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Design of Cell Balancing Mechanism for Real-Time Battery Management System

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Abstract: Electric vehicles are increasingly promoted as environmentally friendly and energy-efficient alternatives to conventional internal combustion engine vehicles, yet their performance and safety depend critically on the behavior of the battery pack. When lithium-ion cells are connected in series and parallel, manufacturing tolerances, temperature variations, and operating conditions lead to unequal charging and discharging, causing cell imbalance, reduced usable capacity, higher losses, and accelerated degradation. This study investigates a real-time Battery Management System (BMS) with integrated cell balancing to mitigate these issues in electric vehicle applications. An equivalent circuit model of a lithium-ion battery is developed in MATLAB/Simulink, using experimentally derived open-circuit voltage, internal resistance, and RC network parameters to capture both steady-state and transient behavior during charge–discharge cycles. The work evaluates passive, active, and hybrid balancing concepts and proposes an adaptive passive balancing strategy that selects different resistor values based on state-of-charge differences among cells. The resulting BMS architecture performs continuous monitoring of voltage, current, temperature, and state of charge, while executing the adaptive balancing algorithm and enforcing CCCV-based charging and protection limits. Simulation results demonstrate improved balancing speed, reduced energy loss, enhanced efficiency, and more uniform cell voltages compared with conventional passive methods, thereby supporting safer operation, longer battery life, and extended driving range in electric vehicles.

Index Terms - Battery Management System; Lithium-ion battery; Cell balancing; State of Charge estimation; Adaptive passive balancing; MATLAB/Simulink modelling.

1. INTRODUCTION

Background: Conventional vehicles based on internal combustion engines have historically dominated road transport because of their mature technology and low initial cost, but they contribute significantly to greenhouse gas emissions and fossil fuel depletion. In India, the road transport sector emits a substantial amount of carbon dioxide annually, reinforcing the need for cleaner mobility solutions. Electric vehicles (EVs) offer reduced local emissions, lower operating costs, and improved energy efficiency, and their adoption is supported by advances in battery technologies and strong policy initiatives, including national targets for large-scale electrification of transport. Modern EVs rely primarily on lithium-ion batteries owing to their high energy density, long cycle life, fast charging capability, and relatively low self-discharge, making them suitable as the main energy storage system. However, lithium-ion batteries present challenges such as cell imbalance, thermal instability, overcharging, deep discharge, and gradual capacity loss, all of which directly affect driving range, safety, and reliability. Reports of battery-related incidents and fire events in electric two-wheelers have underscored the importance of robust Battery Management Systems capable of monitoring, protecting, and balancing EV battery packs under real-world operating conditions. Consequently, there is a strong need to design real-time BMS architectures that integrate accurate state estimation with efficient cell balancing to ensure safe, reliable, and efficient EV operation.

Research Problem: In series-connected lithium-ion battery packs, even small variations in cell capacity, internal resistance, and temperature lead to differences in voltage and state of charge, which progressively grow with repeated charge–discharge cycles. This imbalance causes some cells to reach overcharge or deep discharge earlier than others, increasing thermal stress, reducing available capacity, lowering energy efficiency, and shortening battery lifespan. Conventional passive balancing dissipates surplus energy from high-SoC cells through fixed resistors, which is simple but slow and energetically inefficient, while active balancing techniques can transfer charge between cells but require complex circuitry and higher cost. Furthermore, many existing Battery Management Systems treat monitoring, protection, and balancing as separate functions and do not provide tightly integrated, adaptive, real-time control over voltage, current, temperature, and cell balancing simultaneously. Under dynamic load conditions typical of EV operation, limitations in state-of-charge estimation methods, combined with non-adaptive balancing strategies, result in delayed detection of imbalance, sub-optimal energy utilization, and elevated safety risks. Therefore, the central research problem addressed in this work is the development of a simple yet efficient real-time BMS that can accurately model battery behavior, estimate state of charge, and implement an adaptive balancing mechanism that reduces energy loss and balancing time while improving pack reliability and safety.

Research Objectives: Based on the identified gaps in existing battery management and balancing approaches, the present study formulates specific objectives for designing a real-time BMS suitable for electric vehicle applications. The first objective is to develop an equivalent circuit model of a lithium-ion battery that can capture the nonlinear voltage–SoC relationship, internal resistance variation, and transient response under practical charging and discharging conditions. This involves estimating key parameters such as open-circuit voltage, internal resistance, and RC network elements from experimental charge–discharge data for integration into MATLAB/Simulink models. The second objective is to design and implement a real-time BMS architecture capable of continuous monitoring of cell voltages, pack current, temperature, and state of charge, and of enforcing appropriate protection limits for safe EV operation. The third objective is to develop and evaluate an adaptive passive cell balancing strategy for series-connected lithium-ion battery packs, in which balancing resistors are selected according to state-of-charge differences to minimize energy dissipation, reduce balancing time, and improve voltage uniformity and overall battery performance. Together, these objectives aim to deliver a BMS solution that is accurate, reliable, and computationally efficient, while remaining suitable for practical implementation in electric vehicle battery packs.

2.Literature Review

Cell Balancing Techniques in EV Battery Packs: Existing literature recognizes cell balancing as a core function of Battery Management Systems, distinguishing mainly between passive and active balancing methods for series-connected battery strings. Passive balancing schemes equalize cells by dissipating excess energy from higher-SoC cells as heat through resistive elements, offering simple, low-cost circuits but suffering from high energy loss and long balancing times. In contrast, active balancing topologies employ switched-capacitor networks, multi-winding transformers, or power electronic converters to redistribute charge among cells, thereby improving efficiency and reducing balancing duration at the expense of increased circuit complexity and cost. Several studies have proposed modular cell balancers, multi-switched inductor systems, and fuzzy-logic-based controllers that enhance balancing speed and voltage uniformity, achieving high balancing efficiencies and low voltage deviations. Other works have explored dynamic reconfigurable battery pack architectures and deep reinforcement learning algorithms to further improve energy transfer efficiency, reduce degradation, and extend pack lifespan under varying EV operating conditions. Collectively, these contributions highlight the trade-off between simplicity, cost, and performance, and motivate the search for adaptive balancing strategies that retain passive simplicity while approaching the effectiveness of active methods.

Battery Management Systems and State Estimation: The literature on Battery Management Systems for electric vehicles emphasizes comprehensive monitoring of battery voltage, current, temperature, and state variables to ensure safety, efficiency, and long service life. Numerous reviews and experimental studies document the roles of BMS in protection against overvoltage, undervoltage, overcurrent, and thermal runaway, along with functions such as state-of-charge (SoC) and state-of-health (SoH) estimation, fault detection, and thermal management. A wide range of SoC estimation techniques has been reported, including Coulomb counting, open-circuit voltage methods, equivalent circuit model-based approaches, Kalman filtering variants, and data-driven methods using neural networks or other machine-learning algorithms. Advanced estimation algorithms, such as Extended Kalman Filters and deep learning models, have achieved high accuracy under dynamic load conditions but require detailed battery models and higher computational resources. Related studies have also investigated digital-twin-based BMS architectures, wireless monitoring systems, and AI-based predictive control, all aimed at improving utilization, reducing degradation, and enhancing safety. These works collectively demonstrate that integrating accurate state estimation with robust monitoring and intelligent control is crucial for realizing reliable, efficient, and scalable BMS solutions in modern electric vehicles.

3.METHODOLOGY

3.1Battery Fundamentals and Equivalent Circuit Modelling: The methodological framework begins with a detailed analysis of lithium-ion battery fundamentals and performance characteristics relevant to electric vehicle applications. The study considers typical parameters such as nominal cell voltage, maximum charging voltage, cut-off voltage, capacity, operating temperature range, and energy efficiency, as well as the nonlinear variation of terminal voltage with state of charge. Recognizing that direct electrochemical modeling is complex for real-time systems, an Equivalent Circuit Model (ECM) is adopted to represent the battery electrically using an open-circuit voltage source, an internal resistance, and an RC polarization network. Experimental charge–discharge data are used to estimate open-circuit voltage values at different SoC levels, internal resistance variations, and RC parameters, including time constants, resistor values, and capacitances. These parameters are organized into lookup tables and implemented in MATLAB/Simulink, where the first-order RC model is selected to balance accuracy and computational simplicity. The ECM thereby provides realistic voltage prediction, transient response, and internal loss estimation, forming the basis for subsequent state-of-charge estimation and BMS algorithm development.

3.2Battery Parameter and State of Charge Estimation: Battery parameter estimation is a key methodological step that ensures the equivalent circuit model accurately reflects practical battery behavior. Open-circuit voltage is characterized by measuring stabilized terminal voltages after controlled charging and discharging cycles, revealing a nonlinear relationship with SoC that is relatively flat in mid-range but steep near fully charged and deeply discharged states. Internal resistance is obtained through current pulse tests, where voltage drops under specified currents are used to calculate resistance at different SoC values, showing increased resistance at low and high SoC regions and lower resistance near the mid-SoC range. RC network parameters are similarly identified from pulse discharge experiments by observing transient voltage recovery and deriving time constants and component values that represent polarization effects. For SoC estimation, the methodology compares different techniques and adopts Coulomb counting with correction logic for real-time implementation, given its simplicity and low computational demands. The controller integrates measured current over time, updates SoC, and applies classification ranges to distinguish fully charged, normal, medium, and low battery conditions, thereby supporting range prediction, charging control, and protection against overcharge and deep discharge.

3.3MATLAB/Simulink Implementation and Model Validation: The developed battery model and estimation algorithms are implemented using MATLAB/Simulink and the Simscape Electrical toolbox to simulate battery behavior and evaluate BMS performance. The simulation framework includes subsystems for the equivalent circuit battery model, SoC estimation, voltage and current sensing, temperature monitoring, and control logic. Input datasets consist of charging and discharging current profiles, terminal voltage measurements, temperature data, and derived SoC values. The model is subjected to a variety of operating scenarios, including CCCV charging, controlled discharging, pulse current loading, and dynamic load patterns representative of EV duty cycles. Results such as voltage–SoC characteristics, internal resistance behavior, transient responses, and SoC estimation accuracy are analyzed to verify that the ECM and estimation methods reproduce realistic battery behavior. Performance indicators include maximum and minimum terminal voltages, average internal resistance, SoC estimation accuracy, and stability of simulation responses, confirming that the model is suitable for integration into real-time BMS design and analysis.

4.PRESENT WORK

4.1Design of Real-Time Battery Management System Architecture: The present work designs a real-time Battery Management System specifically tailored for lithium-ion battery packs in electric vehicles. The proposed BMS architecture integrates a series-connected battery pack, voltage sensing circuits for individual cells, a bidirectional current sensor, temperature sensors, a microcontroller unit, cell balancing circuits, protection circuits, and a communication interface. The system continuously measures cell voltages to prevent overcharge and deep discharge, monitors pack current to impose safe charging and discharging limits, and tracks temperature to avoid thermal runaway and excessive heating. The microcontroller processes these inputs to estimate state of charge, execute balancing algorithms, and apply protection actions such as disconnecting charging or load when limits are exceeded. Defined safety thresholds for voltage, current, and temperature guide CCCV charging and discharging control, ensuring that the battery operates within its recommended envelope. This integrated architecture provides real-time monitoring, control, and protection that collectively enhance battery safety, efficiency, and reliability under dynamic EV driving conditions.

4.2Adaptive Passive Cell Balancing Strategy: A central contribution of the present work is the development of an adaptive passive cell balancing strategy for series-connected lithium-ion battery packs. Traditional passive balancing uses fixed resistors to bleed excess energy from higher-SoC cells, which can result in prolonged balancing times and substantial energy dissipation as heat. In the proposed approach, different resistor values are selected dynamically based on the state-of-charge difference (ΔSoC) between each cell and the minimum-SoC cell. Large ΔSoC values trigger low-resistance paths to accelerate energy dissipation, medium differences use intermediate resistor values, and small differences employ higher resistance to fine-tune voltage equalization with reduced losses. The balancing algorithm implemented in the controller follows systematic steps: measuring cell voltages, estimating individual SoC, identifying the minimum-SoC cell, calculating ΔSoC, selecting appropriate resistors, and activating MOSFET switches to initiate balancing until a threshold condition is met. This adaptive strategy reduces balancing time, minimizes unnecessary power dissipation, improves voltage uniformity across cells, and enhances overall battery efficiency, while maintaining the simplicity and low cost of passive balancing hardware.

4.3Simulation Results and Performance Analysis of BMS : The proposed BMS and adaptive balancing scheme are evaluated through MATLAB/Simulink simulations under various charging, discharging, dynamic load, and cell imbalance scenarios. Simulation results demonstrate that the adaptive passive balancing significantly decreases voltage differences between cells, reducing initial imbalance to a much smaller residual spread and thereby improving pack stability. Comparative performance analysis between existing fixed-resistor passive methods and the proposed adaptive strategy shows notable reductions in balancing time and energy loss, as well as higher efficiency and lower average power dissipation during balancing operation. The BMS maintains stable voltage response and accurate SoC tracking during CCCV charging and controlled discharging, confirming that protection mechanisms effectively prevent operation beyond safe limits. Performance metrics such as balancing time, energy loss, power loss, and overall efficiency clearly indicate that the adaptive passive balancing method outperforms conventional approaches without introducing significant additional hardware complexity. These results validate the effectiveness of the designed real-time BMS in delivering improved battery performance, safety, and operational reliability for electric vehicle applications.

5.RESULT

5.1Battery model validation

The lithium-ion cell model was validated with the MATLAB/Simulink simulation software under various charge and discharge profiles, showing the voltage response very close to the practical lithium-ion cell OCV/SoC characteristics, and the internal resistance trends very close to the practical lithium-ion cell operating range.The maximum terminal voltage found for the simulated battery was 4.16 V, the minimum terminal voltage 2.95 V, and the average internal resistance of the modeled cell was about 0.0085 Ω.The Extended Kalman Filter (EKF) was used for state of charge estimation and the error was approximately 97%, while the simulation response was numerically stable for all operating conditions tested, proving the model can be used in real time BMS applications.

5.2 The battery management system's performance.

A developed Battery Management System (BMS) is built in MATLAB/Simulink for real time monitoring and protection under various charging and discharging conditions as well as different dynamic load conditions.The BMS was able to keep the cell voltage, pack current and temperature within a predetermined safety range during charging and discharge of CCCV tests to ensure that there is no over voltage, over current and excessive temperature.The integrated SoC estimation block was able to accurately provide range indication and provide early warning of low SoC conditions to optimize energy use and ensure safe operation of the battery pack in EV duty cycles.

5.3 Cell balancing performance

There were resistors with fixed values to balance the cells passively which took longer balancing time, dissipated more energy and resulted in less balancing efficiency.The energy loss and balancing time could be reduced by changing the value of the resistors in the proposed adaptive passive balancing strategy depending on the SoC difference between the cells and the weakest cell.The results from simulations showed that the adaptive method achieved higher pack voltage uniformity during and after balancing, had higher balancing efficiency, and was superior in the voltage response to the fixed-resistor passive balancing methods.

6.CONCLUSION

This study presented the design and implementation of a real-time Battery Management System for lithium-ion battery packs used in electric vehicles, emphasizing accurate modeling, state-of-charge estimation, and adaptive passive cell balancing. An Equivalent Circuit Model was developed using experimentally derived open-circuit voltage, internal resistance, and RC parameters, and implemented in MATLAB/Simulink to reproduce realistic voltage and transient characteristics under charging and discharging conditions. The BMS architecture combined continuous monitoring of voltage, current, temperature, and SoC with CCCV-based charging and carefully defined protection limits to safeguard the battery against overvoltage, undervoltage, overcurrent, and thermal instability. The adaptive passive balancing strategy dynamically selected resistor values based on SoC differences, thereby reducing balancing time and energy loss while improving cell voltage uniformity and pack efficiency compared with conventional passive methods. Simulation results confirmed stable battery behavior, high SoC estimation accuracy, and enhanced balancing performance, indicating that the proposed system offers a simple, economical, and computationally efficient solution for real-time EV battery monitoring, protection, and balancing applications.

Future Works

1. Extend the proposed Battery Management System to real-time hardware implementation using advanced embedded platforms such as microcontrollers, DSPs, or FPGAs to achieve faster processing and improved control precision.

2. Incorporate advanced state-of-charge estimation techniques, including Extended or Unscented Kalman Filters and artificial intelligence-based algorithms, to enhance accuracy under highly dynamic operating conditions.

3. Combine the adaptive passive balancing scheme with suitable active balancing circuits to further reduce energy dissipation and improve balancing efficiency in large, high-power battery packs.

4. Develop wireless and intelligent Battery Management System architectures with integrated state-of-health estimation, fault diagnosis, and fast-charging control to support scalable, low-complexity, and high-reliability EV battery applications.

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