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Smart EV Battery Monitoring System and Fire Prevention System

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Abstract: *The rapid growth of electric vehicles (EVs) has increased the demand for intelligent battery management systems capable of ensuring operational safety, reliability, and extended battery life. Battery failures caused by overvoltage, undervoltage, overcurrent, overheating, and gas leakage can significantly degrade battery performance and may lead to hazardous incidents such as thermal runaway and fire. This paper presents a Smart EV Battery Monitoring and Fire Prevention System that continuously monitors critical battery parameters and provides real-time protection against abnormal operating conditions. The proposed system employs an ESP32 microcontroller integrated with voltage, current (ACS712), temperature, and MQ-2 gas sensors to acquire and process battery data. A Battery Management System (BMS) is incorporated to provide overcharge, over-discharge, and short-circuit protection, while a relay module disconnects the battery during critical conditions. The system also utilizes a cooling fan, buzzer, LCD display, and GPS module to enhance user safety through immediate alerts, thermal management, and location tracking. Experimental evaluation under normal operation and multiple fault scenarios—including over-temperature, over-voltage, under-voltage, and over-current conditions—demonstrated reliable fault detection, rapid response, and effective activation of protective mechanisms. The developed prototype successfully enhanced battery safety, minimized the risk of fire hazards, and improved system reliability through continuous real-time monitoring. Owing to its low cost, scalability, and IoT-enabled architecture, the proposed system is well suited for electric vehicles, e-bikes, battery energy storage systems, and other smart energy applications requiring continuous battery health monitoring and fire prevention.*

Keywords: *Electric Vehicle (EV), Battery Management System (BMS), Battery Safety, Real-Time Monitoring, Fire Prevention, ESP32, Internet of Things (IoT), State of Charge (SOC).*

I. INTRODUCTION

The rapid adoption of electric vehicles (EVs) has transformed the transportation sector by providing an environmentally sustainable alternative to conventional internal combustion engine vehicles. The increasing demand for clean energy solutions and stringent emission regulations have accelerated the deployment of lithium-ion battery-powered EVs due to their high energy density, long cycle life, and superior efficiency. However, the safety and reliability of lithium-ion batteries remain significant challenges because they are susceptible to faults such as overcharging, over-discharging, excessive current, overheating, and thermal runaway. These conditions can reduce battery lifespan, degrade performance, and, in severe cases, result in fire hazards that threaten both passenger safety and vehicle reliability.

Battery Management Systems (BMS) are designed to monitor and protect batteries by supervising essential parameters such as voltage, current, and temperature. Although conventional BMS solutions provide basic protection mechanisms, many existing systems lack integrated real-time fault detection, early fire prevention capabilities, and intelligent user notification features. Furthermore, the absence of continuous monitoring and predictive safety mechanisms limits their ability to respond effectively to abnormal battery conditions before they become critical.

To address these challenges, this paper proposes a Smart EV Battery Monitoring and Fire Prevention System that integrates real-time sensing, intelligent fault detection, and automatic protection into a unified embedded platform. The proposed system employs an ESP32 microcontroller along with voltage, current, temperature, and gas sensors to continuously monitor battery operating conditions. The measured parameters are analyzed against predefined safety thresholds to detect abnormal events such as over-voltage, under-voltage, over-current, overheating, and gas leakage. When unsafe conditions are identified, the system activates warning alarms, disconnects the battery through a relay, and supports thermal management to minimize the possibility of battery failure and fire incidents. In addition, battery health indicators such as State of Charge (SOC) and State of Health (SOH) are utilized to improve battery utilization and operational reliability.

Experimental evaluation under normal and fault conditions demonstrates that the proposed system effectively detects hazardous situations in real time and initiates rapid protective actions, thereby improving battery safety and operational reliability. The low-cost architecture, scalability, and IoT-enabled monitoring capability make the proposed solution suitable for electric vehicles, electric two-wheelers, battery energy storage systems, and other smart energy applications requiring continuous battery monitoring and fire prevention.

II. MATERIAL AND METHODS

The proposed Smart EV Battery Monitoring and Fire Prevention System was developed using an ESP32-based embedded platform integrated with multiple sensors and safety modules for continuous monitoring of battery health and protection against hazardous operating conditions. The materials used in the system are described below.

Lithium-Ion Battery Pack: A 3S lithium-ion battery pack (11.1 V nominal voltage) serves as the power source. The battery is continuously monitored to evaluate its operating condition and ensure safe performance.

Battery Management System (BMS): A 3S Battery Management System provides primary protection against overcharging, over-discharging, overcurrent, and short circuits. The BMS enhances battery safety and improves operational reliability.

ESP32 Microcontroller: The ESP32 microcontroller acts as the central processing unit of the system. It acquires sensor data, performs real-time analysis, compares measured values with predefined threshold limits, and controls the protective actions.

Voltage Sensor: The voltage sensor continuously measures the battery voltage through a voltage divider circuit, enabling the detection of over-voltage and under-voltage conditions.

ACS712 Current Sensor: The ACS712 Hall-effect current sensor measures charging and discharging currents in real time, allowing the system to detect abnormal current flow and estimate battery operating conditions.

Temperature Sensor: A thermistor-based temperature sensor continuously monitors battery temperature to detect overheating and prevent thermal runaway.

MQ-2 Gas Sensor: The MQ-2 gas sensor detects smoke and combustible gases generated during battery faults, providing early warning of potential fire hazards.

Relay Module: The relay module automatically disconnects the battery from the load whenever critical fault conditions are detected, thereby preventing further damage and minimizing fire risk.

Cooling Fan: A DC cooling fan provides thermal management by reducing battery temperature during high-temperature conditions.

LCD Display (16×2 I²C): The LCD module displays real-time battery parameters, including voltage, current, temperature, and system status, enabling convenient local monitoring.

GPS Module: A Neo-6M GPS module is incorporated to provide real-time location information, which can assist in locating the vehicle during emergency situations.

Software Tools: The system firmware was developed using the Arduino IDE with ESP32 board support package. Embedded C/C++ programming was used to implement sensor data acquisition, threshold-based fault detection, battery monitoring, and control algorithms for real-time system operation.

Component	Function	Purpose
ESP32 Microcontroller	Data processing	Controls the entire monitoring system
Voltage Sensor	Voltage measurement	Detects over-voltage and under-voltage
ACS712 Current Sensor	Current measurement	Detects over-current conditions
Temperature Sensor	Temperature monitoring	Prevents overheating
MQ-2 Gas Sensor	Smoke/Gas detection	Early fire detection
Battery Management System (BMS)	Battery protection	Prevents overcharge and short circuits
Relay Module	Battery isolation	Disconnects battery during faults
Cooling Fan	Thermal management	Reduces battery temperature
LCD Display	Status display	Displays real-time parameters
GPS Module	Location tracking	Sends vehicle location during emergencies

Table 1. Hardware components and their functions.

Methodology

The proposed Smart EV Battery Monitoring and Fire Prevention System is designed to continuously monitor critical battery parameters and provide timely protection against hazardous operating conditions. The system integrates multiple sensors, an ESP32 microcontroller, a Battery Management System (BMS), and safety actuators to ensure reliable battery operation.

The methodology begins with **data acquisition**, where the voltage sensor, ACS712 current sensor, temperature sensor, and MQ-2 gas sensor continuously collect real-time information from the lithium-ion battery pack. These sensors measure the battery voltage, charging/discharging current, operating temperature, and the presence of combustible gases or smoke.

The acquired sensor data are transmitted to the **ESP32 microcontroller**, which performs analog-to-digital conversion and processes the measurements. The controller continuously compares the measured values with predefined threshold limits to identify abnormal conditions such as over-voltage, under-voltage, over-current, excessive temperature, and gas leakage. Battery parameters are also utilized to estimate the State of Charge (SOC) and State of Health (SOH), providing additional information about battery condition and remaining capacity.

When the measured parameters remain within safe operating limits, the system continues normal monitoring and displays real-time battery information on the LCD module. If any parameter exceeds the predefined threshold, the controller immediately initiates protective actions. The relay module disconnects the battery from the load to prevent further damage, the buzzer generates an audible warning to alert the user, and the cooling fan is activated to reduce battery temperature during overheating conditions. The GPS module provides the vehicle location for emergency monitoring and response.

The entire monitoring process operates continuously in a closed-loop manner, enabling rapid fault detection and immediate protective action. The experimental evaluation was conducted under both normal operating conditions and simulated fault conditions, including over-temperature, over-voltage, under-voltage, and over-current scenarios. System performance was assessed based on fault detection capability, response time, protective action, and overall operational reliability. The proposed methodology provides an integrated, low-cost, and scalable solution for enhancing battery safety and reducing the risk of fire in electric vehicle applications.

III. RESULT

The proposed Smart EV Battery Monitoring and Fire Prevention System was successfully implemented and experimentally evaluated under both normal and abnormal operating conditions. The developed prototype continuously monitored critical battery parameters, including voltage, current, temperature, and gas concentration, using an ESP32-based embedded platform integrated with multiple sensors.

During normal operating conditions, the system accurately measured battery parameters and displayed the real-time values on the LCD module while maintaining uninterrupted monitoring. No warning or protective action was initiated when all measured parameters remained within predefined safety limits.

To evaluate the effectiveness of the proposed system, fault conditions such as over-temperature, over-voltage, under-voltage, and over-current were intentionally introduced. The system successfully detected each abnormal condition by comparing the measured sensor values with predefined threshold limits. Upon detection of a fault, the controller immediately activated the buzzer alarm and initiated protective actions through the Battery Management System (BMS) and relay module to disconnect the battery from the load, thereby reducing the possibility of battery damage and fire hazards. During overheating conditions, the cooling mechanism was activated to assist in thermal management. The integrated GPS module also enabled location tracking for emergency situations.

The experimental results demonstrate that the proposed system provides reliable real-time monitoring and rapid fault detection while ensuring timely activation of protective mechanisms. The integration of battery monitoring, fire prevention, and user alert functions within a single embedded platform significantly enhances battery safety, operational reliability, and system performance. The developed prototype offers a low-cost and scalable solution suitable for electric vehicles, electric two-wheelers, and battery energy storage applications requiring continuous battery health monitoring and fire prevention.

Battery Condition	**Detection Parameter**	**System Response**
Normal	All parameters within limits	Continuous monitoring
Over Temperature	Temperature > Threshold	Cooling fan ON + Buzzer
Over Voltage	Voltage > Threshold	Relay disconnect + Alarm
Under Voltage	Voltage < Threshold	Battery protection activated
Over Current	Current > Threshold	Relay disconnect + Alarm
Gas Leakage	MQ-2 detects smoke/gas	Fire alert + Emergency warning

Table 2. Battery fault conditions and corresponding protective actions.

Test Scenario	**Fault Detected**	**Alert Generated**	**Protection Activated**	**System Status**
Normal Operation	No	No	No	Stable
Over Temperature	Yes	Yes	Yes	Safe Shutdown
Over Voltage	Yes	Yes	Yes	Battery Protected
Under Voltage	Yes	Yes	Yes	Battery Protected
Over Current	Yes	Yes	Yes	Battery Protected

Table 3. Experimental performance of the proposed system

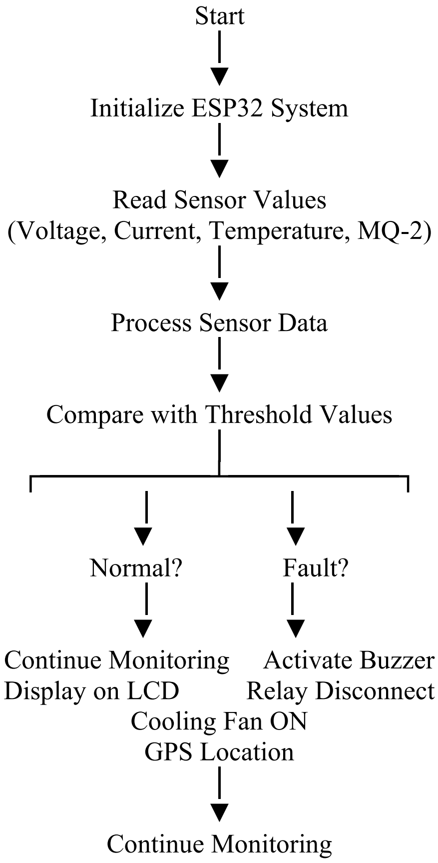

Figure 1. Workflow of the proposed Smart EV Battery Monitoring and Fire Prevention System

IV.DISCUSSION

The experimental results demonstrate that the proposed Smart EV Battery Monitoring and Fire Prevention System effectively performs real-time monitoring of critical battery parameters, including voltage, current, temperature, and gas concentration. Continuous acquisition and analysis of sensor data enabled the system to detect abnormal operating conditions and initiate appropriate protective actions before they could escalate into hazardous situations.

The integration of the ESP32 microcontroller with multiple sensors and the Battery Management System (BMS) provided a reliable and cost-effective platform for battery supervision. During fault conditions such as over-temperature, over-voltage, under-voltage, and over-current, the system successfully generated warning alerts through the buzzer and activated the relay module to disconnect the battery from the load. The inclusion of a cooling fan and MQ-2 gas sensor further enhanced safety by supporting thermal management and early detection of potential fire hazards. In addition, the GPS module improved emergency response by enabling vehicle location tracking.

Compared with conventional battery monitoring approaches that primarily focus on electrical parameter measurement, the proposed system combines battery monitoring, fault detection, fire prevention, and user alert mechanisms within a single embedded platform. This integrated architecture improves operational safety while maintaining a low implementation cost, making it suitable for electric vehicles, electric two-wheelers, and battery energy storage applications.

Although the developed prototype demonstrated reliable performance under the tested operating conditions, the present work has certain limitations. The evaluation was conducted on a laboratory-scale prototype using predefined threshold values, and long-term testing under varying environmental conditions and real-world driving scenarios was not performed. Future research may incorporate adaptive threshold estimation, machine learning-based fault prediction, cloud-based data analytics, and advanced battery health estimation techniques to further improve monitoring accuracy, predictive maintenance capability, and overall system reliability.

V.CONCLUSION

This paper presented a Smart EV Battery Monitoring and Fire Prevention System that enhances the safety, reliability, and operational performance of lithium-ion batteries used in electric vehicles. The proposed system integrates an ESP32 microcontroller with voltage, current, temperature, and gas sensors to continuously monitor critical battery parameters in real time. By comparing sensor readings with predefined safety thresholds, the system effectively detects abnormal operating conditions such as over-voltage, under-voltage, over-current, overheating, and gas leakage.

Experimental evaluation demonstrated that the developed prototype successfully identified fault conditions and activated appropriate protective mechanisms, including battery disconnection through a relay module, audible warning alerts, thermal management, and location tracking during emergency situations. The integration of these monitoring and protection features into a single embedded platform significantly improves battery safety while reducing the risk of thermal runaway and fire hazards.

The proposed system offers a low-cost, scalable, and IoT-enabled solution that can be implemented in electric vehicles, electric two-wheelers, and battery energy storage systems. Overall, the developed prototype demonstrates the feasibility of intelligent real-time battery monitoring and fire prevention for modern electric mobility applications. Future work may focus on incorporating machine learning-based fault prediction, cloud-based remote monitoring, and advanced battery health estimation techniques to further improve system accuracy, predictive capability, and long-term reliability.

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