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An IoT-Enabled Battery Management System with Passive Cell Balancing for Enhanced Battery Safety and Performance

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Abstract — Battery Management System (BMS) are essential for rechargeable battery applications such as electric vehicles, portable electronics, renewable energy storage, and industrial equipment. In multi-cell battery packs, manufacturing variations and operating conditions can cause cell voltage and state-of-change (SoC) imbalance, excessive temperature rise, creating potential safety risks. This paper presents an IoT-enabled BMS that integrates individual cell voltage sensing, passive cell balancing, and temperature monitoring for safe and reliable battery operations.

Keywords— Battery Management System, IoT, Passive Cell Balancing, State of Charge, State of Health, Lithium-Ion Battery, ESP32, Real-Time Monitoring, Thermal Protection, Energy Storage.

I. INTRODUCTION

A Battery Management System (BMS) monitors and protects rechargeable battery packs by continuously tracking individual cell conditions. Since cell voltage and temperature can vary due to charging, discharging, aging, and manufacturing differences, individual voltage and temperature sensing is essential for maintaining safe and rel iable operation.

Passive cell balancing helps reduce voltage differences between cells by dissipating excess energy from higher-voltage cells. Integrating IoT technology enables real-time monitoring, recording, and remote visualization of important battery parameters, improving overall battery safety, reliability, and performance.

The proposed system combines individual cell voltage sensing and passive cell balancing to maintain a safe and balanced battery pack. When a cell reaches a higher voltage during charging, the passive balancing circuit dissipates excess energy through a resistive element, bringing its voltage closer to the other cells. The system also monitors cell temperature and other battery parameters for improved safety and reliability. Through IoT integration, the sensed data can be processed and monitored in real time, enabling cell -level monitoring, effective balancing, thermal supervision, and remote battery management.

Objectives

- Voltage, Current & Temperature Sensing: To monitor the battery's voltage, current, and temperature for safe and reliable operation.
- State of Charge (SoC) Estimation: To accurately estimate the battery's remaining charge.
- Passive Cell Balancing: To maintain uniform charge levels among individual battery cells.
- State of Health (SoH) Estimation: To evaluate the battery's health and degradation over its operating life.

II. LITERATURE REVIEW

- Itagi et al. (2024) reviewed advanced cell-balancing types, algorithms, and optimization frameworks, emphasizing efficient energy transfer, reduced balancing time, and extended battery lifespan.
- R. Ranjith Kumar et al. (2023) reviewed batteries, battery modeling, BMS, thermal management, SOC and SOH, highlighting the importance of monitoring and cell balancing for battery safety, performance, and lifespan.
- Karmakar et al. (2025) reviewed AI , ML, and ANN-based balancing techniques, comparing passive and active methods and their impact on battery temperature, efficiency, and lifespan.
- Khan et al. (2024) presented passive and active balancing circuits along with DC-DC converter-based balancing methods, evaluating their efficiency, balancing speed, and suitability for EV battery packs.

- Singh et al. (2024) showed how AI algorithms improve SoC estimation, fault detection, and BMS performance, and discussed intelligent balancing methods for safer, more reliable EV batteries.
- Itagi et al. (2024) reviewed passive and active balancing techniques, their working principles, challenges, applications, and future research directions for the transportation sector.
- Omariba et al. (201 9) compared passive and active balancing methods and highlighted their importance in improving battery efficiency, lifespan, and safety.
- Safari et al. (2025) covered traditional and AI-based cell-balancing methods, digital twin technology, and emerging BMS trends, showing how intelligent algorithms improve battery health and performance.
- Nassim et al. (2021) examined SoC estimation, cell imbalance, and balancing strategies in lithium-ion battery packs, highlighting how accurate SoC estimation and effective balancing improve reliability and lifespan.
- Pillai et al. (2023) focused on open-circuit-voltage (OCV) modeling for accurate SoC estimation, highlighting how OCV-based methods improve battery monitoring and BMS reliability.

III. METHODOLOGY

The proposed IoT-based BMS is devel oped in five stages: (1) system architecture design, defining the sensing, processing, and communication layers; (2) hardware setup, interfacing the sensors and protection circuits with the microcontroller; (3) firmware development for data acquisition and SoC/SoH estimation logic; (4) IoT integration for real-time data collection and monitoring; and (5) testing and validation of accuracy and fault response through repeated charging and discharging cycles.

The ESP32 microcontroller continuously reads each of the four cell voltages through precision-resistor voltage dividers, the pack current through an ACS71 2 sensor, and the pack temperature through a DHT1 1 sensor. The firmware compares all four cell voltages to identify the highest- and lowest-voltage cells. If a cell's voltage exceeds the others by a set threshold (approximately 20-30 mV), it is flagged for balancing, and the ESP32 turns on the IRLZ44N MOSFET connected to that cell's bleed resistor. The bleed resistor dissipates the excess energy of the higher-vol tage cell as heat, gradually bringing its voltage in line with the rest of the pack. Once all cell voltages fall within the safe band, the ESP32 switches the MOSFET off, completing the balancing cycle. In parallel, SoC and SoH are estimated, and a relay disconnects charging or load in the event of over-temperature or overvoltage conditions. All readings - individual cell voltages, current, temperature, SoC, and SoH - are transmitted over Wi-Fi to an IoT dashboard for real-time battery status and safety monitoring.

IV. EQUIPMENT DETAILS

- ESP32 Dev Module: Main controller with built-in Wi-Fi/Bluetooth that reads sensor data, runs the balancing logi c, and sends readings to the IoT dashboard.
- 1 8650 Li-ion Cells (4S Pack): Rechargeable lithium-ion cells (3.7 V nominal, 1 200 mAh each) that form the battery pack under management.
- ACS71 2 Current Sensor: Measures the current flowing into and out of the battery pack.
- DHT1 1 Temperature Sensor: Measures the pack temperature for thermal protection and monitori ng.
- Precision Resistors (Voltage Divider): Scale down each cell 's voltage to a safe level for accurate ESP32 ADC measurement.
- IRLZ44N N-Channel MOSFET: Acts as an el ectronic switch that turns the bleed resistor on or off during passive cell balancing.
- Bleed Resistors: Dissipate the excess energy of a higher-voltage cell as heat, bringi ng its voltage down to match the others.
- Gate Resistors: Limit the gate current to the MOSFET and reduce switching noise and oscillation.
- Pull-down Resistors: Hold the voltage-sensing lines at a defined low state when no signal is applied, ensuring stable readings.
- Capacitors: Filter high-frequency noise (ceramic) near the sensors and smooth the voltage supply (electrolytic).
- Relay Module: Disconnects the battery pack or load during overvoltage or fault conditions, providing electrical protection.
- Buck Converter (LM2596): Steps down the pack voltage to a regulated 5 V supply for the ESP32 and other electronics.
- 1 6× 2 LCD with I²C Module: Displays live cell voltages, current, temperature, SoC, and SoH readings.
- 4S Li-ion Battery Pack Charger: Safely charges the four-cell series pack using proper CC/CV charging at 1 6.8 V.
- DC Geared Motor: Represents an electrical load dri ven by the battery pack for testing and validation.

V. RESULTS

At the present stage of development, the individual cell voltages of all four cells are being successfully measured and displayed, pack current is monitored in real time using the integrated ACS71 2 sensor, and pack temperature sensing has been implemented and is displayed alongside the other readings. State of Charge is currently calculated and displayed based on the sensed parameters. The major hardware components - the ESP32, voltage-divider circuits, ACS71 2, DHT1 1 , LM2596 buck converter, and relay module - have been integrated into a working hardware prototype, confirming that the sensing and monitoring subsystem operates as intended.

VI. CONCLUSION

This work presents an IoT-enabled Battery Management System that combines individual cell-voltage sensing, passive cell balancing, and temperature monitoring to improve the safety and reliability of multi-cell lithium-ion battery packs. By estimating State of Charge and State of Health from real-time voltage, current, and temperature data and transmitting these parameters to a remote IoT dashboard, the system gives users continuous visibility into battery condition while automatically correcting cell-to-cell voltage imbalance. The proposed BMS offers a scalable and cost-effective approach that can improve battery safety, lifespan, and performance across EVs, portable electronics, and energy-storage applications.

Future Scope

- Implementation and display of State of Health (SoH) estimation for the battery pack.
- Completion of the MOSFET and bleed-resistor-based passive cell balancing system.
- Implementation of the balancing algorithm to identify the highest-voltage cell and activate balancing once the voltage difference exceeds the set threshold.
- Validation testing to confirm that cell voltages are brought within the desired voltage difference.
- Final integration of monitoring, SoC/SoH estimation, passive balancing, and protection into a complete BMS, followed by charging/discharging tests to validate overall performance.

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