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Electric Vehicle Integrated Battery Management System Using IOT

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Abstract:
The operational efficiency and longevity of electric vehicles are fundamentally dependent on lithium-ion battery packs, which are highly sensitive to variations in operating temperature and electrical load. Uncontrolled heat accumulation not only hastens component degradation but also poses severe safety threats, including the potential for thermal runaway. Addressing these challenges, this research details the development of a smart Battery Management System (BMS) equipped with an active Peltier-based thermal regulation unit. The system is engineered to provide continuous oversight of critical parameters—voltage, current, and temperature—while utilizing embedded logic to estimate both State of Charge (SoC) and State of Health (SoH). A key feature of the design is its automated protection protocol, which triggers the Peltier cooling module when thermal limits are exceeded and simultaneously derates motor power to mitigate stress on the battery. Constructed around an ESP32 microcontroller and affordable sensor arrays, the prototype has been validated through extensive hardware testing. The results confirm the system's capability to enforce effective temperature control and real-time monitoring, offering a cost-effective and compact safety solution tailored for small electric vehicles and energy storage applications.

Keywords: Lithium-ion battery packs, Battery Management System (BMS), Peltier-based thermal regulation, State of Charge (SoC), State of Health (SoH), ESP32 microcontroller.

1. Introduction

The accelerating adoption of electric mobility demands intelligent Battery Management Systems (BMS) to mitigate the inherent risks of lithium-ion batteries, such as thermal runaway and performance decay. This project presents a scalable **Battery Health Management System prototype** designed to ensure operational safety and longevity in electric vehicles (EVs).

The system utilizes a microcontroller-based architecture to process real-time data from precision sensors. A critical feature is the **active thermal control loop**: if temperatures breach safety thresholds, the system automatically triggers cooling mechanisms and derates motor power. This dual-response strategy mimics commercial EV logic to effectively minimize thermal stress.

Beyond safety, the system emphasizes diagnostic transparency. Key metrics—including **State of Charge (SoC), State of Health (SoH), voltage, and temperature**—are visualized in real-time via a digital interface. Validated on a single-cell module but designed for multi-cell scalability, this prototype effectively bridges the gap between advanced sensing, safety logic, and user awareness, contributing to safer and more efficient electric transportation.

2. Literature Review

Recent studies consistently highlight that an effective Battery Management System (BMS) must continuously monitor battery voltage, current, and temperature to ensure safety, reliability, and long service life in electric vehicles. ESP-based implementations demonstrate that real-time sensing combined with embedded computation can successfully estimate key battery states such as State of Charge (SoC) and State of Health (SoH). Techniques such as coulomb counting and energy-based estimation are widely used due to their simplicity and suitability for real-time systems. Research also emphasizes that accurate sensing is critical, as errors in voltage, current, or temperature measurements directly affect SoC/SoH accuracy and fault detection. These works establish the foundation for small-scale yet functional BMS designs suitable for prototyping and academic research.

Thermal management emerges as one of the most critical aspects of battery health, as elevated temperatures significantly accelerate degradation and pose safety risks. Multiple studies demonstrate the effectiveness of active cooling systems using Peltier (thermoelectric) modules to maintain battery temperature within safe limits. Peltier-based systems have been shown to both cool overheated batteries and stabilize temperature under fluctuating conditions, thereby extending battery lifespan and improving operational safety. Literature confirms that integrating temperature-based control logic—such as activating cooling beyond a defined threshold and reducing electrical load—can prevent thermal runaway and reduce long-term capacity fade. These findings directly support the use of Peltier modules as an innovative and practical cooling solution in the proposed project.

3. Methodology

A. Parameter Measurement

The Battery Management System (BMS) continuously monitors key battery parameters to ensure safe and efficient operation. At startup, the ESP32 microcontroller initializes all sensors, communication interfaces, display units, and control outputs, while predefined voltage, current, and temperature thresholds are loaded for fault detection.

During each control cycle, battery voltage, current, and temperature are measured in real time using dedicated sensing circuits and temperature sensors mounted on the battery surface. These parameters are sampled at fixed intervals to maintain consistency and reliability. Battery temperature is treated as a critical safety parameter due to its strong impact on degradation and thermal stability. For initial validation, temperature rise is simulated at a controlled rate of 1 °C per second; in practical operation, this is replaced by real-time sensor data.

B. Parameter Calculation and Estimation

Measured electrical parameters are processed to compute battery power and energy consumption. These values serve as inputs for battery health estimation.

The State of Charge (SoC) is calculated using the coulomb counting method, where the battery current is integrated over time relative to the rated capacity:

$$SoC(t) = SoC(t-1) - \frac{I(t) \cdot \Delta t}{C}$$

Where $I(t)$is the battery current, $\Delta t$is the sampling interval, and $C$is the rated battery capacity.

The State of Health (SoH) is estimated using a stress-based degradation model. Expected energy transfer derived from SoC variation is compared with the actual measured energy from voltage–current integration. Deviations indicate battery aging, while prolonged high current and elevated temperature operation contribute to gradual SoH reduction.

C. Control and Protection Actions

Based on calculated parameters, a rule-based protection algorithm evaluates battery operating conditions. Overvoltage and undervoltage conditions trigger charging or discharging restrictions, while excessive current draw results in load reduction to minimize electrical stress.

Thermal protection is implemented as a key control function. When battery temperature exceeds 40 °C, an active Peltier-based cooling system is activated, and the electric vehicle motor load is derated by approximately 25% to reduce thermal and electrical stress. If unsafe conditions persist, the system initiates a controlled motor cutoff to prevent battery damage.

D. Data Display and Cloud Storage

All measured and computed parameters—including voltage, current, temperature, power, SoC, SoH, motor status, and cooling state—are displayed locally on an OLED interface for real-time monitoring.

For remote monitoring and long-term analysis, the system integrates with the ThingSpeak cloud platform. The ESP32 establishes a secure Wi-Fi connection and transmits telemetry data using authenticated API channels. Uploaded data are archived on the cloud, enabling remote visualization, historical trend analysis, and fault diagnosis.

E. System Operation Cycle

The BMS operates in a continuous closed-loop cycle consisting of parameter measurement, calculation, control action execution, and data visualization and logging. This structured, flowchart-driven operation ensures timely response to changing conditions and demonstrates the effective integration of sensing, estimation, protection, thermal management, and cloud-based monitoring in an intelligent battery health management system for electric vehicle applications.

4. Mathematical Calculations

The system under consideration employs a lithium-ion battery as the primary energy storage element, operating at a nominal voltage of 12 V with a rated capacity of 2 Ah. During normal operation, the measured battery voltage is observed to be 11.8 V, indicating healthy operating conditions close to the nominal value. The battery supplies a load current of 1.2 A, which lies well within the safe operating limits for the selected capacity. The system is evaluated under an ambient temperature of 28 °C, representing standard room-temperature conditions. All measurements and estimations are updated at a time interval of 1 second, allowing real-time monitoring and control. At the beginning of operation, both the State of Charge (SoC) and State of Health (SoH) are assumed to be 100 %, serving as reference initial conditions for subsequent calculations and performance assessment.

1. **Power Calculation (Normal Condition)**

$$P = V \times I$$
$$P = 11.8 \times 1.2 = 14.16 \text{ W}$$

Battery is delivering **14.16 W**, which is within safe operating limits.

2. **State of Charge (SoC) Calculation**
Coulomb Counting Method

$$\Delta Q = I \times \Delta t$$
$$\Delta Q = 1.2 \times 1 = 1.2 \text{ As}$$

Convert rated capacity to Coulombs:

$$2 \text{ Ah} = 2 \times 3600 = 7200 \text{ As}$$

SoC reduction:

$$\Delta\text{SoC} = \frac{1.2}{7200} \times 100$$
$$\Delta\text{SoC} = 0.0167\%$$

Updated SoC:

$$\text{SoC}_{new} = 100 - 0.0167 = 99.98\%$$

Battery charge level remains **healthy and stable**.

3. **State of Health (SoH) Calculation**
Energy Deviation Method

$$\Delta E = \mid E_{expected} - E_{measured} \mid$$
$$\Delta E = \mid 14.43 - 14.16 \mid = 0.27 \text{ J}$$

Percentage deviation:

$$\text{Deviation} = \frac{0.27}{14.43} \times 100 = 1.87\%$$

SoH estimation:

$$\text{SoH} = 100 - 1.87 = 98.13\%$$

SoH = 98.13%, indicating **very healthy battery condition**.

5. Components

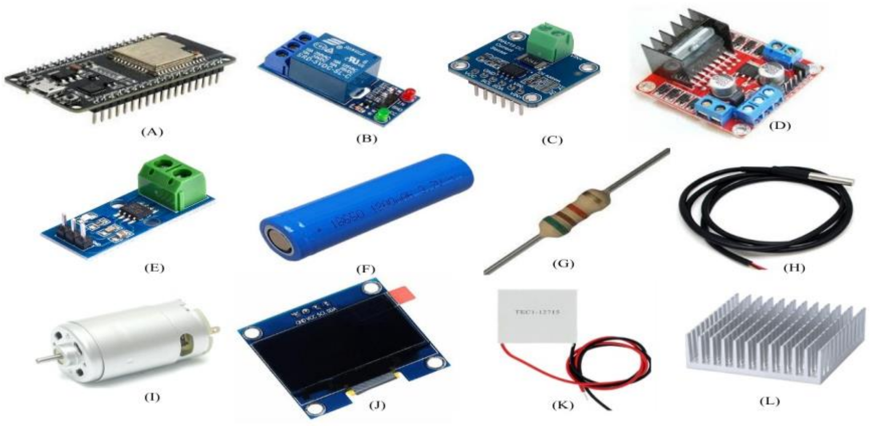

Fig.1 Components of Battery Management System

A. ESP32

The ESP32 is a high-performance system-on-chip that combines a microcontroller with wireless communication capabilities on a single platform. It delivers substantial computational performance while maintaining a compact physical footprint. The device supports integrated Wi-Fi and Bluetooth connectivity, offers multiple GPIO interfaces, and operates at clock speeds of up to 240 MHz Furthermore, it is designed to support real-time processing applications with efficient power consumption. The ESP32 architecture is highly integrated, incorporating antenna switching circuitry, RF balun, power amplification units, low-noise receiver amplifiers, signal filtering components, and on-chip power management modules.

B. Relay and Transistor

A 5V SPDT relay, driven by a generic NPN switching transistor (such as the BC547 or 2N2222), acts as the robust electromechanical safety switch for the circuit. The transistor amplifies the low-current control signal from the ESP32 to energize the relay coil, which in turn physically disconnects the high-current path to the motor during critical failures like thermal runaway, ensuring complete system isolation.

C. INA219

The INA219 is a current and power monitoring sensor that communicates through an I²C compatible interface. It is capable of monitoring both voltage and current with a maximum accuracy of 0.5% across a wide temperature range (–40°C to 125°C). The device can sense bus voltages from 0 to 26 V while operating from a supply voltage between 3 and 5.5 V and consuming approximately 1 mA of supply current. A programmable calibration register, in combination with an internal scaling multiplier, allows direct measurement of current in amperes.

D. H-bridge motor driver module

The L298N is a dual H-bridge motor driver module designed to control inductive loads such as relays, solenoids, DC motors, and stepper motors. It enables independent bidirectional control of two motors, each capable of delivering currents of up to 2 A. The module interfaces easily with microcontrollers and operates over a wide supply voltage range from 6 V to 35 V. The board is equipped with power LED indicators, an onboard 5 V voltage regulator, and protection diodes to ensure reliable operation. Additionally, the enable inputs are TTL-compatible; when the enable pin is set to a low logic level, the corresponding H-bridge is disabled. Pulse-width modulation (PWM) signals can be applied to the enable pins to regulate motor speed, which requires removal of the default jumper that otherwise connects the enable pin to 5 V for full-speed operation.

E. ACS712 Current Sensor

The ACS712 is a Hall-effect based current sensor integrated into the battery's discharge path to measure the flow of current in real-time, which is fundamental for calculating the State of Charge (SoC) via Coulomb counting. Operating on a 5V supply with a measurement range of ±5A (for the ACS712-05B variant), it outputs an analog voltage proportional to the current, allowing the microcontroller to detect over-current faults and monitor energy consumption with high precision.

F. Li-Ion Battery (18650)

The primary energy storage unit for this system is a cylindrical 18650 Lithium-Ion cell, chosen for its high energy density and relevance in modern electric vehicle battery packs. With a nominal voltage of 3.7V and a capacity of 1200mAh, a combination of such three cell serves as the device under test (DUT), allowing the BMS to monitor critical parameters such as voltage sag, capacity degradation, and thermal response under load.

G. Resistors

Fixed-value carbon film resistors, typically rated at 0.25W with ±5% tolerance, are utilized throughout the circuit to maintain signal stability and protect sensitive components. Specifically, a 4.7kΩ pull-up resistor is essential for the DS18B20's 1-Wire communication data line, while 220Ω to 1kΩ resistors are employed to limit current flowing into the LED indicators and the base of the switching transistors.

H. DS18B20

The DS18B20 is a precision digital thermometer placed in direct physical contact with the battery cell to enable active thermal management. Capable of measuring temperatures from -55°C to +125°C with ±0.5°C accuracy and powered by 3.0V–5.5V, it provides the critical thermal data required for the ESP32 to execute safety protocols, such as motor derating at 45°C and emergency shutdown at 50°C.

I. DC Motor

A 12V DC motor is employed as the system's electrical load to simulate the dynamic power demands of an electric vehicle's powertrain. Rated for a typical load current of 0.3A to 1A, this component is controlled via Pulse Width Modulation (PWM), allowing the project to practically demonstrate speed regulation and the system's protective derating response during high-temperature events.

J. OLED Display

The 0.96-inch OLED module serves as the visual interface for the BMS, communicating via the I2C protocol to display real-time telemetry such as voltage, current, and temperature. With a high resolution of 128x64 pixels and low power consumption, it offers a clear and immediate dashboard for users to monitor the battery's health and view alert notifications without external equipment.

K. Peltier Module

The TEC1-12715 (Peltier Module) Thermoelectric Cooler acts as the active cooling engine for this project, tasked with preventing thermal runaway by physically pumping heat away from the battery cells. Unlike passive fans, this solid-state module is triggered by the BMS specifically when temperatures exceed 45°C, ensuring aggressive cooling during critical faults. It is a high-performance component rated for a maximum voltage of **15.4V** and a peak current of **15A**, capable of moving approximately **130 Watts** of heat to maintain the battery within its safe operating limits.

L. Heat Sink and Thermal Paste

To facilitate efficient thermal management, an aluminum heat sink is attached to heat-generating components using high-conductivity thermal paste (typically less than 3 W/m-K). This interface eliminates microscopic air gaps and maximizes heat transfer away from the source, playing a vital role in stabilizing the temperature of active cooling modules or power transistors during continuous operation.

6. Circuit Diagram of the Proposed Model

Fig.2 Circuit of proposed system

Here the software board is used as the main controller unit of the entire system. Here breadboard is designated to create a common ground and 5V supply and these connections are taken from the software board. IR detector output is connected to 9th pin of software board and two relay inputs are connected to 8th and 10th of the software board. Negatives of batteries and DC pump are connected together, and two battery positive sections are connected to NO of one relay and NO of another relay and positive sections of both the pumps are given to the commons of both the relays. Two 9 volts batteries are used to power the DC pumps. The DC pumps are used so as to make it possible to use it for higher power rating. The LED panel is connected via 12 pins to the software board. The pins are arranged as per given in Table 1.

7. Flowchart for Proposed Controlling

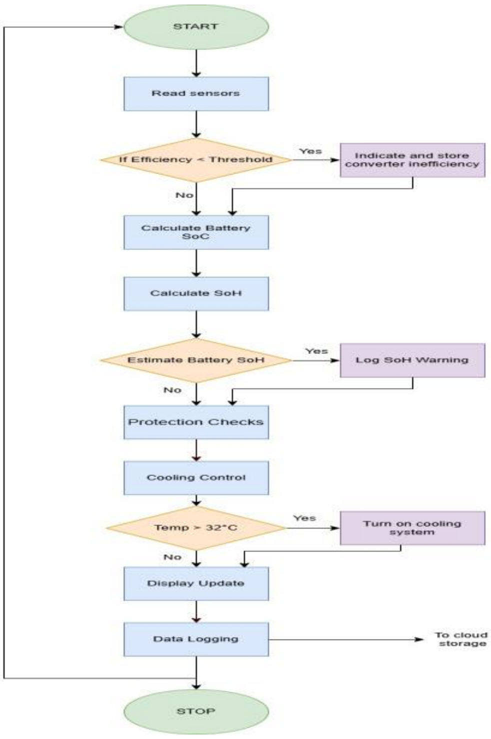

Fig.3 Flowchart for the BMS

8. Challenges and Solutions

One of the major challenges in conventional Battery Management Systems (BMS) is the reliance on glycol-based liquid cooling, which introduces complexity in terms of plumbing, leakage risk, maintenance requirements, added weight, and reduced reliability over long-term operation. This project addresses these limitations by eliminating liquid coolant altogether and replacing it with a solid-state thermal management approach using a Peltier module coupled with an optimized heat sink. The Peltier device functions as a bidirectional heat pump, enabling active cooling of the battery during overtemperature conditions and hot ambient weather, while also providing controlled heating to raise the battery temperature to its optimal operating range under cold environmental conditions. This dual-mode operation is particularly beneficial for lithium-ion batteries, whose performance and safety are highly temperature-dependent. By avoiding glycol circulation and mechanical pumps, the system reduces failure points, improves compactness, and enhances safety. At the same time, intelligent control logic ensures that thermal regulation is activated only when required, thereby minimizing energy consumption. This solid-state thermal management solution effectively overcomes the drawbacks of liquid cooling while providing precise, adaptive temperature control, making it well-suited for compact and intelligent electric vehicle battery health management systems.

9. Conclusion

The rapid adoption of electric vehicles (EVs) has created a critical need for intelligent management systems capable of mitigating the safety risks inherent in lithium-ion technology. Since these batteries are highly sensitive to thermal stress, improper monitoring can lead to accelerated degradation or catastrophic thermal runaway. This research presents a scalable Battery Health Management System (BMS) designed to transcend traditional passive monitoring by implementing active, real-time protection. centred on an ESP32 microcontroller, the architecture continuously processes sensor data to evaluate battery status and enforce safety protocols. A distinguishing feature of this design is its closed-loop thermal control: if safe temperature thresholds are breached, the system autonomously triggers active cooling and initiates a "motor derating" sequence to significantly reduce the electrical load. This proactive intervention effectively prevents thermal accumulation and enhances system longevity, offering a practical, intelligent foundation for next-generation electric mobility safety solutions.

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