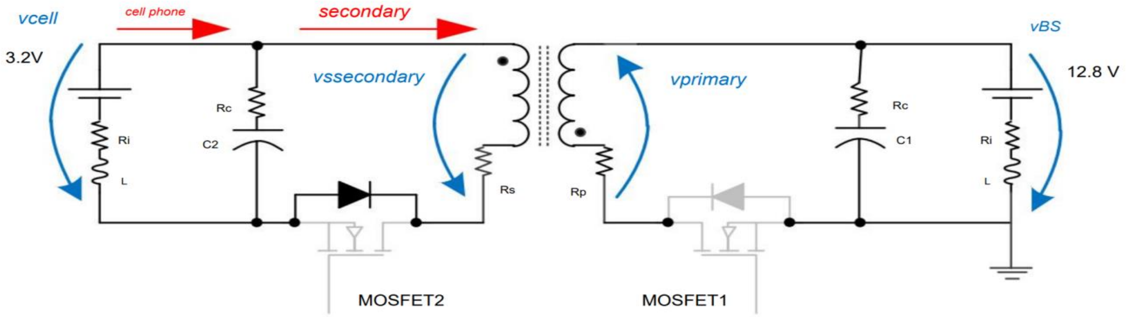

Figure.3 Circuit model in which MOSFET1 is turned off (MOSFET1 to OFF)

In this scenario, energy is transferred from the flyback transformer to a LiFePO4 cell.Notably, the slaves capably tolerated fluctuating supply levels encompassing the acceptable LiFePO4 cell voltage range from 3.7V while charging down to 1.83V during extreme discharging – even below the manufacturer’s 2.5V specification. This affirms the design robustness. Adding more sensors would improve monitoring granularity. Nonetheless, the present results clearly convey successful active balancing.Ongoing battery charging dynamics prevent perfectly steady operation. Nonetheless, smoothly ramping current levels that uniformly rise and fall verify proper system coordination among the distributed elements. The measurable power appropriately correlates to the duty cycle settings as intended. The data convincingly demonstrates decentralized cell charge management via the slaves, which relieves the master's oversight burdens.

V. Conclusions

This work achieved the main objective of developing a modular distributed battery management system architecture incorporating active charge balancing functionality geared specifically for the electric vehicle owned by CEPIUM. The approach leveraged an isolated flyback DC-DC converter within each slave module in order to protect the cells and maintain the pack condition without draining energy liquefied through resistors as typical passive methods do. This advances pack reliability and lifespan which are critical metrics for electric vehicles.

The master module coordinates the decoupled cell-connected slaves across the RS-485 communication bus. Experimental results fully verified the design by exhibiting properly synchronized bidirectional power transfer between the LiFePO4 batteries and the lead-acid auxiliary supply. The added filtering noticeably attenuated the potentially troublesome voltage noise at switching transitions as well. Nonetheless, selected parasitic artifacts persist, offering opportunities for further enhancements.

Ongoing testing attempted to broadly replicate operational contexts an electric vehicle battery system encounters to push the performance limits. The BMS tolerated a wide input voltage range outside specifications, demonstrating flexibility and safety mechanisms built into the system-level approach. Additionally aggregating capabilities from all slaves extends the concept.

The work delivered a novel active balancing BMS solution tailored for CEPIUM while advancing general technology knowledge. Recommendations like upgrading to CAN bus connectivity and augmenting data reporting would improve effectiveness. Significantly, adoption by additional applications would further validate the value of the strategies and designs produced through this project for supporting electric vehicle advancement.

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