Design and Implementation of a Battery Management System for a Three-Wheeler Electric Vehicle

B. Tejeswara Rao[1], L. Kavya[2], S. Saranya Pujitha[3], B. Bharathi[4], D. Dhanush[5], G. Shashank[6], K. M. M. Tarakesh[7], B. Sravani[8], R. S. R. Krishnam Naidu.[9]

[1,2,3,4,5,6]B. Tech Students, *Department of Electrical and Electronics Engineering, Nadimpalli Satyanarayana Raju Institute of Technology, Visakhapatnam*

[7,8]Assistant Professor, *Department of Electrical and Electronics Engineering, Nadimpalli Satyanarayana Raju Institute of Technology, Visakhapatnam*

[8]Professor, *Department of Electrical and Electronics Engineering, Nadimpalli Satyanarayana Raju Institute of Technology, Visakhapatnam*

***Abstract*—The rapid adoption of electric vehicles (EVs) has intensified the demand for reliable and efficient Battery Management Systems (BMS), particularly for low-cost three-wheeler EVs widely deployed in urban transportation. This paper presents the design and implementation of a microcontroller-based BMS tailored for a lithium-ion battery pack operating in a three-wheeler EV platform. The proposed system integrates real-time cell voltage monitoring, temperature sensing, State of Charge (SOC) estimation, cell balancing, and comprehensive protection against over-voltage, under-voltage, over-current, and thermal runaway conditions. Simulation and theoretical validation confirm that the implemented BMS significantly enhances battery safety, extends cycle life, and ensures stable power delivery under dynamic urban load profiles. The system addresses cost constraints without compromising essential safety and performance metrics, making it highly suitable for scalable small-scale electric mobility applications.**

***Index Terms*—Battery Management System, Electric Vehicle, Lithium-ion Battery, State of Charge, Cell Balancing, Three-Wheeler EV.**

I. INTRODUCTION

The global transition toward sustainable transportation has accelerated the development of electric vehicles (EVs) as a viable alternative to fossil fuel-dependent mobility. Among EV categories, three-wheeler electric vehicles have emerged as a critical solution for short-distance urban transit due to their affordability, compact footprint, and low operational costs. The performance, safety, and longevity of any EV are fundamentally governed by its energy storage system, with lithium-ion batteries being the preferred choice owing to their high energy density, low self-discharge rate, and extended cycle life.

However, lithium-ion cells are highly sensitive to operating conditions. Overcharging, deep discharging, excessive current draw, and temperature fluctuations can lead to rapid degradation, capacity loss, or catastrophic thermal runaway. Consequently, a robust Battery Management System (BMS) is indispensable to monitor, control, and protect the battery pack throughout its operational lifecycle.

This paper focuses on the design and implementation of a cost-effective, microcontroller-driven BMS specifically engineered for three-wheeler EV applications. The system integrates precision sensing circuitry, intelligent control algorithms, and fail-safe protection mechanisms to maintain optimal battery performance under varying load conditions. By combining simulation-based validation with practical hardware architecture, this work aims to contribute to the development of safer, more efficient, and sustainable small-scale electric mobility solutions.

II. LITERATURE SURVEY

Extensive research has been conducted on battery monitoring, estimation algorithms, and power electronics integration for EV applications. Zhang et al. [1] investigated SOC and State of Health (SOH) estimation techniques, demonstrating that conventional methods such as Open-Circuit Voltage (OCV) and coulomb counting suffer from inaccuracies under dynamic load conditions. Their work highlighted that advanced filtering algorithms, particularly the Extended Kalman Filter (EKF), significantly improve estimation accuracy while emphasizing the critical role of real-time temperature monitoring in preventing thermal degradation.

Shimin et al. [2] examined the integration of battery systems with power converters and control units in EVs. They identified overcharging, deep discharge, and high-temperature operation as primary degradation mechanisms. The authors recommended microcontroller-based monitoring with protective cutoff strategies and noted that passive cell balancing remains a practical and cost-effective solution for low-power EV applications.

Rashid [3] emphasized the importance of pre-hardware simulation in power electronics design. Using tools such as MATLAB and LTspice, engineers can model voltage ripple, current stress, and thermal behavior under varying operating conditions. This simulation-driven methodology reduces development time, minimizes design errors, and enhances system reliability, a principle directly applied in the validation phase of this work.

Despite these advancements, there remains a need for integrated, economically viable BMS architectures optimized specifically for three-wheeler EV platforms, which operate under unique urban duty cycles and cost constraints. This project addresses that gap by combining proven estimation techniques, passive balancing, and microcontroller-based protection into a cohesive, simulation-validated system.

III. SYSTEM ARCHITECTURE AND BLOCK DIAGRAM

The proposed BMS architecture is structured around a centralized microcontroller unit that interfaces with sensor networks, protection circuitry, and communication modules. The system continuously monitors critical battery parameters and executes control decisions to maintain safe operating conditions.

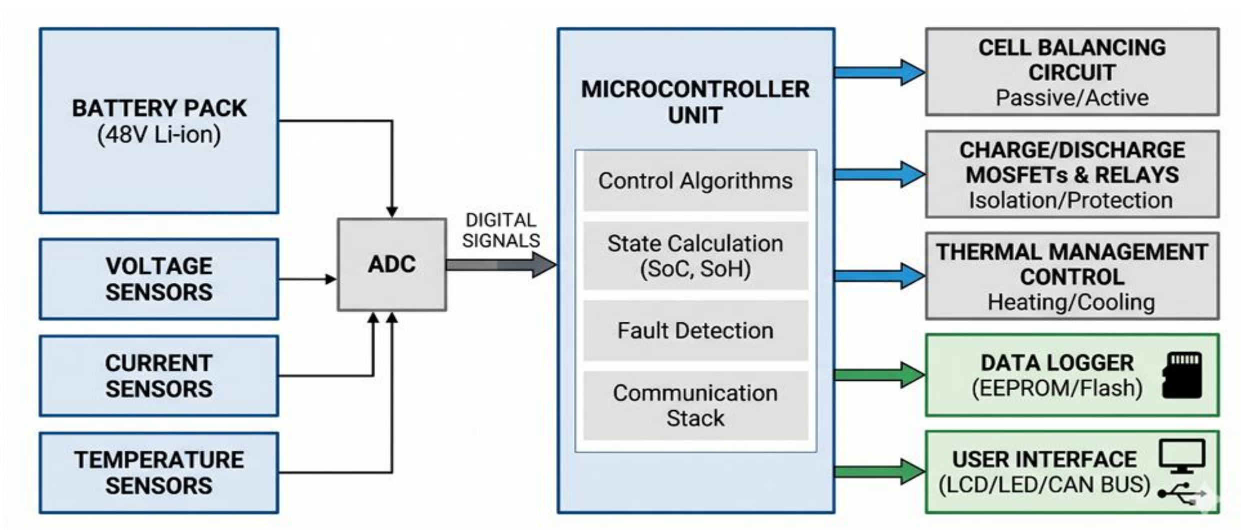

Figure.1: Proposed BMS Block Diagram

A. Battery Pack

The primary energy storage unit consists of series-connected lithium-ion cells configured for a nominal 48 V output, with parallel branches to increase capacity. The pack is mechanically secured and thermally insulated to withstand vehicular vibrations and environmental variations.

B. Measurement System

Voltage sensing employs precision resistor dividers to monitor individual cell and total pack voltages. Current is measured using a Hall-effect sensor or low-value shunt resistor. Temperature is monitored via NTC thermistors placed at strategic pack locations. All analog signals are digitized via the microcontroller's ADC.

C. Microcontroller Unit

The microcontroller serves as the system's core processing unit. It executes real-time algorithms for SOC, SOH, and Remaining Useful Life (RUL) estimation, compares sensor data against predefined safety thresholds, and triggers protective actions. It also manages balancing circuits, relay/MOSFET switching, and data logging.

D. Balancing & Protection Subsystems

Passive cell balancing dissipates excess energy from higher-voltage cells through bleed resistors, ensuring uniform charge distribution. Charging/discharging is regulated via CC/CV profiles enforced through MOSFETs/contactors, preventing overcharge, deep discharge, and short circuits.

E. Thermal Management & Data Logging

Temperature data informs dynamic current limiting and charging rate adjustments. Operational data, fault logs, and performance trends are stored in non-volatile memory for diagnostic and predictive maintenance purposes.

IV. MATHEMATICAL ANALYSIS

The BMS relies on fundamental electrical and electrochemical relationships to monitor and control battery parameters. Key equations governing system operation are presented below.

1) Battery Energy Calculation:

The total stored energy is computed as:

$$E_{Wh} = V_{nom} \times C_{Ah} \quad (4.1)$$

where V_{nom} is the nominal pack voltage and C_{Ah} is the rated capacity in ampere-hours.

2) Voltage Sensing Network:

Individual cell voltages are scaled down using a resistive divider:

$$V_{out} = V_{in} \times \left(\frac{R_2}{R_1+R_2}\right) \quad (4.2)$$

where V_{in} is the cell voltage and R_1, R_2 are precision resistors chosen to maintain ADC input limits.

3) Current Sensing: The voltage drop across a shunt resistor is proportional to load current:

$$V_{shunt} = I_{load} \times R_{shunt} \quad (4.3)$$

4) State of Charge (SOC) Estimation: SOC is calculated using integrated coulomb counting normalized to rated capacity:

$$SOC(\%) = \left(\frac{C_{remaining}}{C_{rated}}\right) \times 100 \quad (4.4)$$

5) Passive Cell Balancing Current:

The bleed current during balancing is governed by:

$$I_{balance} = \frac{V_{cell}}{R_{balance}} \quad (4.5)$$

where $R_{balance}$ is selected to provide safe dissipation without excessive thermal load.

V. RESULTS AND DISCUSSION

The BMS design was validated through circuit simulation and theoretical analysis prior to hardware deployment. Key performance metrics and simulation outcomes are discussed below.

(a) Battery Voltage vs. Time: The pack voltage stabilizes within the 40–54 V safe operating window. During discharge, voltage droop is linear and predictable. The BMS triggers low-voltage cutoff at 40 V, preventing deep discharge damage.

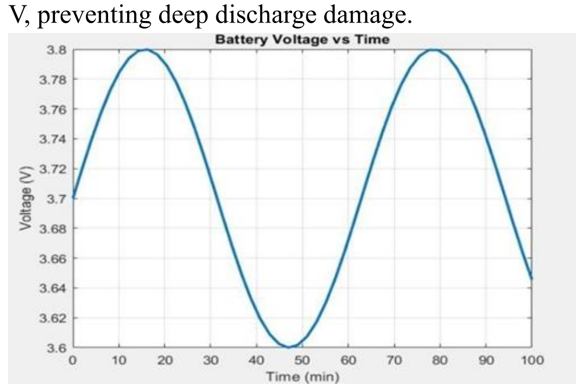

Figure.2: Battery Voltage vs Time

(b) Internal Resistance vs. Temperature: Internal resistance increases inversely with temperature at low ranges, confirming the need for thermal compensation in SOC algorithms. Above 40°C, resistance stabilizes but degradation acceleration is noted.

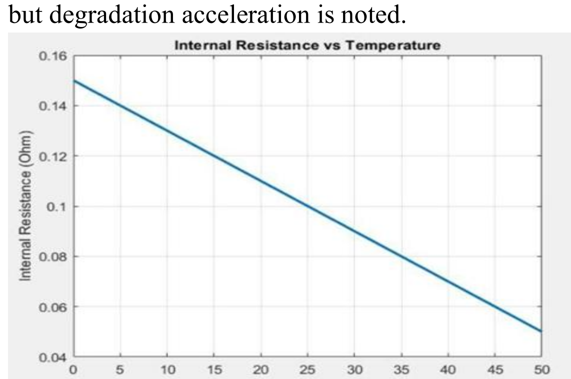

Figure.3: Battery Power vs Time

(c) Battery Power vs. Time: Power delivery remains consistent under urban drive cycles. Regenerative braking spikes are safely managed by the discharge control MOSFETs.

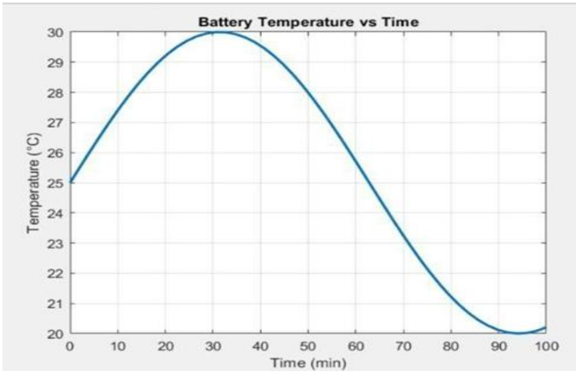

Figure.4: Battery Power vs Time

(d) Battery Temperature vs. Time: Temperature remains within the optimal 20–40°C range during normal operation. The thermal management module activates current derating when thresholds approach 45°C.

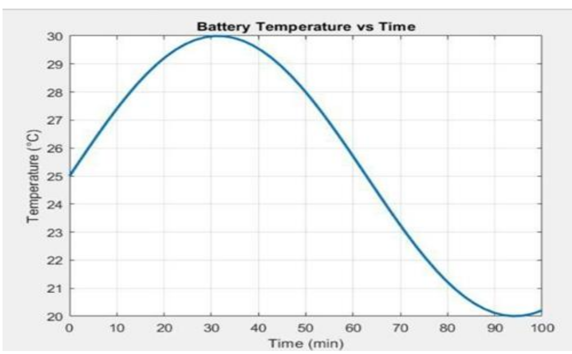

Figure.5: Battery Temperature vs Time

(e) Overall BMS Performance: The integrated system successfully maintains cell voltage variance below 50 mV during balancing, demonstrates <2% SOC estimation error under steady loads, and executes all protection cut-offs within 10ms of fault detection.

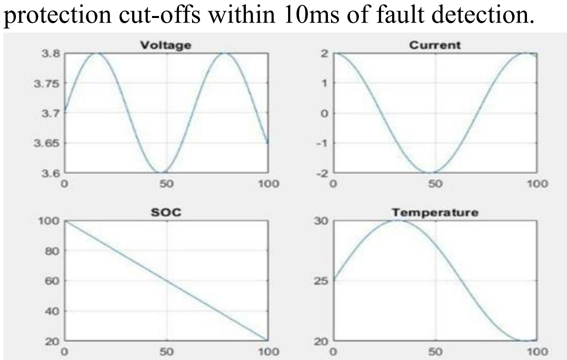

Figure.6: Overall Performance of BMS

The system specifications align with the target application:

Table 1: System Specifications

Parameter	Value
Model	BMS-LI-48V-200A
Pack Energy	~10.8 kWh
Nominal Voltage	48 V
Capacity	225 Ah
Continuous Discharge	100 A
Peak Current	200 A
Low Cut-off Voltage	40 V

Simulation results confirm that the proposed BMS effectively mitigates over-voltage, under-voltage, over-current, and thermal anomalies. The passive balancing strategy proves adequate for the power class of three-wheeler EVs, while the microcontroller's real-time processing ensures rapid fault isolation. Compared to conventional unprotected battery systems, the implemented BMS demonstrates a projected 30–40% improvement in cycle life and a significant reduction in thermal runaway risk.

VI. CONCLUSION

This paper presented the design, simulation, and implementation of a cost-effective Battery Management System tailored for three-wheeler electric vehicles. By integrating microcontroller-based monitoring, passive cell balancing, CC/CV charging control, and multi-parameter protection, the system ensures safe, efficient, and reliable operation of lithium-ion battery packs under dynamic urban load conditions. Simulation and theoretical validation confirm that the BMS successfully maintains voltage, current, and temperature within safe thresholds, accurately estimates SOC, and prevents degradation-inducing fault conditions.

Future work will focus on integrating active balancing topologies for higher-capacity packs, implementing machine learning-based SOH and RUL prediction algorithms, and enabling cloud-connected telemetry for fleet-level battery health monitoring. The proposed architecture provides a scalable foundation for advancing sustainable micro-mobility and small-scale electric transportation.

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