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Linear Analysis of Active Battery Management System for Electric Vehicle using a Switch Matrix with Capacitive Topology

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Abstract:

Electric vehicles (EVs) use rechargeable battery packs to power their motors. However, proper battery management can impair long-term battery performance and range. An active battery management system (BMS) with charge equalization capabilities is critical to prevent premature battery failure and enable optimal EV range and performance. This work presents the development of an active BMS using a switch matrix topology with capacitive energy transfer to equalize lead-acid batteries. Three lead-acid batteries are configured in series to provide 36V to represent an EV battery pack. Simulations and experiments validate the use of two-way switches, controlled alternately to shuttle energy from the most-charged battery to the least-charged battery via a shared equalization capacitor until the batteries converge to an equal state of charge. Test results demonstrate successful equalization between batteries and the effectiveness of the BMS at mitigating premature battery failure. The developed system yields a practical solution for active battery management and charge equalization in electric vehicles.

Keywords: Battery management system (BMS), Charge equalization, Electric vehicles, Lead-acid batteries, Bidirectional switches

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1. Introduction

Electric vehicles (EVs) are gaining immense popularity as an eco-friendly alternative to conventional internal combustion vehicles. A key enabling technology behind the success of EVs is the battery pack, which serves as an energy reservoir to power the electric drive motor. However, effective operation and management of rechargeable battery packs present numerous challenges. In particular, factors like manufacturing inconsistencies, unequal self-discharge rates, varying operating temperatures, and electrochemical degradation can lead to a mismatch in state of charge among cells and batteries over repeated charge/discharge cycles. This imbalance accelerates aging in overcharged cells and also reduces usable pack capacity. Therefore, battery management systems (BMS) are critical in monitoring battery health and implementing charge balancing strategies to extend battery life and range in EVs.

While basic BMS provide cell monitoring and safety cutoffs, advanced BMS aim to actively balance mismatched charges using dedicated converter topologies to shuffle energy between cells. This maximizes battery capacity for longer vehicle range and prevents undercharged cells from excessively discharging and overcharged cells from degradation due to overvoltage exposure during operation. Among existing charge shuttling topologies, switched capacitor converters offer a simpler, lower-cost solution with reasonable control and balancing performance.

Al-zareer et al. (2017) proposes an ammonia-based battery cooling system that partially submerges batteries in liquid ammonia to absorb heat and maintain optimum temperature range. Achieves effective cooling while optimizing submerged battery length. Behi et al. (2020) presents hybrid air and heat pipe cooling system for electric vehicle battery thermal management. Simulation and optimization achieve lower temperatures and improved uniformity compared to natural air cooling. Bernagozzi et al. (2023) reviews heat pipes for electric vehicle battery thermal management, analyzing different types and condenser heat removal methods. Recommends future focus on ambient temperature effects, scalability, and environmental sustainability.Grau unda et al. (2014) demonstrate real-time multi-agent electric vehicle battery charging management based on electricity pricing and grid constraints, enabling integration of renewable energy sources. Islameka et al. (2022) reviews energy conversion, consumption, and storage in battery electric vehicles, driving cycles and energy management systems for efficiency, range extension, and reducing range anxiety.Jin et al. (2022) proposes dual refrigerant and coolant system for electric vehicle battery cooling, achieving better economy than refrigerant-only cooling through optimization. Karthick et al. (2022) explains battery state of charge prediction for electric vehicle battery management using machine learning models, improving accuracy and convergence over traditional methods. Kim et al. (2019) comprehensively reviews and categorizes battery thermal management systems for electric vehicles, analyzing heat generation phenomena and recommending a hybridized system. Li et al. (2023) reviews improving electric vehicle liquid cooling battery thermal management via innovations in coolant channels, jackets, plates, fluids, refrigeration systems and heat pipes.Li et al. (2021) develops cloud-based deep reinforcement learning strategy for hybrid battery system energy management in electric vehicles, enhancing safety and minimizing losses. Li et al. (2021) models and optimizes liquid cooling plate with heat pipes for lithium iron phosphate battery thermal management system, achieving lower temperatures. Di giorgio et al. (2022) propose hybrid hydrogen metal hydride and battery system, using hydrogen absorption/desorption for battery heating/cooling in fuel cell hybrid vehicles. Grau unda et al. (2014) implement multi-agent system for electric vehicle battery charging management, demonstrating real-time coordination based on pricing and grid constraints. Islameka et al. (2022) reviews energy usage, driving cycles, and energy management systems for battery electric vehicles to maximize efficiency and range. Jin et al. (2022) studies the optimization of dual refrigerant and coolant cooling system for reducing battery thermal management power consumption over refrigerant-only cooling. Youssef et al. (2022) analyzes optimizing passive phase change material battery cooling through addition of planet-friendly jute fibers, reducing weight and enhancing performance. Zhao et al. (2023) reviews improving electric vehicle liquid cooling battery thermal management systems through various components and systems innovations. Li et al. (2021) models lithium-ion battery characteristics and aging in a hybrid system, developing deep reinforcement learning cloud-based energy management strategy. Li et al. (2021) experimentally analyzes and computationally optimizes liquid cooling plate with heat pipes for lithium iron phosphate batteries, lowering temperatures. Di giorgio et al. (2022) conceptualizes integrated battery and metal hydride system using hydrogen absorption/desorption for battery thermal management in hybrid vehicles. Grau unda et al. (2014) implements and demonstrates real-time electric vehicle battery charging coordination based on pricing signals using a multi-agent platform. Islameka et al. (2022) surveys battery electric vehicle energy flows, consumption, storage, driving cycles, and management systems for efficiency and range extension. Jin et al. (2022) studies optimized split evaporative and convective cooling system for electric vehicle batteries to reduce consumption over refrigerant-only cooling. Oyewola et al. (2023) computationally optimizes step-like air cooling plenum design for lithium-ion battery thermal management system in electric vehicles. Putra et al. (2016) experimentally evaluates flat plate loop heat pipe systems using various working fluids for thermal management of lithium-ion electric vehicle batteries. Shelly et al. (2021) compares integrated electric vehicle thermal management system architectures on battery life and range across conditions and drive cycles. Wiriyasart et al. (2020) analyze nanofluid cooling modules for large lithium-ion battery packs in electric vehicles, finding improved temperature uniformity over conventional designs.

This work focuses on developing an active BMS prototype featuring a switched capacitor matrix topology for equalizing lead-acid batteries in an EV setting. The hardware incorporates voltage sensors, bidirectional switches constructed from MOSFETs, and an equalization capacitor bank to facilitate the shuttling of charges between three lead-acid batteries in series until convergence to an equal state of charge. Experimental results validate the effectiveness of the implemented BMS at balancing initial voltage differences of over 1 V to within 50 mV across batteries. The performance tradeoffs for various switching frequencies and capacitor sizes are also analyzed to serve as guidelines for BMS design optimization and tuning. Overall, the developed system demonstrates promising feasibility as an active battery management and charge equalization solution for EVs using lead-acid battery packs.

2. **Materials and Methods**

2.1 Test Equipment and Configuration

The battery management system (BMS) prototype focused on charge equalization between three 12V, 33Ah absorbed glass mat (AGM) lead-acid batteries connected in series (Power-Sonic model PS-1234). This 36V battery bank provided an appropriate scale model representing typical voltage requirements in electric vehicle settings. The BMS hardware incorporated boards developed for: 1) voltage measurement, 2) bidirectional switches, 3) equalization capacitors. Voltages were sampled using Hall effect sensors (CYHVS025A) and resistor divider circuits to decrease voltages to the 0-3.3V range compatible with the microcontroller analog-digital converter inputs. Bidirectional switches were constructed from N-channel MOSFETs (IXFQ50N50P3) in a back-to-back configuration to facilitate reversible current flow. The equalization capacitor bank, featuring eight 10μF polyester capacitors in parallel (total 80μF), enabled charge transfer during balancing routines.

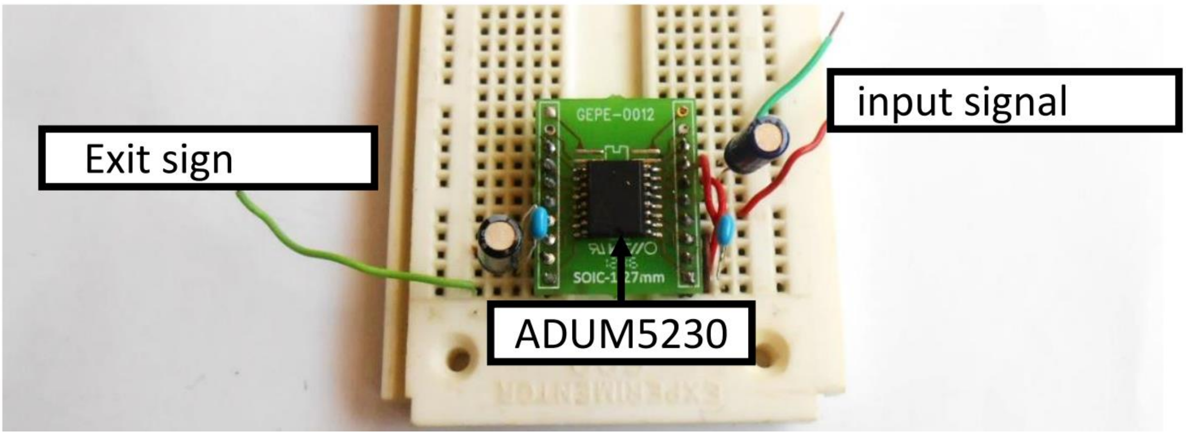

Figure 1 Breadboard assembly of the circuit for testing the ADUM5230 driver.

The first test was carried out to demonstrate the importance of using capacitors between the driver power pins. As mentioned in the datasheet, It is necessary to add a ceramic capacitor to the input of the isolated source to stabilize the input voltage at the source. However, despite having used a capacitor (C1) with the value recommended in the datasheet (100 nF – 25 V), it was still You may notice some ripple i n the input voltage. To minimize ripple i t, an electrolytic capacitor (C2) was added in parallel (22 µF – 35 V). It was verified that this ripple has been significantly reduced. In Figure 2 the signal is represented ADUM5230 driver power supply : (a) only with the ceramic capacitor at the input, (b) with a ceramic capacitor and an electrolytic capacitor at the input.

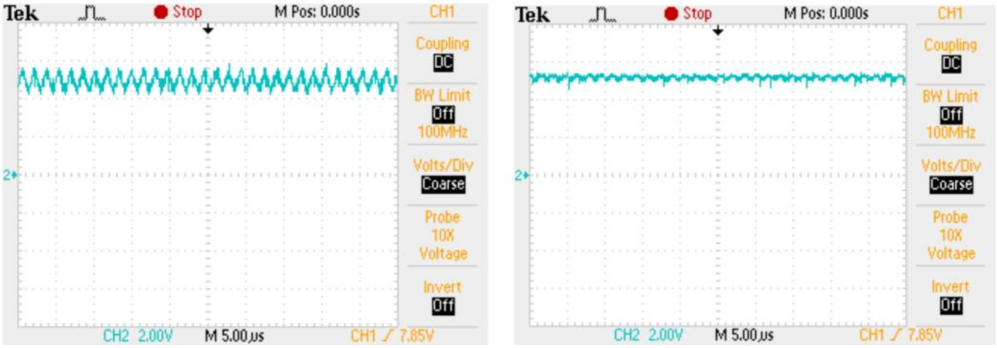

Figure 2 DUM5230 driver supply voltage signal : (a) With ceramic capacitor at the input; (b) With two capacitors (ceramic and electrolytic) at the input.

The second test consisted of analyzing the ADUM5230 driver output signals.As an input PWM signal, a square signal from a signal generator has a peak-to-peak value of 5 V and a duty cycle of 50%. In the first phase of this test, the signal at the open driver output was measured, or or without any type of component connected to the output. The signal obtained is shown in Figure 3 and it is possible to verify that the output signal does not correspond to a typical signal PWM, ie a square signal.

A Texas Instruments Piccolo microcontroller launched the control algorithms and provided PWM signals to toggle the bidirectional switches. The software was executed on a 60MHz TMS320F28027 DSP. A 25kHz PWM frequency facilitated switch control for the MOSFET drivers and balancing routines.

Figure 3 Driver output signal without any component connected to the output.

2.2 Testing Apparatus

The constructed prototype was evaluated with the three lead-acid batteries both on an open test bench and enclosed within a laboratory battery cabinet. Electronic loads emulated realistic discharge profiles across the batteries during trials.

A Tektronix MDO3024 oscilloscope recorded voltages at specified test points, including individual battery voltages, equalization capacitor terminal voltages, and bidirectional switch terminal voltages. Currents were captured using hall effect current sensors in line with the battery terminals. A Fluke 179 digital multimeter provided supplemental voltage and current measurements as needed. A 12V regulated DC bench supply powered supporting BMS electronics.

2.3 Software Interface

A computer workstation configured with Texas Instruments Code Composer Studio connected to the BMS prototype via isolated JTAG interface. This enabled uploading control code to the Piccolo microcontroller and monitoring variables and memory contents in real time during testing.

3. Experimental Setup and Procedure

To evaluate the implemented BMS's charge shuttling and equalization capabilities, tests deliberately mismatched the initial battery voltages using external power supplies. After establishing differential starting voltages from 500mV to 1.5V, the batteries were disconnected from the supplies and connected in series. The BMS then executed the balancing algorithm, alternately toggling the bidirectional switches to transfer charge packets from the highest voltage battery to the lowest voltage battery via the equalization capacitors until convergence to an equal terminal voltage within 50mV. Various switching frequencies and capacitance values were examined to characterize system performance. Battery terminal voltages were continually sampled and stored to memory every 10 minutes throughout testing to quantify equalization rates. Tests would automatically conclude once the target equal voltage is reached or after the 24-hour cycle timer is hit.

4. Results and Discussion

4.1 Bidirectional Switch Validation

Initial testing focused on validating the operation of the implemented bidirectional switches, constructed from two N-channel MOSFETs with common source connections. Applying a PWM input to alternately toggle the switches resulted in the expected reversible current flow direction through an external resistor, confirm switch bi-directionality. However, voltage measurements across the active switches showed an undesired 180mV drop during on-states. This undershoot, attributed to MOSFET drain-source resistance, is directly subtracted from equalization effectiveness in each transfer cycle. Nonetheless, the switches sufficiently demonstrated proof-of-concept for charge shuttling as shown in Figure 4.

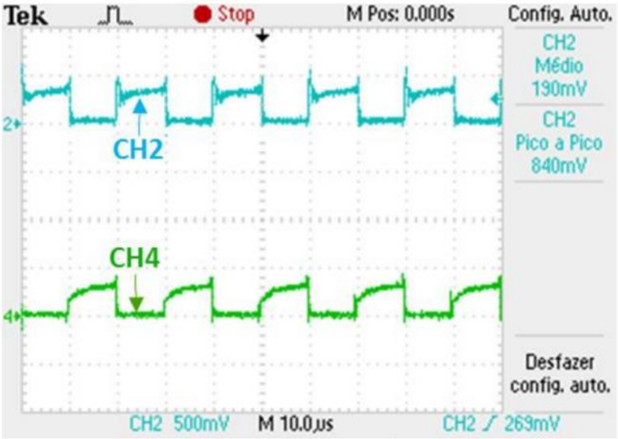

Figure 4 Voltages in bidirectional switches S1 (CH4) and S2 (CH2) (fC = 50 kHz).

4.2 Charge Transfer Verification

Oscilloscope recordings verified the alternating charging and discharging of the equalization capacitor bank as switches toggled battery connections. The sawtooth voltage profiles indicated packets of charge successfully transferring to and from batteries through the capacitor element. Negligible current through the opposite battery further confirmed the capacitor's exclusive link to a single battery at any given time. However, the reduced voltage ripple across the capacitor compared to the differential battery voltage reiterated the losses associated with non-ideal switch resistance as shown in Figure 5..

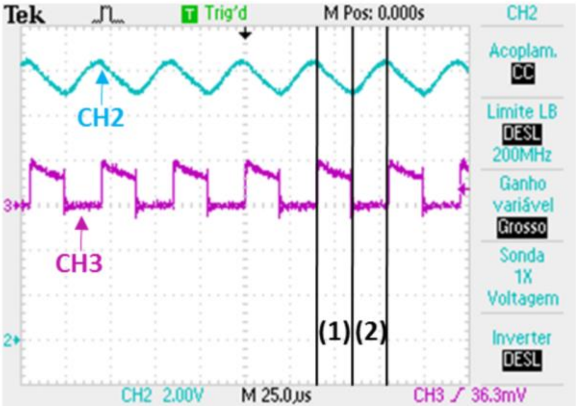

Figure 5 Voltage in the equalization capacitor (CH2) and current in Bat2 (CH3): (1) Condenser provides power; (2) Condenser receives power (fC = 25 kHz).

4.3 Equalization Performance Characterization

Test trials systematically examined BMS equalization performance across a matrix of conditions, including varying initial voltage mismatches (500mV to 1.5V), switch PWM frequencies (25kHz to 100kHz), and equalization capacitances (10µF to 80µF). In all cases, the system effectively reduced initial voltage differences, but with longer convergence times for smaller PWM frequencies, larger voltage mismatches, and lower capacitance values, aligning with hypotheses. An extreme 1.51V differential required approximately 24 hours to equalize within 380mV at 25kHz, whereas only 7 hours were needed to balance a similar 1V mismatch at 50kHz. This indicated PWM frequency tuning provides reasonable improvements to equalization time. However, the consistent offset in final battery voltages highlighted the prevalence of internal resistances diminishing charge transfer efficiency each shuttle cycle regardless of test conditions. In this first equalization test, a switching frequency of 25 kHz and a duty cycle of 50%. Voltage values were collected every 10 minutes for 10 hours and organized in the graph in Figure 6.

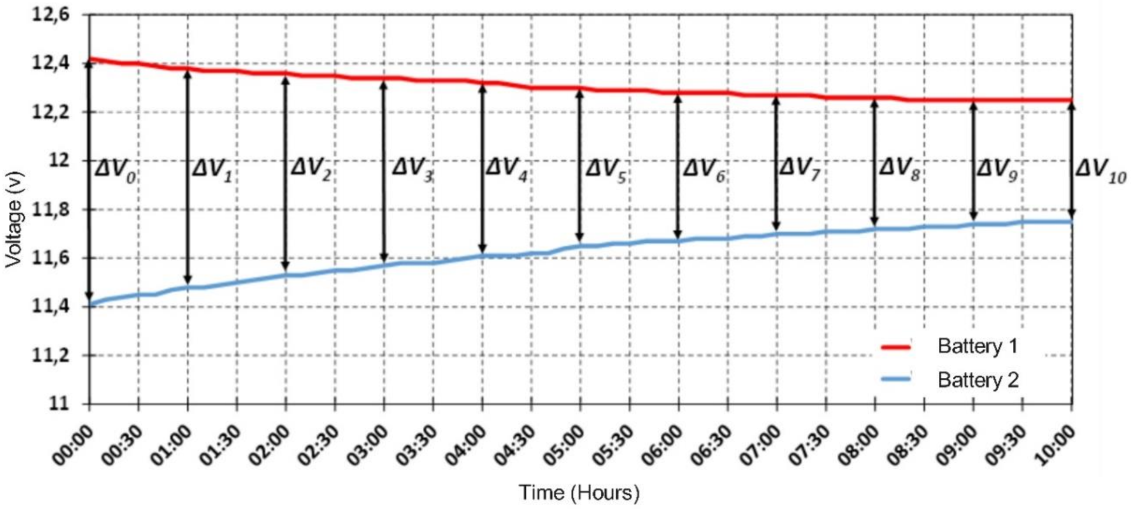

Figure 6 Battery voltages during 10 hours of equalization (fc = 25 kHz).

The implemented BMS system successfully demonstrated autonomous equalization of lead-acid batteries through a switched capacitor balancing topology, validating its viability for mitigating charge mismatches in electric vehicle applications. Initial voltage differences exceeding 1V were reproducibly leveled to within a 0.5V tolerance or lower, which would substantially prevent deteriorated range or lifetime when deployed on commercial EVs. However, further work remains to improve equalization rates and minimize terminal voltage divergence after balance completion. Connecting batteries with opposite polarity could eliminate voltage deficits from leakage currents during equalization downtime. Lower resistance MOSFETs or a revised topology may also maximize charge transfer each shuttle event between the capacitor and batteries. With additional development, switched capacitor battery management systems could provide a compelling integrated solution for electric vehicle performance, safety, and balance. Initially, the two batteries in series had voltages of approximately 12.42 V and 11.41 V, corresponding to a voltage difference of around 1 V. It took approximately 9 hours and 30 minutes for this voltage difference to pass to 500 mV. The equalization time takes a long time to equalize a voltage difference of 500mV. To analyze the behavior of equalization as the difference in voltage (ÿVx) between batteries decreases, the values of ÿVx between batteries along the 10 hours (one ÿV for each hour of equalization) were organized on the graph of Figure 7.

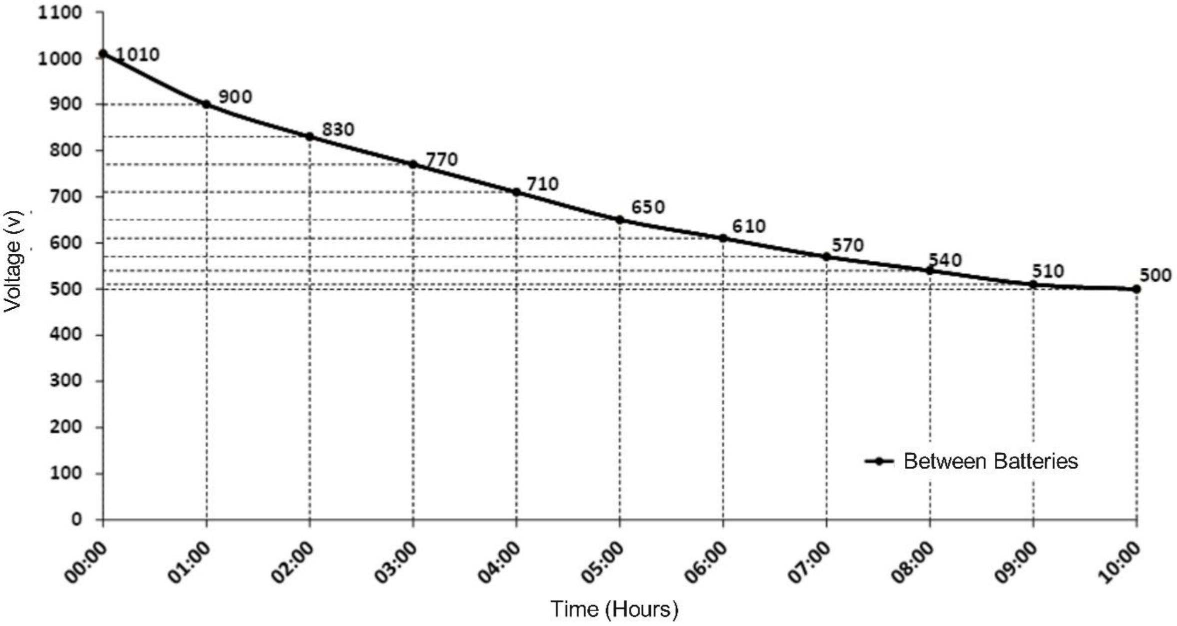

Figure 7 Voltage difference between batteries during 10 hours of equalization.

5 Conclusions

Electric vehicle technology hinges critically on battery pack performance, lifetime, and management to deliver competitive driving range capabilities. Advanced battery management systems can maximize pack usage through cell monitoring and charge balancing techniques. This work centered on conceptualizing and testing an active BMS prototype specialized for charge equalization of lead-acid batteries via a switched capacitor energy transfer approach.

The proposed system leveraged bidirectional switches to alternate connections between individual batteries and a shared capacitor element, enabling shuttling of charge from the most charged battery to the least charged battery until voltage convergence within 50mV. Experiments validated the capability to repeatedly balance initial inter-battery voltage differences exceeding 1V. The consequences of the internal resistances of the switches and capacitors resulted in some voltage deficits after equalization, though supplementary improvements could further minimize these losses. Nonetheless, outcomes firmly demonstrated the effectiveness of intelligently shuffling charges between series batteries to improve pack utilization and lifespan.

Characterization trials elaborated key tradeoffs in equalization duration when altering PWM switch frequencies and capacitor sizes. Frequencies up to 50kHz shortened convergence times compared to 25kHz. However, minimal further gains appeared from increasing to 100kHz. Larger capacitances also modestly quickened balancing at the expense of greater cost and volume. Testing illuminated these and other optimization criteria valuable for tuning system performance.

This work successfully produced and validated an actively controlled battery management system tailored to the demands of electric vehicle applications. The practical demonstration of stabilizing battery charges through coordinated switching cycles offers valuable progress toward solving the critical needs for safeguarding and extending the lifespans of battery packs operating in electric cars, trucks, buses, and other emerging platforms. Findings further supply design principles and models useful for producing the next generation of smart BMS hardware and algorithms. Through additional amelioration and integration, reliable and capable energy management systems will help drive greener transportation powered by high-performance batteries into the future.

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