IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 17, April 2026
Impact Factor: 8.2

Design and Implementation of Smart Cell Balancing for EV Batteries

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Abstract: *The rapid growth of electric vehicles (EVs) has increased the demand for efficient, safe, and long- lasting battery management systems. One of the major challenges in EV battery packs is cell imbalance, which occurs due to variations in cell voltage, temperature, internal resistance, aging, and charging/discharging conditions. Cell imbalance can reduce battery efficiency, decrease usable capacity, shorten battery life, and create safety risks such as overheating or thermal runaway. To address these issues, this project presents a Smart Cell Balancing System for EV Batteries that improves the overall performance and reliability of lithium-ion battery packs. The proposed system continuously monitors the voltage, temperature, and state of charge (SOC) of individual battery cells using sensors and a microcontroller-based control unit. Based on real-time data, the system identifies weak or overcharged cells and performs balancing automatically to ensure uniform energy distribution among all cells in the battery pack.*

Keywords: *Electric Vehicles (EVs), Cell Balancing, Battery Management System (BMS), Lithium-ion Battery, State of Charge (SOC), Smart Monitoring, Active Balancing, Passive Balancing, Battery Safety, IoT-based Battery Monitoring*

I. INTRODUCTION

Electric vehicles (EVs) are becoming increasingly important as the world shifts toward cleaner and more sustainable transportation systems [1][2]. The battery pack is the most critical component of an EV because it directly affects driving range, charging performance, safety, and overall vehicle efficiency [3][4]. Most EV battery packs are made up of many lithium-ion cells connected together, and for the battery to perform properly, all these cells must operate in a balanced manner [5][6].

However, due to differences in manufacturing, temperature, internal resistance, aging, and charging/discharging conditions, battery cells often become unbalanced over time [7][8]. This condition, known as cell imbalance, causes some cells to charge or discharge faster than others, reducing the effective battery capacity and increasing the risk of overheating or damage [9][10]. In such cases, the performance of the entire battery pack is limited by the weakest cell [11][12].

To solve this problem, a Battery Management System (BMS) is used to monitor important battery parameters such as voltage, temperature, and state of charge [13][14]. One of the most important functions of the BMS is cell balancing, which ensures that all cells maintain nearly equal charge levels [15][16]. Smart cell balancing systems improve this process by using sensors, control algorithms, and real-time monitoring to identify imbalance and balance the cells more efficiently [17][18].

This project focuses on the development of a Smart Cell Balancing System for EV Batteries to improve battery performance, safety, energy utilization, and lifespan. By maintaining uniform cell conditions, the proposed system can enhance the reliability and efficiency of EV battery packs and support the future growth of electric mobility [19][20].

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II. PROBLEM STATEMENT

In electric vehicle (EV) battery packs, individual lithium-ion cells often develop voltage and charge imbalance due to differences in manufacturing, temperature, aging, and charging/discharging conditions. This imbalance reduces battery efficiency, limits usable capacity, shortens battery life, and increases safety risks such as overheating and cell damage. Therefore, there is a need to develop a smart cell balancing system that can continuously monitor battery cells and maintain uniform charge distribution to improve the performance, safety, and lifespan of EV batteries.

III. OBJECTIVES

• To design a smart cell balancing system for electric vehicle battery packs.
• To monitor individual battery cell parameters such as voltage, temperature, and state of charge.
• To detect cell imbalance conditions during charging and discharging operations.
• To balance the cells automatically for uniform energy distribution and improved battery performance.
• To enhance the safety, efficiency, and lifespan of EV batteries through intelligent battery management.

Comparison of Traditional vs Active Cell Balancing

Parameter	Traditional Balancing (Passive)	Active Balancing
Working Principle	Excess energy from higher- voltage cells is dissipated as heat using resistors	Energy is transferred from higher-charged cells to lower-charged cells
Energy Efficiency	Low (energy is wasted as heat)	High (energy is reused within the battery pack)
Heat Generation	High heat generation	Very low heat generation
Circuit Complexity	Simple design (resistors, switches)	Complex (uses inductors, capacitors, MOSFETs)
Cost	Low cost	Higher cost due to advanced components
Balancing Speed	Slow	Faster balancing process
Battery Life Impact	Reduces battery life due to energy loss and heat	Improves battery life by efficient energy redistribution
Suitable Applications	Small battery packs, low-cost systems	Large battery packs, electric vehicles (EVs)
Control Requirement	Simple control	Requiresintelligent control (microcontroller-based)
Efficiency in EVs	Less suitable	Highly suitable for EV applications

Traditional balancing is simple and low-cost but wastes energy as heat, making it less efficient and unsuitable for large EV battery systems. In contrast, active balancing is more advanced and efficient as it redistributes energy between cells, improving battery performance, safety, and lifespan, which is why it is widely used in modern EV battery management systems.

IV. LITERATURE SURVEY

Ritika Sharma et al. (2026), in the paper "Smart Cell Balancing System for Electric Vehicle Battery Packs," proposed an intelligent battery balancing system designed to improve the efficiency and lifespan of lithium-ion battery packs used in electric vehicles. The system continuously monitors the voltage and temperature of each cell and detects imbalance conditions in real time. A microcontroller-based control unit is used to identify weak and overcharged cells and initiate balancing operations automatically. The proposed model improves battery safety, energy utilization, and

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charging consistency. The system also helps in reducing the chances of overheating and uneven degradation among battery cells.

Aman Verma et al. (2025), in the paper “Battery Management and Cell Balancing Techniques for Electric Vehicles,” presented a battery management framework that focuses on maintaining uniform charge levels across all cells in an EV battery pack.

Priya Deshmukh et al. (2025), in the paper “IoT-Based Battery Health Monitoring and Smart Balancing for EV Applications,” proposed an IoT-enabled battery monitoring system integrated with smart cell balancing. The system collects real-time battery parameters such as voltage, current, temperature, and state of charge from each battery cell. These values are transmitted to a cloud platform for remote monitoring and analysis.

Comparison Table

Author & Year	Technology Used	Key Feature	Limitation
Ritika Sharma et al. (2026)	Microcontrolle r, Voltage & Temperature Sensors	Real-time smart cell balancing	Limited to small battery packs
Aman Verma et al. (2025)	Battery Management System, Active & Passive Balancing	Compariso n of balancing methods	High implementatio n complexity
Priya Deshmuk h et al. (2025)	IoT, Cloud Monitoring, Sensors	Remote battery health monitoring	Internet dependency

IV. WORKING OF SYSTEM

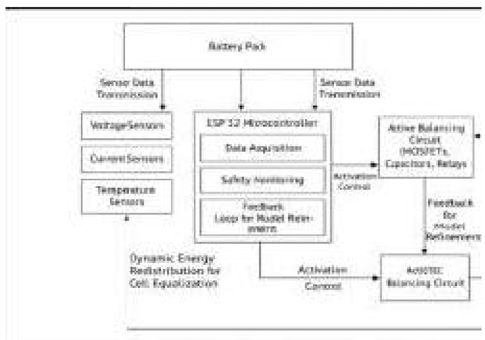

Fig 1: Design of the system

1. Battery Pack Monitoring

The battery pack consists of multiple cells whose voltage, current, and temperature are continuously monitored.

2. Sensor Data Collection

Voltage sensors, current sensors, and temperature sensors collect real-time battery parameters from the battery pack.

3. Data Transmission to ESP32

The collected sensor data is transmitted to the ESP32 microcontroller for processing and decision-making.

4. Data Acquisition and Analysis

The ESP32 performs data acquisition and analyzes the received battery parameters to detect imbalance or abnormal conditions.

5. Safety Monitoring

The system continuously checks for unsafe conditions such as overvoltage, overheating, and overcurrent to protect the battery pack.

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6. Feedback-Based Control
A feedback mechanism is used for model refinement, helping the system improve balancing accuracy and response over time.
7. Activation of Balancing Circuit
When cell imbalance is detected, the ESP32 sends an activation control signal to the balancing circuits.
8. Active Balancing Operation
The active balancing circuit (using MOSFETs, capacitors, or relays) transfers energy from higher- charged cells to lower-charged cells.
9. Assisted Balancing Support
The assistive balancing circuit helps in maintaining uniform cell voltage and supports effective energy redistribution.
10. Dynamic Cell Equalization
The system performs dynamic energy redistribution to ensure all battery cells remain balanced and efficient.
11. Data Logging and Analysis
Battery performance data is sent to a laptop for monitoring, logging, and further analysis.
12. Improved Battery Performance
As a result, the system improves battery safety, efficiency, lifespan, and overall EV performance.

Performance Analysis
Assume:
- Cell A voltage = 4.2 V (high)
- Cell B voltage = 3.8 V (low)
- Capacity = 2 Ah

1. Passive Balancing (Traditional) Excess energy is dissipated as heat. Voltage difference = $4.2 - 3.8 = 0.4\ V$ Energy wasted:

$$E = V \times I \times t$$

Assume balancing current = 1 A, time = 1 hour

$$= 4.2 \times 1 \times 1 = 4.2\ Wh$$

This energy is lost as heat

2. Active Balancing
Energy is transferred instead of wasted. Energy transferred:

$$E = V \times I \times t$$

$$E = 4.2 \times 1 \times 1 = 4.2\ Wh$$

This energy is used to charge the lower cell (Cell B)
Final Result
- Passive Balancing → 4.2 Wh wasted
- Active Balancing → 4.2 Wh reused

Active balancing improves efficiency by saving energy, while passive balancing wastes energy as heat.

V. SYSTEM DESIGN

1. Overview of System
The proposed Smart Cell Balancing System for EV Batteries is designed to monitor and maintain equal charge distribution among all battery cells in an electric vehicle battery pack. The system uses sensors, an ESP32 microcontroller, balancing circuits, and a laptop/cloud interface to detect imbalance and perform intelligent energy redistribution for improved battery safety and performance.

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2. Components with Description

1. Battery Pack

The battery pack consists of multiple lithium-ion cells connected in series and/or parallel to provide the required voltage and capacity. It acts as the main energy source of the EV and is continuously monitored for cell imbalance.

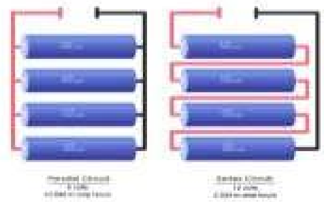

Fig.2.Battery Pack

2. Voltage Sensors

Voltage sensors are used to measure the voltage of each individual battery cell. They help in identifying overcharged, undercharged, or unbalanced cells for proper balancing action.

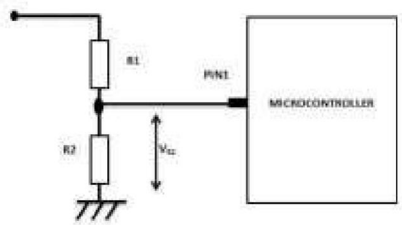

Fig.3.Voltage Sensors

3. Current Sensors

Current sensors monitor the charging and discharging current flowing through the battery pack. This helps in analyzing energy flow and ensuring the battery operates within safe current limits.

Fig.4.Current Sensors

4. Temperature Sensors

Temperature sensors detect the thermal condition of battery cells during operation. They are essential for preventing overheating and ensuring battery safety during charging, discharging, and balancing.

DOI: 10.48175/568

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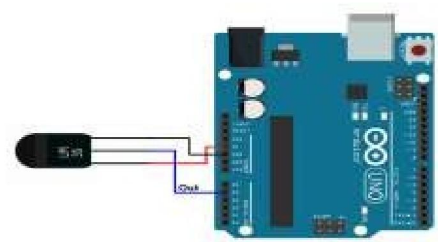

Fig.5.Temperature Sensors

5. ESP32 Microcontroller

The ESP32 acts as the central controller of the system, collecting data from all sensors and processing it in real time. It decides when balancing is required and sends control signals to the balancing circuits.

Fig.6. ESP 32

6. Active Balancing Circuit

The active balancing circuit uses components such as MOSFETs, capacitors, or relays to transfer energy from higher-charged cells to lower-charged cells. This improves energy efficiency and reduces unnecessary power loss.

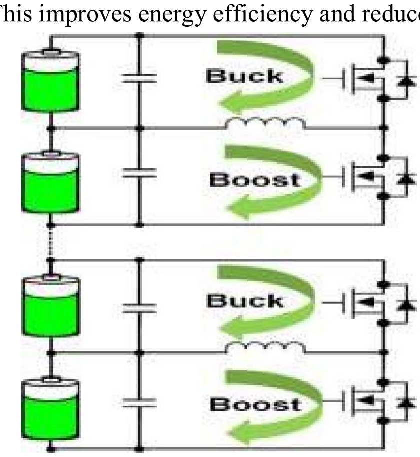

Fig.7. Active Balancing Circuit

The power supply unit provides the required regulated voltage to the ESP32 and other electronic components. It ensures stable and reliable operation of the monitoring and balancing system.

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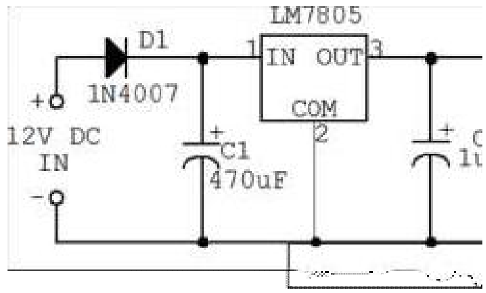

Fig.8. Power Supply

Voltage-Based Cell Balancing Algorithm

The Voltage-Based Cell Balancing Algorithm works by continuously monitoring the voltage of each battery cell. The algorithm first collects voltage values from all cells through sensors and stores them for comparison. It then identifies the maximum and minimum voltage among the cells and calculates the voltage difference.

If the difference exceeds a predefined threshold value, the system detects that the battery pack is unbalanced. The algorithm then selects the cell with the highest voltage and activates the balancing circuit. In active balancing, energy is transferred from the higher-voltage cell to the lower-voltage cell until the voltages become nearly equal.

This process runs continuously in a loop, ensuring that all cells maintain uniform voltage levels. As a result, the algorithm improves battery efficiency, prevents overcharging or deep discharging, and enhances the overall lifespan of the battery pack.

VI. RESULTS

The developed Smart Cell Balancing System for EV Batteries successfully demonstrated the ability to monitor and balance individual battery cells in real time. The system continuously measured important parameters such as cell voltage, current, and temperature using the connected sensors and processed the data through the ESP32 microcontroller. During testing, the system was able to identify voltage differences among cells and activate the balancing circuit whenever imbalance was detected. This helped in maintaining more uniform charge levels across the battery pack and improved the overall stability of the system.

Overall, the proposed system improved battery efficiency, cell equalization, operational safety, and expected battery lifespan. The results indicate that smart cell balancing can play an important role in enhancing the performance and reliability of EV battery packs. The project proves that the use of intelligent monitoring and balancing techniques can support the development of safer, more efficient, and longer-lasting electric vehicle energy storage systems.

VIII. FUTURE SCOPE

In the future, the Smart Cell Balancing System for EV Batteries can be improved by integrating more advanced balancing techniques and intelligent control algorithms. The system can be upgraded with machine learning or AI-based prediction models to detect imbalance conditions earlier and perform balancing more efficiently. Additional features such as State of Health (SOH) estimation, fault diagnosis, and predictive maintenance can also be included to make the battery management system more reliable and smarter.

The project can also be expanded by adding IoT and cloud- based monitoring for real-time remote access to battery data through mobile or web applications. This would allow users and manufacturers to track battery performance, receive alerts, and analyze long-term battery behavior more effectively. In large-scale EV applications, the system can be further developed for high-capacity battery packs, making it suitable for electric cars, buses, and energy storage systems.

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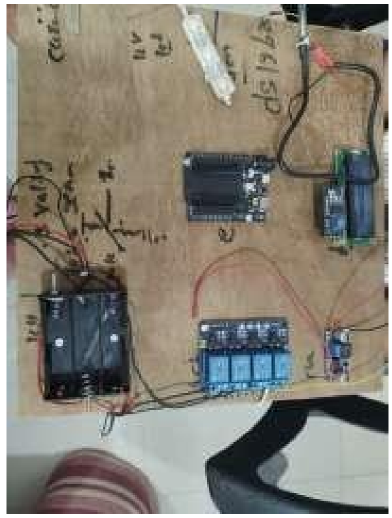

Fig 10: Prototype model

VII. CONCLUSION

The Smart Cell Balancing System for EV Batteries was successfully designed to improve the performance, safety, and lifespan of electric vehicle battery packs. By continuously monitoring important battery parameters such as voltage, current, and temperature, the system was able to detect cell imbalance and perform efficient balancing in real time. The use of the ESP32 microcontroller and balancing circuits helped maintain uniform charge distribution among cells, resulting in better energy utilization and safer battery operation. Overall, the project demonstrates that smart battery balancing is an effective solution for enhancing the reliability and efficiency of EV battery systems. Additionally, the project highlights the importance of integrating intelligent monitoring and control techniques into modern battery management systems. The developed system not only reduces the risk of overcharging, overheating, and uneven cell degradation, but also supports the future advancement of electric vehicles by making battery packs more dependable and efficient.

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