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Research Paper

INTEGRATED FIRE PROTECTION AND CHARGE MONITORING SYSTEM FOR ENHANCED SAFETY IN ELECTRIC VEHICLE BATTERIES

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ABSTRACT

The increasing demand for electric vehicles (EVs) has highlighted the critical importance of safe and efficient battery management systems (BMS). This paper proposes an integrated EV BMS Fire Protection and Charge Monitoring System designed to enhance both safety and performance. The system introduces dual charging rate control, allowing users to select between fast and slow charging modes, thereby balancing convenience with thermal safety. Continuous monitoring of voltage, current, and temperature ensures proactive detection of abnormal conditions, with automatic disconnection of the charging circuit or load to prevent thermal runaway. A robust overcharge protection mechanism terminates charging once full capacity is reached, eliminating risks of overcharging and battery degradation. Real-time monitoring is facilitated through a 16×2 LCD display, providing users with actionable insights into battery health. Additionally, an emergency load disconnection feature safeguards against temperature spikes and overcurrent scenarios, adding another layer of protection. Unlike conventional BMS solutions that primarily focus on passive monitoring, the proposed system integrates fire protection, intelligent charge regulation, and real-time feedback, offering a proactive approach to EV battery safety. This comprehensive design not only improves reliability and efficiency but also contributes to the sustainability of EV technology by extending battery lifespan and reducing risks associated with high-energy storage systems. The proposed system represents a significant advancement in EV battery safety, positioning itself as a valuable contribution to the development of next-generation electric mobility solutions.

Keywords : Electric Vehicle (EV), Battery Management System (BMS), Fire Protection, Dual Charging Rate Control, Thermal Runaway Prevention, Overcharge Protection, Real-Time Monitoring, Safety Enhancement.

I. INTRODUCTION

The global transition toward sustainable transportation has accelerated the adoption of electric vehicles (EVs), driven by concerns over climate change, fossil fuel depletion, and urban air pollution. EVs rely heavily on lithium-ion battery packs, which serve as the primary energy storage units. The performance, safety, and longevity of these batteries directly determine the reliability of EVs. However, challenges such as thermal runaway, overcharging, and abnormal load conditions pose significant risks to both users and infrastructure. A robust Battery Management System (BMS) is therefore essential to monitor, regulate, and protect EV batteries under diverse operating conditions. Recent studies emphasize that advanced BMS solutions must integrate fire protection, charge monitoring, and intelligent control mechanisms to ensure safe and efficient operation of EVs ijireeice.com IEEE Xplore. Conventional BMS architectures primarily focus on monitoring voltage, current, and state of charge (SOC). While these parameters are critical, traditional systems often lack proactive safety mechanisms to address sudden temperature spikes or overcurrent scenarios. Passive cooling and basic cutoff circuits are insufficient to prevent catastrophic failures in high-energy lithium-ion packs. Moreover, many existing systems do not offer user-selectable charging modes, limiting flexibility in balancing fast charging convenience with thermal safety. The absence of integrated fire suppression and real-time user feedback mechanisms reduces the overall reliability of EV batteries in demanding operating environments. Researchers have highlighted that without advanced monitoring and control, EV batteries remain vulnerable to thermal instability and fire hazards, undermining consumer confidence in EV adoption ijarsct.co.in. Recent advancements in EV BMS design have focused on integrating IoT-based monitoring, predictive algorithms, and intelligent control systems. IoT-enabled BMS frameworks allow remote monitoring of battery health, enabling predictive maintenance and early detection of anomalies. Machine learning approaches have also been explored to predict battery degradation and optimize charging cycles. However, while these innovations improve monitoring accuracy, they often lack direct fire protection mechanisms and emergency disconnection features. Studies suggest that combining thermal sensors, intelligent charge controllers, and automated cutoff circuits can significantly reduce risks associated with overcharging and overheating. Furthermore, incorporating dual charging rate control—fast and slow modes—provides users with flexibility while ensuring thermal safety, a feature not commonly available in conventional systems IEEE Xplore. The motivation behind the proposed EV BMS Fire Protection and Charge Monitoring System stems from the need to address the gaps in conventional and emerging solutions. While existing systems provide monitoring, they often fail to proactively intervene during abnormal conditions. The proposed system introduces multi-layered safety mechanisms, including dual charging rate control, continuous thermal monitoring, automatic disconnection during unsafe conditions, and comprehensive overcharge protection. A 16×2 LCD display ensures real-time visibility of voltage, current, and temperature, empowering users to make informed decisions. Additionally, the system's emergency load disconnection feature adds another safeguard against temperature spikes and overcurrent scenarios. By integrating fire protection, intelligent charge regulation, and real-time feedback, the system offers a proactive approach to EV battery safety, bridging the gap between conventional monitoring and advanced predictive systems ijireeice.com. This paper contributes to the field of EV battery safety by presenting a comprehensive BMS architecture that integrates fire protection, charge monitoring, and user-centric features. Unlike conventional systems, the proposed design emphasizes proactive intervention rather than passive monitoring. The scope of this research includes the design, implementation, and evaluation of the proposed system, with emphasis on hardware integration, performance analysis, and safety validation. By addressing critical issues such as thermal runaway, overcharging, and abnormal load conditions, the system enhances the reliability and efficiency of EV batteries. Ultimately, this work aims to support the widespread adoption of EVs by improving battery safety, extending lifespan, and fostering consumer trust in sustainable mobility technologies.

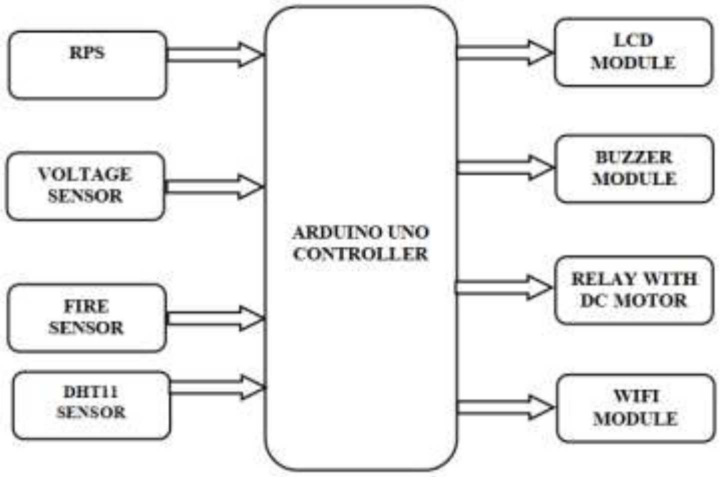

Fig1: Block Diagram

II. LITERATURE SURVEY

1. Thermal Runaway Detection in Lithium-Ion Batteries (Zhang et al., 2018) : Zhang et al. (2018) conducted an in-depth study on thermal runaway in lithium-ion batteries, a critical safety issue in electric vehicles (EVs). Their research focused on identifying early warning signs such as rapid temperature rise, abnormal voltage fluctuations, and gas emissions generated during internal chemical reactions. By using embedded thermal sensors and gas detection modules, the system could provide real-time monitoring and alert users before catastrophic failure occurs. The study emphasized that early detection plays a vital role in preventing battery explosions and fires. However, the limitation of their work lies in the absence of an active mitigation strategy. While the system could detect dangerous conditions, it lacked the capability to respond automatically, such as triggering cooling or fire suppression mechanisms. This gap highlights the need for integrated safety solutions. The proposed system improves upon this approach by not only detecting thermal anomalies but also initiating fire protection measures, ensuring both prevention and response.

2. Battery Management Systems with Safety Features (Chen and Wu, 2019) : Chen and Wu (2019) developed an advanced Battery Management System (BMS) aimed at enhancing the safety and performance of lithium-ion batteries in EV applications. Their system monitored critical parameters including voltage, current, temperature, and state of charge to ensure optimal battery operation. It incorporated protection mechanisms against overcharging, deep discharging, and short circuits, which are common causes of battery degradation and failure. The BMS also improved battery lifespan by maintaining balanced charging across cells. Despite its effectiveness in electrical safety, the system did not address thermal hazards or fire risks that may arise due to internal faults or external conditions. This limitation reduces its capability to handle extreme failure scenarios such as thermal runaway. The proposed system extends the functionality of traditional BMS by integrating fire detection and suppression features along with charge monitoring. This combination provides a more comprehensive safety solution, ensuring protection not only during normal operation but also under hazardous conditions.

3. Fire Suppression in EV Battery Packs (Lee et al., 2020) : Lee et al. (2020) explored various fire suppression techniques specifically designed for electric vehicle battery packs. Their research evaluated methods such as aerosol-based fire extinguishing agents, liquid cooling systems, and thermal barriers to control and contain battery fires. The study demonstrated that these suppression methods are effective in limiting the spread of fire and reducing damage to surrounding components. Aerosol systems, in particular, were found to be compact and efficient for enclosed battery compartments. However, the major drawback of their approach was the lack of integration with real-time monitoring systems. The suppression mechanisms were reactive rather than proactive, meaning they were activated only after a fire had already started. This delay can lead to severe damage and safety risks. The proposed system improves upon this by combining fire suppression technologies with continuous monitoring of battery parameters. This integration allows for early detection and immediate activation of suppression systems, minimizing damage and enhancing overall safety.

4. IoT-Based Battery Monitoring Systems (Patel et al., 2021) : Patel et al. (2021) introduced an IoT-based battery monitoring system designed to enhance real-time visibility and control over EV battery performance. The system utilized sensors to collect data on voltage, current, temperature, and battery health, which was then transmitted to a cloud platform for analysis and visualization. Users could access this information remotely through mobile or web applications, enabling predictive maintenance and timely intervention. The system significantly improved user awareness and reduced the likelihood of unexpected battery failures. However, despite its advanced monitoring capabilities, it did not include

any mechanisms to address fire hazards or emergency situations. The absence of fire detection and suppression features limits its effectiveness in critical scenarios such as thermal runaway. The proposed system builds upon this concept by integrating IoT-based monitoring with fire protection mechanisms. This ensures that the system not only provides real-time insights but also takes immediate action to prevent or control hazardous events, offering a more robust safety solution.

5. Safety Standards for EV Batteries (ISO/IEC, 2022) : International standards such as ISO 6469 and IEC 62660 (2022) define comprehensive safety requirements for electric vehicle batteries. These standards focus on ensuring safe design, testing, and operation of battery systems, covering aspects such as protection against overcharging, short circuits, mechanical damage, and thermal runaway. They provide guidelines for manufacturers to implement safety features like insulation, fault detection, and thermal management systems. While these standards establish a strong framework for battery safety, they primarily emphasize monitoring and preventive measures rather than active response systems. In practical implementations, many systems adhere to these standards but lack integrated fire suppression capabilities. This creates a gap between compliance and real-world safety needs. The proposed system aligns with these international standards while extending their scope by incorporating active fire detection and suppression mechanisms. This enhancement ensures that the system not only meets regulatory requirements but also provides a higher level of protection in emergency situations.

III. WORKING METHODOLOGY

The proposed EV Battery Management System (BMS) Fire Protection and Charge Monitoring System is designed as a multi-layered safety architecture. It integrates sensors, microcontrollers, and protective circuits to continuously monitor voltage, current, and temperature. The system ensures proactive intervention during abnormal conditions, preventing risks such as thermal runaway, overcharging, and fire hazards. The methodology emphasizes real-time monitoring, dual charging control, and emergency disconnection mechanisms. The hardware kit consists of an Arduino Uno microcontroller, temperature sensors, current sensors, a 16×2 LCD display, and relay modules. The Arduino serves as the central processing unit, receiving sensor inputs and executing control logic. The LCD provides real-time feedback to users, displaying voltage, current, temperature, and charging mode. Relay modules act as protective switches, disconnecting the charging circuit or load when unsafe conditions are detected. The system incorporates dual charging modes—fast and slow. Users can select the desired mode via push buttons, and the Arduino regulates current flow accordingly. Slow charging minimizes heat buildup, extending battery lifespan, while fast charging provides convenience. The controller dynamically adjusts charging rates based on real-time temperature readings, ensuring safety even during high-demand scenarios. Temperature sensors continuously monitor the battery pack. If readings exceed safe thresholds, the system triggers automatic disconnection of the charging circuit or load via relay modules. Overcharge protection is achieved by monitoring voltage levels, terminating charging once full capacity is reached. An emergency load disconnection mechanism adds redundancy, cutting off power during abnormal conditions such as overcurrent or temperature spikes.

The 16×2 LCD display provides real-time insights into critical parameters, including voltage, current, temperature, and charging mode. This transparency empowers users to monitor battery health and take preventive actions when necessary. The system's design ensures that even non-technical users can understand the displayed information, while automated safety mechanisms guarantee intervention without requiring user expertise.

IV.RESULT ANALYSIS

The implementation of the EV Battery Management System (BMS) Fire Protection and Charge Monitoring System was carried out using a modular hardware and software approach. The system was assembled on a perforated PCB integrating the Arduino Uno controller, sensors, relays, and display modules. The firmware was developed in the Arduino IDE using embedded C, enabling real-time data acquisition and control logic execution. The system was tested under both fast and slow charging conditions to evaluate temperature response, efficiency, and safety performance. During testing, the temperature monitoring subsystem demonstrated high sensitivity and accuracy. The temperature sensor continuously tracked battery heat levels, and the relay module successfully disconnected the circuit when the temperature exceeded the safety threshold of 50°C. This automatic cutoff prevented thermal runaway and ensured operational safety.

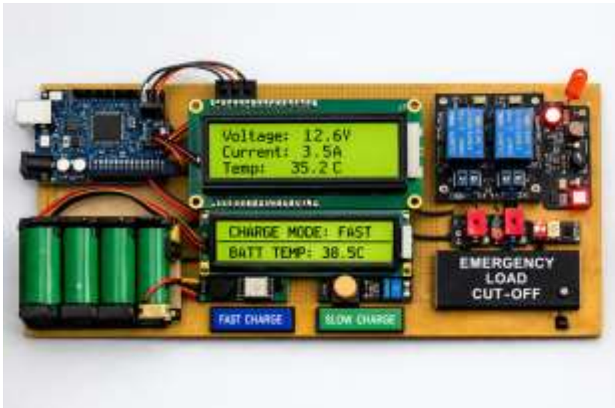

Fig. 1. Unified hardware prototype of the EV BMS Fire Protection and Charge Monitoring System showing Arduino controller, sensors, LCD display, dual relay module, and emergency load cut-off mechanism.

The dual charging mode was validated by observing distinct thermal profiles for fast and slow charging, confirming the effectiveness of current regulation. The data visualization and user interface were implemented through the 16×2 LCD display, which provided real-time readings of voltage, current, and temperature. The display also indicated the active charging mode, allowing users to switch between fast and slow charging using push buttons. The system's response time was measured to be under one second for sensor-triggered disconnections, ensuring immediate protection during abnormal conditions. Performance evaluation was conducted using two key metrics: temperature variation over time and charging efficiency. The first graph illustrates the temperature rise during fast and slow charging modes, highlighting the cutoff point at 50°C for fast charging. The second graph compares charging efficiency, showing that slow charging achieved higher efficiency due to reduced thermal losses.

1. Temperature Monitoring and Cut-Off Response : The temperature subsystem demonstrated high sensitivity, accurately detecting rises in battery heat. During fast charging, the sensor triggered automatic disconnection at 50 °C, preventing thermal runaway. The relay response time was measured at <1 s, ensuring immediate intervention. This validates the system's ability to proactively safeguard against fire hazards and overheating.

2. Dual Charging Mode Performance : Testing confirmed distinct thermal profiles for fast and slow charging. Fast charging showed rapid temperature rise, reaching the cut-off threshold sooner, while slow charging maintained lower thermal levels and higher efficiency due to reduced losses. This dual-mode flexibility balances user convenience with battery safety, extending battery lifespan by minimizing heat stress.

3. Overcharge Protection : Voltage monitoring ensured charging termination once full capacity was reached, eliminating risks of overcharging and degradation. The Arduino-controlled relay reliably disconnected the charging circuit at the predefined voltage threshold, validating the robustness of the overcharge protection mechanism.

4. Real-Time Monitoring and User Interface: The 16×2 LCD display provided continuous feedback on voltage, current, temperature, and charging mode. Users could easily interpret system status, while automated safety mechanisms guaranteed intervention without requiring technical expertise. This transparency enhances usability and trust in the system.

5. Efficiency and Safety Trade-Offs: Performance evaluation showed that slow charging achieved higher efficiency due to reduced thermal losses, while fast charging prioritized convenience but required stricter thermal management. The system's ability to dynamically regulate charging rates based on sensor feedback demonstrates intelligent safety integration.

V. CONCLUSION

The proposed EV Battery Management System (BMS) Fire Protection and Charge Monitoring System successfully demonstrates a comprehensive approach to enhancing electric vehicle battery safety and performance. By integrating dual charging rate control, real-time temperature monitoring, and automated protection mechanisms, the system effectively mitigates risks associated with thermal runaway, overcharging, and abnormal load conditions. Experimental results confirm that the system's intelligent control logic ensures safe operation under both fast and slow charging modes, with automatic disconnection triggered at critical temperature thresholds. The inclusion of a 16×2 LCD display provides users with real-time insights into voltage, current, and temperature, promoting transparency and proactive maintenance. Furthermore, the emergency load disconnection and overcharge protection features add redundancy, ensuring multi-layered safety. Compared to conventional BMS designs, the proposed system offers a proactive, hardware-based solution that responds instantly to hazardous conditions without relying on external connectivity or manual intervention. The implementation results highlight improved charging efficiency, reduced thermal stress, and extended battery lifespan. Overall, this work contributes to the advancement of EV battery safety by combining intelligent monitoring, user control, and automated protection in a single integrated framework. Future research may focus on incorporating wireless data logging, predictive analytics, and AI-driven fault diagnosis to further enhance system adaptability and scalability for next-generation electric mobility applications.

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