International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 05 | May - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

Enhancing EV Charging Efficiency Through Regenerative Braking and Battery Management Systems

Mahesh Raktate[1], Dr. Alok Kumar[2], Dr. Mangesh Nikose[3]

[2]Student ,Department Of Electrical And Electronics Engineering & Sandip University, School of Engineering & Technology, Nashik

[2]Associate Professor,Department Of Electrical And Electronics Engineering & Sandip University, School of Engineering & Technology, Nashik

[3]Associate Professor,Department Of Electrical And Electronics Engineering & Sandip University, School of Engineering & Technology, Nashik

---***---

Abstract - This paper presents the development of an advanced Battery Management System (BMS) for electric vehicles (EVs), designed to enhance battery performance, safety, and overall system efficiency. Utilizing the ESP32 microcontroller, the proposed BMS integrates regenerative braking technology to recover and convert kinetic energy during deceleration into usable electrical energy. Real-time monitoring is implemented through a network of sensors—including voltage, temperature, current, and flame sensors—to ensure precise power management and early hazard detection. The system incorporates a DC motor and inverter kit to facilitate efficient energy conversion and maximize the recovery of regenerative energy, thereby extending the driving range and improving energy utilization. This innovative approach not only supports sustainability by improving energy efficiency and battery lifespan but also addresses critical safety and reliability concerns in modern electric vehicle systems.

Key Words: Electric Vehicle (EV), Battery Management System (BMS), Regenerative Braking, ESP32 Microcontroller, Real-Time Monitoring, Energy Recovery, Battery Safety, Power Optimization, Sensor Integration, Sustainable Transportation

1.INTRODUCTION

The rapid evolution of electric vehicles (EVs) is transforming the global automotive landscape, offering a cleaner, more environmentally sustainable alternative to traditional internal combustion engine vehicles. Despite their numerous advantages, EVs face persistent challenges related to battery performance, lifespan, and operational safety. These issues remain significant barriers to the widespread adoption of electric mobility.

At the core of these challenges lies the need for a highly efficient **Battery Management System (BMS)**—one that can effectively regulate charging and discharging cycles, ensure thermal stability, and maintain overall battery health. This research focuses on the development of an advanced BMS using the **ESP32 microcontroller**, aimed at enhancing the safety, performance, and energy efficiency of electric vehicles through the integration of **regenerative braking technology**.

Thermal management is a critical component in ensuring battery reliability and longevity. Conventional Battery Thermal Management Systems (BTMS), particularly those employing air-cooling methods, focus on structural enhancements and airflow optimization. However, maximizing battery performance in modern EVs demands more sophisticated solutions—specifically, intelligent monitoring systems capable of delivering real-time data on key battery health indicators.

The proposed BMS leverages the versatility and processing power of the ESP32 to continuously monitor parameters such as **voltage, current, and temperature**, while also incorporating **flame detection sensors** for early hazard identification. This comprehensive monitoring framework is designed to provide real-time feedback via an LCD interface, allowing for informed decision-making and proactive maintenance to prevent system failures.

A standout feature of this project is the **integration of regenerative braking**, which captures kinetic energy typically lost during deceleration and converts it into electrical energy. By employing a **DC motor and inverter kit**, the system effectively redirects this energy back into the battery, thereby improving energy efficiency and extending the vehicle's range—an essential enhancement for the practicality of EVs in real-world conditions.

This project not only proposes a technological solution to several current limitations in EV systems but also contributes to the broader goal of advancing **sustainable transportation**. By bridging the gap between existing battery management approaches and the evolving demands of next-generation electric vehicles, the proposed system represents a significant step forward in improving EV reliability, energy optimization, and user confidence. The findings of this research have the potential to influence future developments in electric mobility, making it a more viable and attractive option for global consumers.

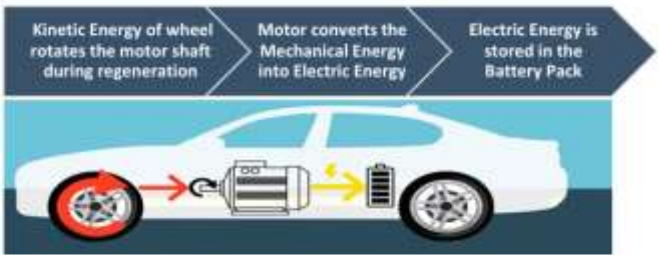

Figure 1. Conceptual diagram of regenerative braking.

2. PROBLEM STATEMENT

The widespread adoption of electric vehicles (EVs) is significantly constrained by persistent challenges related to battery efficiency, lifespan, and operational safety. Current Battery Management Systems (BMS) often fall short in addressing the dynamic demands of modern EVs, particularly in terms of real-time monitoring, energy optimization, and thermal regulation. In addition, a substantial amount of energy is lost during vehicle deceleration, which could otherwise be recovered and reused. This project aims to address these limitations by developing an advanced BMS integrated with regenerative braking technology, thereby enhancing energy recovery, improving battery health, and ensuring greater overall vehicle safety and reliability.

2.1 OBJECTIVE

The primary objective of this research is to develop and evaluate an advanced Battery Management System (BMS) for electric vehicles that integrates regenerative braking and real-time monitoring technologies. Specifically, the study aims to investigate the impact of regenerative braking on energy efficiency and battery performance, while also examining how the integration of an ESP32 microcontroller can enhance the functionality and responsiveness of the BMS. Furthermore, the research focuses on assessing the effectiveness of real-time monitoring systems in maintaining optimal battery health and safety, as well as exploring the role of various sensors—such as voltage, temperature, current, and flame sensors—in detecting potential hazards. Lastly, the study seeks to measure improvements in vehicle range and overall efficiency achieved through the recovery and reuse of energy typically lost during braking, contributing to the advancement of sustainable electric mobility solutions.

2.3 PROPOSED SYSTEM

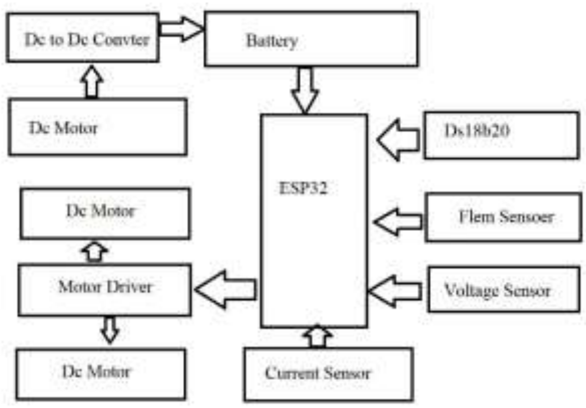

Fig -2: System Architecture

The proposed system architecture presents a comprehensive solution for enhancing electric vehicle (EV) performance through the integration of an advanced Battery Management System (BMS) and regenerative braking, all coordinated by the ESP32 microcontroller. Serving as the central control unit, the ESP32 interfaces with a network of sensors, actuators, and power management components to ensure efficient energy utilization, improved battery health, and enhanced vehicle safety.

A key feature of the system is the DC-to-DC converter, which regulates power flow between the battery and various components. It ensures the ESP32 is reliably powered while maintaining appropriate voltage levels for other subsystems. This stable power management foundation supports the efficient operation of motor control and regenerative energy capture.

The system incorporates **multiple DC motors**, each integrated to facilitate and demonstrate regenerative braking functionality. One motor connects directly to the DC-to-DC converter, while two others are managed via a **motor driver** that receives control signals from the ESP32. This setup allows the system to convert kinetic energy generated during braking into electrical energy, which is then stored back in the battery, effectively extending the EV's range and improving overall energy efficiency.

To maintain safe and optimal operating conditions, the ESP32 interfaces with a suite of sensors for **real-time monitoring**. The **DS18B20 temperature sensor** continuously tracks battery temperature to prevent thermal damage, while a **flame sensor** adds an important layer of safety by detecting fire-related anomalies. Additional **voltage and current sensors** provide constant feedback on the electrical state of the battery and motor systems, allowing dynamic energy management and fault prevention.

This embedded system design not only ensures intelligent motor control and precise power management but also allows for **wireless communication capabilities**, making remote monitoring and system updates possible. The modularity and scalability of the architecture position it as a robust platform for further applications, including **smart EV systems, robotics, and autonomous energy systems**.

In conclusion, the proposed system integrates regenerative braking with a smart BMS using the ESP32 microcontroller, offering a cost-effective and scalable solution to optimize energy efficiency, improve battery longevity, and enhance the environmental sustainability of electric vehicles. By reducing reliance on conventional fuel and promoting intelligent energy recovery, this system contributes meaningfully to the advancement of next-generation transportation technologies.

2.4 State of Charge (SOC) of Battery 2.2.1.

Types of SOC Estimation Techniques State of charge (SOC) is a measurement for understanding remaining battery capacity. Figure 3 shows the state of charge of a battery through regeneration, and Figure 4 shows the numerical expression of the state of charge and health. This knowledge is very important because many systems are sensitive to deep discharging and overcharging. SoC

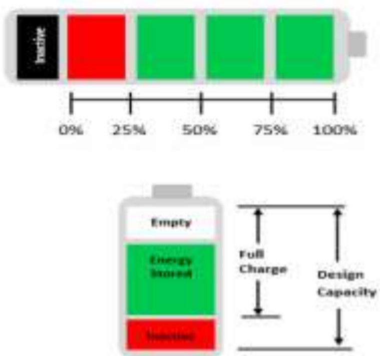

Figure 3- State of charge

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 05 | May - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

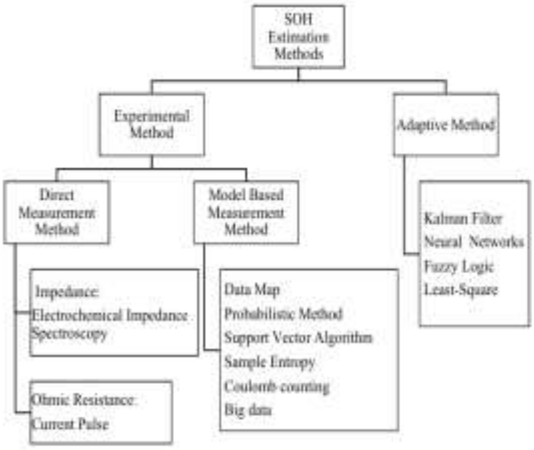

Figure 4- Flow chart of SOH estimation methods

Accurate estimation of a battery's **State of Charge (SOC)** is essential to ensure safe and efficient operation, particularly in electric vehicles (EVs). Typically, the SOC should be maintained between **20% and 95%** to avoid degradation or failure of the battery system [37]. Overcharging or deep discharging outside this range can significantly reduce battery lifespan and performance [3].

SOC estimation becomes especially complex under varying discharge conditions, as different scenarios can influence the battery's behavior and performance. Consequently, various **mathematical and computational approaches** have been developed to accurately estimate SOC, each with unique strengths and applicable contexts.

A. SOC Estimation Methods

Four primary categories of SOC estimation methods are as follows:

1. **Direct Measurement**

This method involves the direct correlation between the **battery voltage and impedance**. Although simple, it may not always yield accurate results under dynamic load conditions.

2. **Book-Keeping (Coulomb Counting)**

This technique calculates SOC by integrating the charging or discharging current over time. While widely used, it is prone to cumulative error due to current sensor drift.

3. **Adaptive Systems**

These systems are self-adjusting and can dynamically adapt SOC estimations based on real-time discharge characteristics. Various adaptive approaches have been developed, including **Kalman filters**, **neural networks**, and **fuzzy logic**.

4. **Hybrid Methods**

Hybrid models combine two or more estimation techniques to leverage the strengths of each and improve overall accuracy. These approaches often outperform individual techniques, especially under variable load and temperature conditions [39]

2.5 DISCUSSION AND SUMMARY

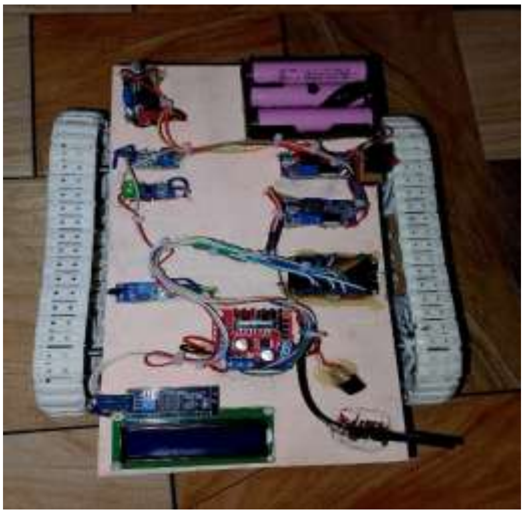

Fig -3: 11. The developed EV

A. Hardware Components

1. **ESP32 Microcontroller**

○ **Specifications**: Dual-core processor operating at up to 160 MHz, with integrated Wi-Fi (802.11 b/g/n) and Bluetooth capabilities. Contains 160 KB SRAM.

○ **Function**: Serves as the central processing unit for the system. It gathers sensor data, executes control algorithms, and manages communication among components to ensure efficient operation of the BMS and regenerative braking system.

2. **DC-to-DC Converter**

○ **Specifications**: Input voltage range typically 10V–60V; adjustable output voltages (e.g., 5V, 12V); output current from 3A to 30A, depending on the design.

○ **Function**: Regulates voltage across the system, ensuring that all modules receive appropriate power levels and improving system stability.

3. **Battery Pack**

○ **Specifications**: Lithium-ion cells with a nominal voltage of 3.7V per cell; capacity up to 200Ah or higher depending on application.

○ **Function**: Stores electrical energy for vehicle propulsion and regenerative energy. Monitored for voltage, temperature, and current as part of the BMS strategy.

4. **DC Motors (×3)**

○ **Specifications**: Brushless DC motors, rated from 1 kW to 5 kW; operational voltage 24V–48V.

○ **Function**: Provide mechanical propulsion and enable regenerative braking by converting kinetic energy into electrical energy during deceleration.

5. **Motor Driver**

○ **Specifications**: Supports voltages up to 60V and currents up to 30A; features PWM (Pulse Width Modulation) control for speed regulation.

○ **Function**: Interfaces between the ESP32 and DC motors, controlling motor direction and speed for both propulsion and regenerative braking.

6. **DS18B20 Temperature Sensor**

○ **Specifications**: Digital sensor with a measurement range from -55°C to +125°C and an accuracy of ±0.5°C.

○ **Function**: Monitors battery and system temperatures to prevent thermal runaway and ensure safe operation.

7. **Flame Sensor**

○ **Specifications**: Detects infrared emissions and high-temperature signatures (typically above 35°C); outputs analog or digital signals.

○ **Function**: Enhances safety by detecting potential fire hazards and initiating emergency shutdown protocols if needed.

8. **Voltage Sensor**

○ **Specifications**: Measures up to 100V with an accuracy of ±1%.

○ **Function**: Monitors the voltage across the battery and other critical components, protecting against overvoltage and undervoltage conditions.

9. **Current Sensor**

○ **Specifications**: Hall-effect based sensor; measures ±100A with ±1% accuracy.

○ **Function**: Tracks the current entering and leaving the battery, essential for SOC estimation and power flow regulation.

B. Software Components

1. **Embedded Firmware for ESP32**

○ **Details**: Custom-developed firmware responsible for sensor data acquisition, signal processing, and control signal generation. Supports communication protocols such as MQTT or HTTP.

○ **Function**: Executes real-time control logic for regenerative braking and battery management, and ensures synchronized operation of all hardware modules.

2. **Data Logging and Analysis Software**

○ **Details**: Records operational data such as temperature, voltage, and current. May interface with cloud storage systems for remote monitoring and analysis.

○ **Function**: Enables system performance evaluation, battery diagnostics, and predictive maintenance through historical data analysis.

3. **Control Algorithms for Regenerative Braking**

○ **Details**: Embedded algorithms that dynamically adjust motor behavior during braking to maximize energy recovery. Algorithms consider vehicle speed, load, and braking intensity.

○ **Function**: Enhances energy efficiency by converting kinetic energy into stored battery power during braking cycles.

4. **Battery Management Software**

5. **Details**: Software modules for monitoring SOC (State of Charge), SOH (State of Health), cell balancing, and safe charging/discharging.

6. **Function**: Maintains battery reliability, optimizes energy usage, and prolongs battery lifespan by controlling charge cycles and managing individual cell performance.

3. CONCLUSIONS

The integration of **regenerative braking** and **advanced Battery Management Systems (BMS)** marks a pivotal advancement in enhancing the efficiency, performance, and sustainability of electric vehicles (EVs). By capturing and reusing kinetic energy during braking events, and by intelligently managing battery charging cycles and health parameters, these technologies collectively improve the overall driving range and operational reliability of EVs.

This synergy not only boosts energy efficiency but also significantly contributes to the reduction of energy waste, reinforcing the role of EVs in promoting **sustainable transportation**. Furthermore, continued innovations in sensor technologies, control algorithms, and energy storage systems are expected to further optimize energy recovery and power management strategies.

As the electric vehicle industry evolves, the deployment of smart, adaptive BMS frameworks—combined with regenerative technologies—will be central to advancing low-emission mobility. These systems are instrumental in reducing the environmental impact of transportation and accelerating the global shift toward a **cleaner, greener, and more sustainable future**.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the faculty and staff of the Electrical And Electronics Engineering, Sandip University, School of Engineering & Technology, Nashik, for their continuous support and guidance throughout this project. Special thanks are extended to our project supervisor, Dr.Alok Kumar , for their valuable insights, feedback, and encouragement that greatly contributed to the successful completion of this work.

We also acknowledge the contributions of our peers and laboratory technicians who assisted during the experimental setup and testing phases. Lastly, we are grateful to our families for their unwavering support and motivation throughout the research journey.

.

REFERENCES

1. Y. Zhang and J. Wu, "A Review of Electric Vehicle Regenerative Braking Systems," *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 6, pp. 2085–2099, 2019, doi: 10.1109/TITS.2018.2885881.
2. D. Gao, H. Xu, and X. Chen, "Battery Management System for Electric Vehicles: A Review," *Journal of Power Sources*, vol. 450, p. 227762, 2020, doi: 10.1016/j.jpowsour.2020.227762.
3. S. Tsygankov and I. Uglov, "Optimization of Regenerative Braking in Electric Vehicles," *Journal of Electrical Engineering & Technology*, vol. 13, no. 4, pp. 1506–1516, 2018, doi: 10.5370/JEET.2018.13.4.1506.
4. Y. Li and L. Wang, "Review of Battery Management Systems for Electric Vehicles," *Renewable and Sustainable Energy Reviews*, vol. 100, pp. 275–290, 2019, doi: 10.1016/j.rser.2018.10.036.
5. S. Chen, H. Wang, and M. Xu, "The Role of Regenerative Braking in Electric Vehicle Efficiency," *Energies*, vol. 13, no. 22, p. 6060, 2020, doi: 10.3390/en13226060.
6. W. A. Moussa and S. S. Shafik, "Impact of Regenerative Braking on Electric Vehicle Performance and Battery Life," *Energy Reports*, vol. 7, pp. 163–171, 2021, doi: 10.1016/j.egyr.2021.01.034.
7. M. Hussain, N. B. Khedher, and A. El-Awady, "Battery Management Systems for Electric and Hybrid Vehicles: A Review," *IEEE Access*, vol. 9, pp. 45710–45731, 2021, doi: 10.1109/ACCESS.2021.3065863.
8. Y. Zhao, J. Hu, and Y. Zhang, "Performance Evaluation of Regenerative Braking Systems in Electric Vehicles," *Sustainable Cities and Society*, vol. 55, p. 102057, 2020, doi: 10.1016/j.scs.2020.102057.
9. X. Song, Z. Wang, and Y. Li, "A Comprehensive Review of Battery Management Systems for Electric Vehicles," *Renewable and Sustainable Energy Reviews*, vol. 131, p. 110021, 2020, doi: 10.1016/j.rser.2020.110021.
10. S. Sharma and D. P. Kothari, "Control Strategies for Regenerative Braking in Electric Vehicles," *Electric Power Systems Research*, vol. 165, pp. 95–103, 2019, doi: 10.1016/j.epsr.2018.11.018.