A Comprehensive Review and Experimental Investigation of Cooling Techniques for Battery Thermal Management Systems in Electric Vehicles

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Abstract — Energy storage batteries, particularly lead-acid and lithium-ion batteries, are critical components in various applications, including solar photovoltaic (SPV) systems. However, their performance and lifespan are significantly influenced by temperature. This paper explores the impact of temperature on battery efficiency, charging/discharging rates, and overall lifespan. It also proposes an enhanced thermal management system using thermoelectric cooling (Peltier effect) to maintain optimal operating temperatures. The system is designed using Arduino-based components, including temperature sensors, relays, and cooling modules. The findings suggest that maintaining a temperature range of 25°C to 30°C is crucial for optimal battery performance and longevity in electric vehicles.

Keywords: Lead Acid Battery, Thermoelectric Cooling, Arduino

I. Introduction

Batteries are integral to energy storage systems, especially in standalone solar photovoltaic (SPV) applications. Lead-acid batteries dominate this sector due to their maturity, recyclability, and cost-effectiveness. However, their performance is highly sensitive to temperature variations. Lithium-ion batteries (LIBs), while more efficient, are also temperature-sensitive, with extreme temperatures affecting their capacity, resistance, and safety. This paper addresses the problem of temperature-induced degradation in energy storage batteries and proposes a thermal management system to mitigate these effects. The system uses thermoelectric cooling (Peltier effect) to regulate battery temperature, ensuring optimal performance and extended lifespan in electric vehicles.

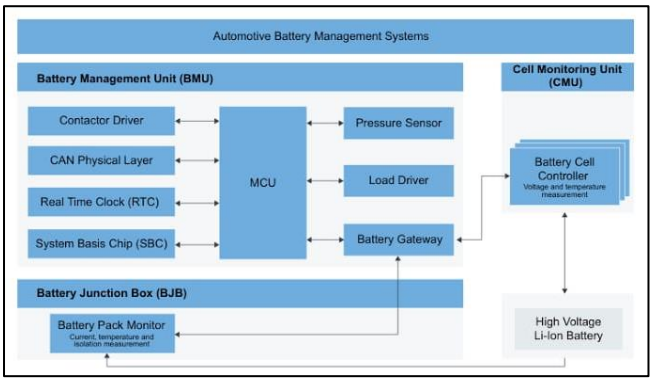

Fig. 1: Block Diagram

II. Problem Statement

Batteries operate most efficiently within a specific temperature range. For lead-acid batteries, the optimal range is 25°C to 30°C (77°F to 86°F). Deviations from this range can lead to reduced efficiency, shorter lifespan, and even safety hazards such as thermal runaway. Seasonal and regional temperature variations, especially in countries like India, exacerbate this problem in electric vehicles. For instance, temperatures in arid regions can range from 5°C in winter to 50°C in summer, making thermal management crucial.

III. Temperature Impact on Battery Performance

A. Charging and Discharging Efficiency

Temperature significantly affects the charging and discharging efficiency of batteries. Studies show that charging efficiency declines at temperatures below and above 30°C. The Arrhenius Law, which describes the temperature dependence of reaction rates, is often used to model this behavior.

B. Voltage Drop and Current Acceptance

Temperature also influences the voltage drop and current acceptance during charging. Higher temperatures generally lead to higher charging currents, but excessive heat can degrade battery components of electric vehicles. Conversely, low temperatures reduce the battery's ability to accept charge, leading to underperformance.

C. Lithium-Ion Batteries (LIBs)

LIBs are particularly sensitive to temperature. High temperatures can accelerate capacity fade and increase internal resistance, while low temperatures can reduce discharge rates and overall performance. Maintaining an optimal temperature range is crucial for LIBs to ensure safety and longevity.

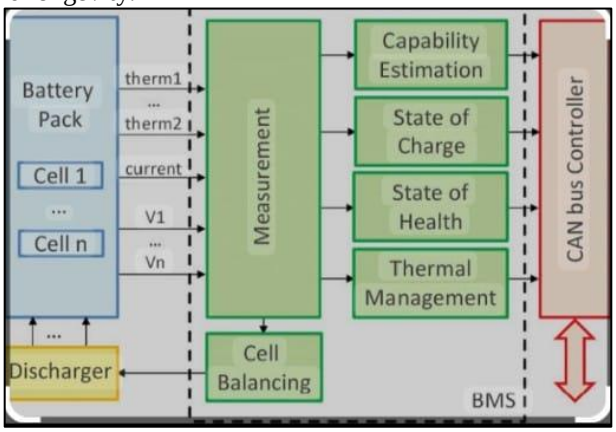

Fig. 2:

IV. PROPOSED THERMAL MANAGEMENT SYSTEM

A. System Design

The proposed system uses a thermoelectric cooler (TEC1-12706) based on the Peltier effect to regulate battery temperature in electric vehicles. The system includes the following components:

Arduino UNO acts as the microcontroller for the system. Temperature Sensor (DS18B20) monitors the battery temperature. Relay Module controls the cooling system based on temperature readings. LCD Display real-time temperature data. Thermoelectric Cooler (TEC1-12706) provides active cooling to maintain optimal battery temperature.

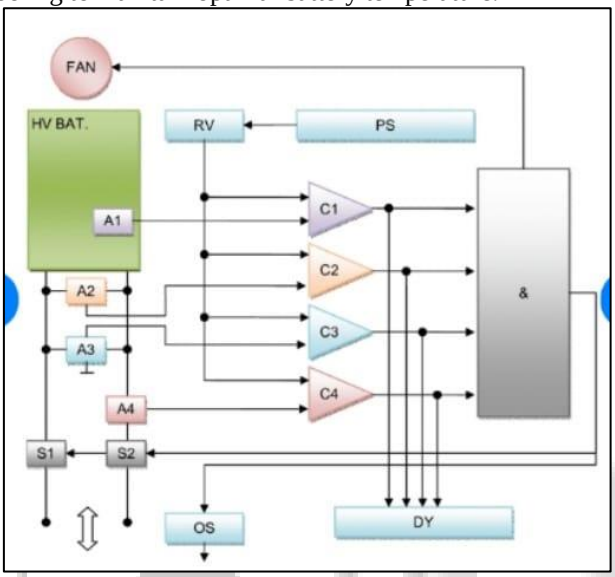

Fig. 3:

B. Working Principle

The system continuously monitors the battery temperature using the DS18B20 sensor. If the temperature exceeds the optimal range (25°C to 30°C), the Arduino activates the thermoelectric cooler via the relay module. The LCD display provides real-time feedback on the battery temperature and system status.

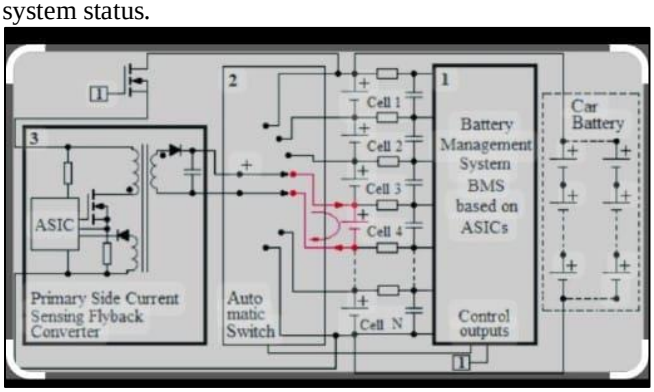

Fig. 4:

C. Hardware Implementation

The hardware setup includes wiring the temperature sensor, relay module, and thermoelectric cooler to the Arduino. The system is programmed to activate the cooling mechanism when the temperature exceeds 28°C and deactivate it when the temperature returns to the optimal range.

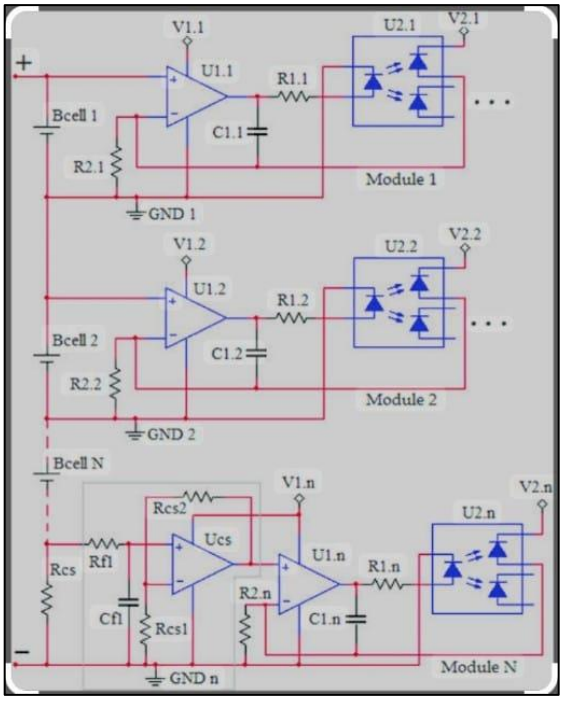

Fig. 5:

V. RESULTS AND DISCUSSION

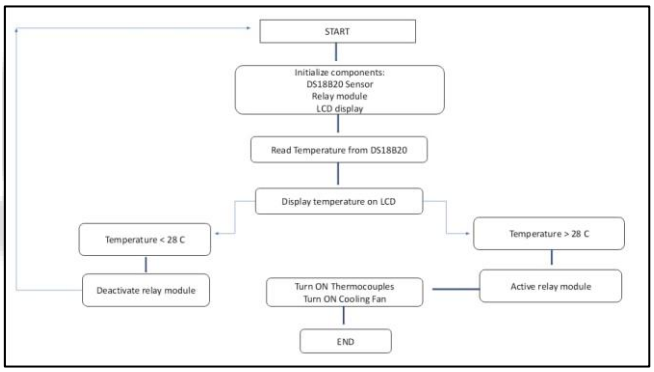

Fig. 6: Flowchart for Heat Management System

Time	Temperature	Activation
Start	26	FAN OFF
11.00 AM	27	OFF
12.00 PM	28	OFF
12.35 PM	35	ON
1.05 PM	27	OFF
2.00 PM	38	ON
2.45 PM	27	OFF

A. Advantages

- Extended Battery Life: Proper temperature regulation prevents overheating, reducing the risk of premature battery failure.
- Improved Performance: Maintaining optimal temperatures ensures consistent performance and reliable power output.
- Reduced Risk of Thermal Runaway: Effective cooling minimizes the risk of thermal runaway, a dangerous condition that can lead to battery failure or fire.
- Suitability for High-Temperature Environments: The system is particularly beneficial in regions with high

ambient temperatures, where batteries are prone to overheating.

B. Challenges

The system adds complexity and cost to the battery setup, requiring additional components such as fans, heat sinks, and cooling fluids. Regular maintenance is needed to ensure the system's proper functioning, including monitoring fluid levels and replacing worn-out parts. Cooling systems consume energy, which can reduce the overall efficiency of the battery system. Additional space is needed for cooling components, which may limit the available space for other applications.

VI. Conclusion

This research paper provides a comprehensive overview of the challenges associated with temperature management in energy storage batteries and proposes a practical solution using thermoelectric cooling. The findings highlight the importance of temperature regulation in enhancing battery performance and lifespan of electric vehicles. The study concludes that maintaining an optimal temperature range of 25°C to 30°C is crucial for the efficient operation and longevity of energy storage batteries. The proposed thermoelectric cooling system offers a viable solution for temperature regulation, particularly in high-temperature environments. However, the system's complexity, cost, and energy consumption must be carefully considered in its implementation.

VII. Future work

Future research could focus on optimizing the cooling system's energy efficiency and exploring alternative cooling methods, such as liquid cooling by nanomaterials, which may offer better performance for industrial applications.

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