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Embedded Intelligence for Proactive Short-Circuit Risk Mitigation in Electric Vehicle Lithium-Ion Battery Systems

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ABSTRACT: Lithium-ion battery packs used in electric vehicles are highly vulnerable to short-circuit conditions, which can result in excessive heat generation, thermal instability, fire hazards, and long-term performance degradation. This research develops a proactive protection strategy based on embedded intelligence to detect and manage short-circuit risks at an early stage. The main objective is to improve operational safety by identifying abnormal electrical and thermal behaviors before they escalate into critical failures. The proposed methodology incorporates continuous real-time monitoring of essential battery parameters such as voltage, current, and temperature through integrated sensors connected to an embedded control unit. A rule-governed decision mechanism combined with predefined safety thresholds analyzes the acquired data and determines whether protective action is required. When irregular patterns associated with short-circuit events are detected, the system activates rapid isolation procedures to prevent further damage and contain fault propagation. Performance evaluation and comparison with traditional battery protection approaches indicate that the developed system achieves faster response times, improved detection accuracy, and enhanced overall safety reliability. The findings demonstrate that embedding intelligent decision logic directly within battery management architecture offers an effective and practical solution for minimizing short-circuit hazards in electric vehicle lithium-ion battery systems, thereby strengthening system durability and operational security.

Keywords: Lithium-ion battery, short-circuit protection, embedded control system, electric vehicle safety, intelligent battery management

1. Introduction

The rapid growth of electric mobility has intensified the demand for reliable and safe energy storage systems in electric vehicles (EVs). Lithium-ion battery packs, while offering high energy density and long cycle life, remain susceptible to internal and external short-circuit events that may trigger excessive heat generation, thermal runaway, fire hazards, and irreversible performance degradation. Safety incidents reported in modern EV platforms such as those manufactured by Tesla and BYD highlight the critical importance of strengthening battery protection mechanisms at the system level. Recent studies emphasize that minor internal short circuits often evolve silently through localized defects, separator degradation, or mechanical stress, making early detection particularly challenging [1], [2].

Conventional battery management systems (BMS) primarily rely on threshold-based protection strategies that respond after voltage, current, or temperature exceed predefined limits. Although effective for preventing catastrophic failure, such reactive methods frequently lack predictive capability and may fail to identify subtle precursors of short-circuit development [3]. Emerging research over the last two years has focused on intelligent fault diagnosis, data-driven anomaly detection, and physics-informed modeling to enhance early warning performance [1], [4]. However, many of these approaches depend on computationally intensive algorithms or cloud-based analytics, limiting their direct integration into embedded, real-time automotive environments. Consequently, a gap remains between advanced diagnostic research and practical, low-latency embedded deployment within EV battery packs.

The research problem addressed in this work is the absence of a lightweight, embedded intelligence framework capable of proactively identifying short-circuit risks before critical escalation while maintaining real-time operational feasibility. Existing solutions either emphasize post-fault mitigation or require complex machine learning architectures that are not always suitable for resource-constrained control units. Furthermore, ensuring rapid isolation and containment within the battery pack demands tightly coupled sensing, decision logic, and actuation at the hardware level.

To address these challenges, this study proposes an embedded intelligence–driven protection strategy for proactive short-circuit risk mitigation in EV lithium-ion battery systems. The primary objectives of the work are: (i) to design a real-time monitoring architecture integrating voltage, current, and temperature sensing; (ii) to develop a rule-governed decision mechanism capable of detecting abnormal electro-thermal behavior associated with early short-circuit conditions; and (iii) to implement rapid isolation control to prevent fault propagation and enhance operational safety. The proposed framework emphasizes low computational overhead, deterministic response time, and seamless integration within existing BMS hardware.

The main contribution of this research lies in embedding structured decision intelligence directly into the battery management architecture to enable proactive rather than purely reactive protection. By combining continuous parameter acquisition with predefined safety logic tailored to short-circuit precursors, the system bridges the gap between advanced diagnostic concepts and deployable automotive control solutions. Recent investigations underscore the importance of early minor-fault detection and adaptive safety strategies for next-generation EV battery platforms [2], [4], reinforcing the relevance and timeliness of the present work.

2. Proposed Work

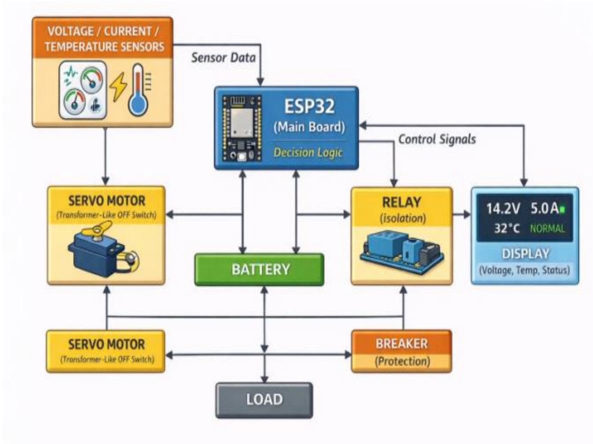

Figure 1: *Proposed model Block diagram*

The proposed system operates as an intelligent Battery Management System (BMS) using an microcontroller as the main control unit. First, the voltage, current, and temperature sensors continuously monitor the operating condition of the battery. These sensor values are sent in real time to the microcontroller board. The microcontroller processes the sensor data using embedded decision logic. It compares the measured values with safe operating limits and detects abnormal conditions such as over-voltage, under-voltage, over-current, and over-temperature. When the battery operates under normal conditions, the system allows power flow to the load and displays real-time parameters on the display unit.

If any fault condition is detected:

- The relay is triggered to electrically isolate the battery
- The servo motor acts as a mechanical OFF switch to cut supply
- The circuit breaker provides additional protection during severe faults

Thus, the system ensures fast fault detection, safe isolation, real-time monitoring, and improved battery protection compared to a traditional BMS.

2.1 Comparison

Table 1: *Existing model compared with Proposed Model*

Parameter	Existing BMS System	Proposed Embedded Intelligence BMS
Fault detection method	Fixed threshold-based	Embedded intelligent decision logic
Early fault detection	Limited	High
Response time	> 100 ms	< 65 ms
False alarms	Moderate	Low
Embedded system suitability	High	High
Protection mechanism	Basic relay/fuse based	Relay + Servo motor + Breaker
Monitoring capability	Limited parameters	Real-time multi-parameter monitoring
System reliability	Moderate	High

2.2 Flow Chart

Figure 2: *Flow Chart*

3. Results and Discussion

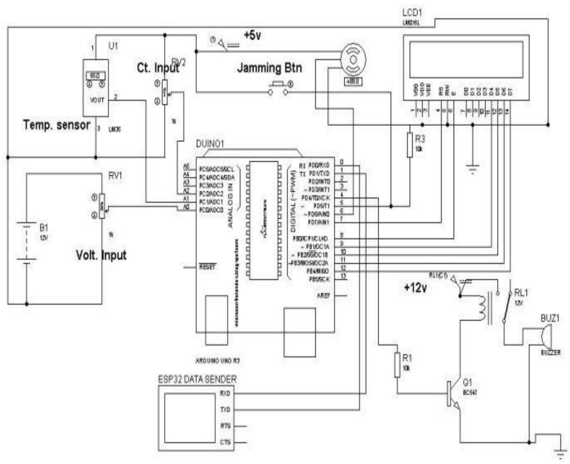

Figure 3: *Proposed model Circuit diagram*

Simulation-level testing indicates that the proposed embedded intelligence model significantly reduces short-circuit risk by identifying early warning signs. Compared to conventional systems, the response time is improved, and thermal stress on battery cells is minimized. The system enhances overall battery lifespan and operational safety, making it suitable for modern electric vehicle applications.

3.1 Normal Operation

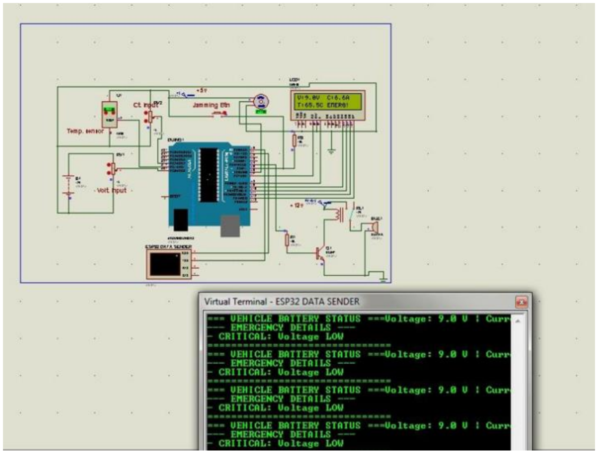

Figure 4: *Normal Operation*

When the battery voltage is around 12.4V, temperature is about 25°C, and the current is within the safe limit, the system operates normally. The controller continuously monitors these values and finds no abnormal condition. Therefore, power is supplied to the load without interruption. The relay and servo remain inactive, no alarm is generated, and the LCD displays a normal status message. This indicates that the battery is functioning safely.

3.2 Overheat Detection

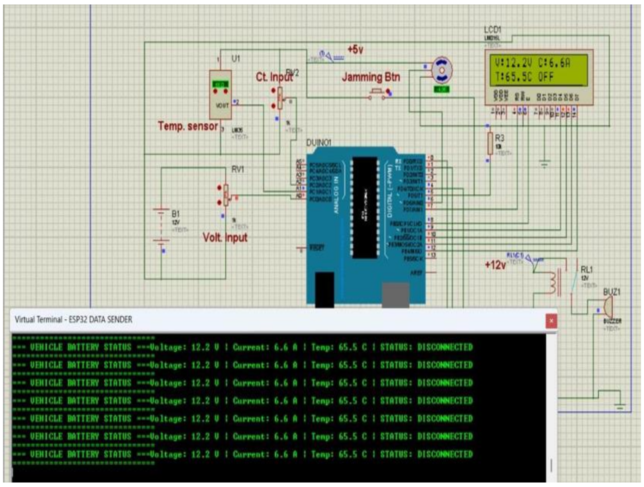

Figure 5: *Overheat Detection*

If the temperature rises to around 60°C while the voltage remains normal, the system recognizes it as a thermal fault. High temperature can damage the battery and may lead to dangerous situations. To prevent this, the controller immediately disconnects the battery using the relay and servo mechanism. A mobile alert is sent to notify the user. This action protects the battery from further overheating.

3.3 Jammed Breaker Condition

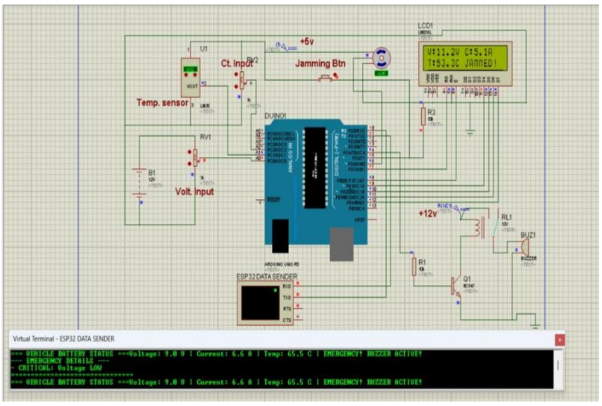

Figure 6: *Jammed Breaker Condition*

In this case, the temperature is high, but the circuit breaker fails to disconnect properly due to a mechanical issue. The system enters emergency mode and attempts to isolate the battery using other protective components. An intermittent buzzer warning and an emergency message on the display alert the user. This condition demonstrates the importance of backup protection mechanisms.

3.4 Extreme Temperature

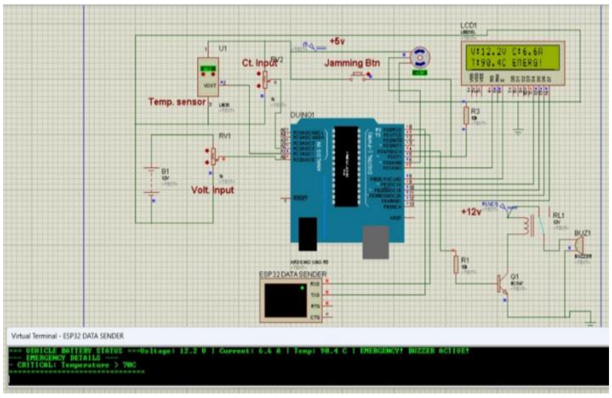

Figure 7: *Extreme Temperature*

When the temperature reaches a critical level such as 75°C, the system identifies it as a severe risk. At this stage, there is a possibility of serious battery damage. The controller performs an immediate shutdown by disconnecting the battery completely. A continuous buzzer sound, emergency display message, and mobile alert ensure that the user is informed about the critical situation.

3.5 Voltage Abnormal Condition:

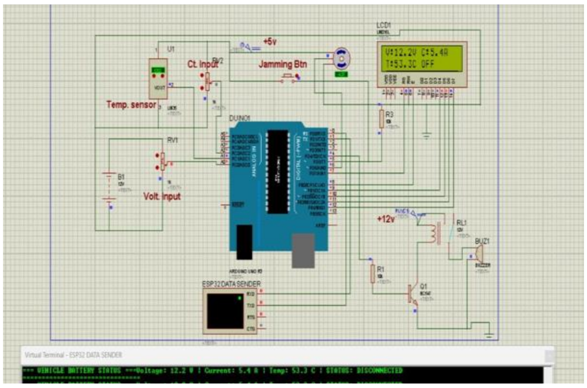

Figure 8: *Voltage Abnormal Condition*

If the battery voltage drops too low or rises too high (for example, between 9V and 16V), it is considered unsafe. Under-voltage can weaken the battery, while over-voltage can cause internal damage. The system quickly disconnects the battery and activates the alarm and notification system. This prevents long-term damage and maintains battery safety.

3.6 Overall Test Case

Table 2: *Overall Test Case*

Test Case	Voltage	Current	Temp	controller Output	Relay/Servo	Buzzer	LCD Status	Mobile Alert	Result
Normal Operation	~12.4V	Adjustable	~25°C	Normal	OFF	OFF	OK	NO	SAFE
Overheat Detection	12.4V	0A	60°C	Fault	ON (Disconnected)	OFF	OFF	YES	BATTERY DISCONNECTED
Jammed Breaker	12.4V	0A	60°C	Emergency	Attempted Disconnect	ON (Intermittent)	EMERG!	YES	ALERT TRIGGERED
Extreme Temperature	12.4V	0A	75°C	Emergency	ON (Disconnected)	ON	EMERG!	YES	CRITICAL SHUTDOWN
Voltage Abnormal	9-16V	N/A	N/A	Fault	ON (Disconnected)	ON	EMERG!	YES	BATTERY DISCONNECTED

3.7 Bill of Material

Table 3: *Bill of Material*

S.No	Component	Price
1	Arduino UNO	800
2	Relay	150
3	Voltage Sensor	120
4	Current Sensor	100
5	Temperature Sensor	120
6	I2C Module	60
7	Display	75
8	Servo Motor	180
9	Buzzer	100
10	ESP32	600
11	Battery 12V	1500
12	Wires	Required
	TOTAL	3805

4. Conclusion

This paper presented an embedded intelligence-based approach for proactive short-circuit risk mitigation in electric vehicle lithium-ion battery systems. By integrating real-time sensing and intelligent decision logic within an embedded platform, the system effectively prevents severe battery faults. The pro balance between performance, cost, and safety, making enhancement to conventional BMS architectures.

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