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Automated Battery Management Systems for Electric Vehicles

Project 2534
July 2026

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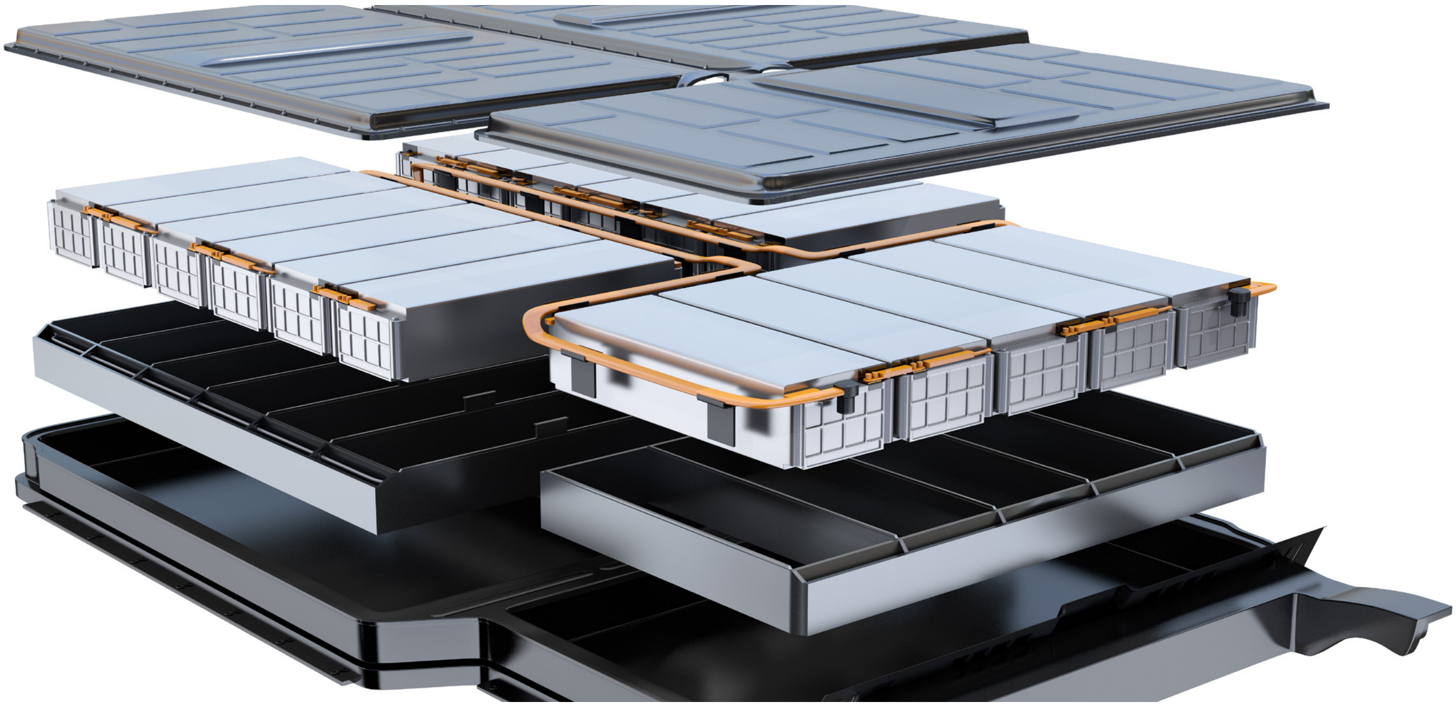

Introduction

Electric vehicles (EVs) are at the heart of the global transition to sustainable transportation. Their performance and safety depend critically on large lithium-ion battery packs—yet these packs face a persistent engineering challenge: cell imbalance. When individual cells charge and discharge at different rates due to manufacturing variability, aging, and uneven heat distribution, the entire pack becomes limited by its weakest cell. Left unaddressed, imbalance accelerates battery degradation, reduces driving range, and can trigger dangerous overheating. This research tackled the question: which active cell-balancing architecture delivers the best combination of speed, efficiency, and safety for next-generation electric vehicles?

Study Methods

The research team conducted a comprehensive, multi-phase study of battery management system (BMS) active cell-balancing technologies. The first phase involved a systematic literature review, classifying and comparing three primary circuit families: switched-capacitor topologies, inductor-based topologies, and DC/DC converter-based architectures—specifically, the dual active bridge (DAB) converter. In the second phase, the team built high-fidelity models of inductor-based and DAB-based balancing circuits in MATLAB/Simulink. These simulations used realistic lithium-ion battery parameters (3.7 V nominal, 5.4 Ah) and tested the systems under dynamic conditions. Two-cell configurations validated basic control logic, while four-cell configurations stress-tested scalability by starting with severe initial imbalances of up to 66 percentage points between cells. The third phase moved to the physical laboratory. Individual Li-ion and NiMH cells underwent a structured battery test protocol: preconditioning cycles, self-discharge screening to identify degraded cells, standard charge-discharge characterization, impedance testing, and rate performance evaluation. Cells were then assembled into balanced and intentionally imbalanced modules to measure how degraded cells affect pack-level behavior before and after balancing control was applied.

The dual active bridge converter achieved energy transfer efficiencies exceeding 90%, outperforming all other tested topologies in speed, safety, and scalability for electric vehicle battery systems.

Findings

The simulation and analysis results produced three major findings: First, switched-capacitor balancing, while inexpensive and simple to implement, proved too slow for high-performance EV packs. Its "bucket-brigade" energy transfer mechanism causes equalization current to decay exponentially as cell voltages converge, making it poorly suited for large battery strings under dynamic driving loads. Second, inductor-based balancing offers a meaningful step forward. Simulations showed a two cell pack reaching full SOC equalization in approximately 18 seconds from a significant initial imbalance. A four-cell pack achieved convergence at roughly 72% SOC within 60 seconds from a 66-point spread. However, sequential energy transfer and magnetic core losses limit its speed as pack size grows. Third, the DAB converter emerged as the superior architecture for demanding applications. Leveraging bidirectional phase-shift modulation, it transferred energy directly between target cells without intermediate stages, achieving efficiencies exceeding 90%. Its built-in galvanic isolation—a critical electrical safety barrier—prevents fault propagation across the battery string. A four-cell DAB simulation achieved equalization within approximately 100–105 seconds from a 30-point initial imbalance. Importantly, the DAB's control logic is software-defined, enabling real time adaptation to changing driving conditions such as rapid acceleration and regenerative braking.

Policy/Practice Recommendations

For EV manufacturers and automotive engineers, this research provides direct design guidance. The DAB converter architecture should be prioritized for high-voltage battery packs—particularly the 400V and 800V systems used in performance and commercial EVs—where safety, balancing speed, and efficiency are non-negotiable. Inductor-based balancing remains a practical choice for mid-range EVs where cost constraints preclude the complexity of a full DAB implementation. Policymakers and transportation agencies should recognize that advanced BMS technologies are not merely a component upgrade—they are a system-level enabler for transportation electrification. Effective cell balancing reduces peak and cumulative grid demand by extending the time between charging sessions and improving charge acceptance during fast charging. This directly eases pressure on electrical grid infrastructure as EV adoption scales. Funding agencies and transit authorities should therefore prioritize BMS innovation in research portfolios, procurement standards, and technology roadmaps for fleet electrification. Finally, the research highlights the readiness of intelligent, data-driven BMS architectures. Combining DAB hardware with Digital Twin modeling and AI-driven predictive control represents the next frontier, enabling real-time degradation tracking and self-optimizing balancing under real-world driving patterns.

About the Authors

Dr. Woonki Na is a Professor of Electrical and Computer Engineering at California State University, Fresno, and a senior IEEE member, with expertise in power electronics, electric drives, and hybrid electric vehicle control systems.

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To Learn More

For more details about the study, download the full report at https://transweb.sjsu.edu/research/2534

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MTI is a University Transportation Center sponsored by the US Department of Transportation, the California Department of Transportation, and public and private grants, including those made available by the Road Repair and Accountability Act of 2017 (SB1). The Institute is part of San José State University's Lucas Graduate School of Business.