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Research Article

Intelligent Hybrid Thermal Management System for Enhanced Electric Vehicle Battery Performance

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ABSTRACT

A multi-tier cooling system has been proposed for the high-performance electric vehicle (EV) battery packs to enhance thermal regulation and improve battery efficiency. The Li-ion batteries, which have mostly been used in electric vehicles (EVs), feature high energy density and a favourable power-to-weight ratio. These features, along with their capacity retention through numerous charge cycles, make them suitable for electric mobility. However, their performance optimizes between a temperature range of 20°C to 25°C. In case of excess heat, especially at high rates of discharging, it can derange their life cycle and range. A three-stage cooling strategy has also been put into practice. In the first stage, air cooling has been performed at the time of moderate heat ranges. If the elevated temperature is to last, a system powered by high power air cooling with a coolant and a pump is turned on to enhance the cooling of the battery. In the third stage, TEGs are deployed in order to keep the temperature of the battery above 25°C. All phases of this thermal management system control and command using intelligent control algorithms and microcontroller-based hardware and make real-time adaptations to temperature changes. All extreme thermal fluctuations are thus minimized, contributing to extended battery life, enhanced safety, and the promotion of more sustainable EV technologies.

Keywords: Electric Vehicle Technology, Hybrid Cooling Technology, Battery Thermal Management System, Thermo- electric- generators.

INTRODUCTION

As the adoption of electric vehicles (EVs) increases, so does the demand for high-performance battery packs that can operate efficiently under diverse environmental conditions also increases [1]. Temperature is a critical factor affecting the performance, lifespan, and safety of these batteries. Extreme temperatures, whether high or low, can reduce energy capacity, accelerate degradation, and pose safety risks such as thermal runaway. While traditional thermal management systems for EV batteries rely on passive or basic active cooling methods, these systems often fall short in managing the thermal dynamics of high-performance battery packs under challenging conditions, such as rapid charging, extended driving, or extreme ambient temperature [3]. This highlights the need for advanced thermal management solutions that ensure optimal battery temperatures, particularly given the automotive industry's focus on improving fuel economy and reducing emissions, which are especially critical in the logistics sector [16]. Lithium-ion batteries, widely used in EVs, have gained popularity due to their high energy density, long cycle life, and ability to deliver consistent performance. However, their safety and performance are significantly impacted by temperature increases during high discharge currents or elevated ambient conditions, which can lead to thermal runaway [24]. Modern thermal management systems (BTMS) are designed to address these issues.

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Advanced solutions include air cooling, heat pipe cooling, liquid cooling, and the use of phase change materials (PCMs). Among these, liquid cooling systems are considered the most effective due to their ability to increase the heat dissipation efficiency through enhanced contact between the battery cells and cooling pipes [23]. PCMs have also gained attention for their ability to absorb heat without a temperature rise, making them ideal for stabilizing battery temperatures in EVs [25]. The EU-funded "OPTEMUS" project has explored such technologies, integrating advanced thermal management techniques and PCMs to enhance battery lifetime and driving range [21]. Battery Management Systems (BMS) play a critical role in ensuring battery safety and optimizing performance. These systems monitor and regulate key parameters, including temperature, voltage, and current, to mitigate hazards such as thermal runaway, electrical faults, and mechanical failures [3]. Recent advancements have also focused on the early detection of internal short circuits (ISC) through real-time monitoring of current, voltage, and temperature signals, which is crucial for preventing fire accidents caused by ISC-induced thermal runaway [8]. Additionally, advanced energy storage devices and converters are being tested for next-generation EVs, offering improved thermal stability and efficiency [9][20]. As the EV market has expand-ed, stringent safety standards have been established to address the risks associated with lithium batteries. These standards focus on functional safety, which involves detecting and mitigating hazardous events to prevent accidents. The Battery Management System (BMS) plays a central role in ensuring safety by monitoring battery performance and protecting against failures. Key safety concerns, including thermal runaway, electrical faults, and mechanical failures, are addressed through hazard and risk assessments. [3]. The increasing use of lithium-ion batteries in EVs has also led to the development of advanced modelling techniques to improve thermal management. Computational Fluid Dynamics (CFD) and thermal network models are used to predict and analyze temperature effects on battery performance.

LITERATURE SURVEY:

Thermal management of electric vehicles (EVs) is imperative for battery longevity, efficiency, and safety. The widespread use of high-energy-density lithium-ion batteries has brought about overheating as a major concern. A well-designed thermal management system (TMS) addresses temperature variations, thus improving battery performance, prolonging its lifespan, and protecting functionality [1][2]. Literature has always emphasized the importance of proficient thermal regulation, especially during high-load conditions like rapid acceleration and rapid charging. During these applications, lithium-ion batteries generate high heat, which, if not efficiently managed, results in thermal runaway—a dangerous process where the production of excessive heat exceeds dissipation capacity, risking fires or explosions [3][4]. Govindharaj et al. (2022) explored a potential battery cooling system for EVs through MATLAB simulations to determine the effect of temperature variations on battery performance [1]. The research depicted how temperature variations significantly affect internal resistance and voltage characteristics, emphasizing the need for hybrid cooling systems that utilize both active and passive cooling mechanisms. Darcovich et al. (2017) explored cooling mechanisms for vehicle-to-grid (V2G) operations, comparing air and liquid cooling methods. Their findings, based on Doyle's electrochemical model, showed that liquid cooling is superior, particularly in operations involving frequent cycling of batteries [2]. Liquid cooling has been recognized as one of the best ways of providing uniform temperature distribution among battery cells. Kesuma et al. (2022) optimized liquid cooling systems for EV battery packs using computational fluid dynamics (CFD) to determine the most appropriate types of coolants and circuit designs. New technologies such as thermoelectric generators (TEGs) and phase-change cooling systems offer promise in solving thermal problems. Boiling liquid cooling was suggested by Hirano et al. (2014), in which battery cells are immersed in a high-thermal-conductivity dielectric liquid to dissipate heat during high-load conditions. But careful controls are required in order to avert operational dangers [10]. Liu et al. (2020) investigated graphene-based thermal management systems and concluded that high thermal conductivity in graphene significantly accelerates heat dissipation. The technology is compact and lightweight as a cooling technique, suitable for EV applications wherein space and weight are critical issues [11]. Takehana et al. (2021) investigated thermoelectric cooling systems for competition electric vehicles and substantiated the efficacy of thermoelectric cooling systems in maintaining optimal battery temperature in high-speed operation [20]. Air cooling continues to be an effective option in EVs, especially in cases where simplicity of operation and low cost are given importance. . The technologies will play a vital role in sustaining battery longevity, safety, and optimal performance in modern electric vehicles [16].

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PROPOSED METHODOLOGY

A pivotal shift in the future of transportation is represented by electric vehicles (EVs), which are offered as an environmentally friendly alternative to traditional internal combustion engine vehicles. One of the key advantages of EVs is their reduced greenhouse gas emissions, contributing to cleaner air and a significant reduction in fossil fuel dependency. Additionally, EVs are known for their cost- effectiveness, particularly in terms of fuel and maintenance costs, making them an increasingly popular choice among consumers and industries focused on sustainability. However, the efficient thermal management of battery packs is recognized as a major challenge in the widespread adoption of EVs. As the core energy source of EVs, these batteries need to be kept at an optimal temperature to maintain safety, performance, and longevity. Batteries can overheat during charging or discharging, which can lead to decreased efficiency, or even permanent damage to the battery cells. This methodology explores the design and implementation of a comprehensive battery cooling system, integrating sensors to monitor temperature, microcontrollers to process data, and sophisticated cooling mechanisms to regulate heat. By precisely controlling the temperature, especially during discharging, the system enhances battery performance and extends the battery's life. ensuring energy efficiency and overall safety for a more reliable EV experience. The main objective of a battery thermal management system is to maintain proper temperature, ensuring optimal performance and improved battery efficiency. Fig. 1 illustrates the functional block diagram of the hybrid cooling system. The process starts with the detection of temperature using a temperature sensor. The sensor output will be transferred to the controller, and the controller will make the controller action. There are three stages of the cooling system implemented. The first stage is the mid-range of temperature (from 25 to 50 degrees Celsius), when the temperature belongs to this temperature, the motor connected to the cooling fan will be executed. The second stage belongs to temperatures ranging from 50 to 90 degrees Celsius, and in this stage, the motor connected with a suction pump will be executed. And when the temperature is more than 90 degrees Celsius, both the motors are running parallelly for better outcomes. In winter and rainy seasons, the temperature of the battery will go below 25 degrees Celsius, reducing the charging efficiency of a battery to reduce this, the Thermoelectric generators are used to maintain optimal battery temperature.

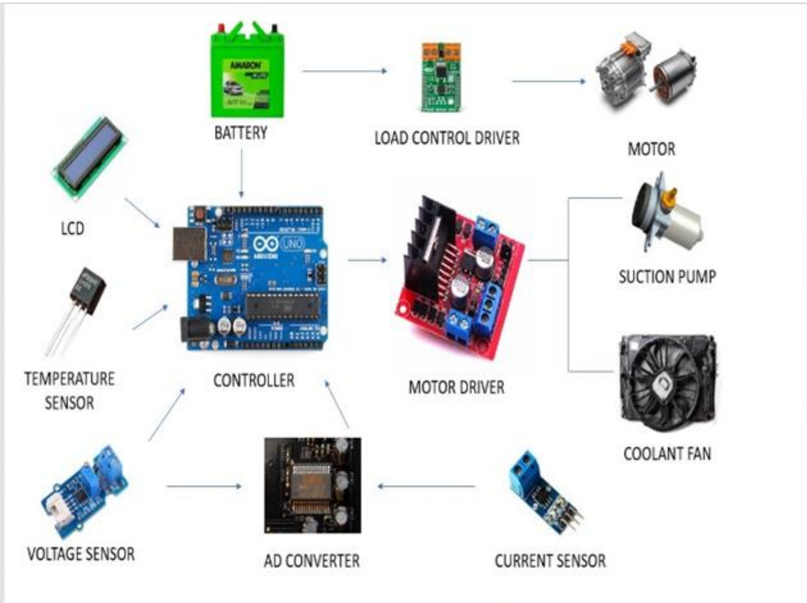

Fig. 1. Block diagram of hybrid cooling system

RESULT AND DISCUSSION

At initial condition, the battery will be set at the charged status of 10 %, and when the supply is given, the battery will slowly get charged and reach the maximum of 100 %. This will be recorded and identified as a state of charge. When the vehicle starts to move, the DC electric motor will get its source from the battery it will be measured and recorded as a state of discharge. The temperature of the battery will increase in both the state of charge and discharge. It will

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be measured by using a lm35 sensor, and the output will be transferred to the controller, and the controller will take the control action in 3 different stages.

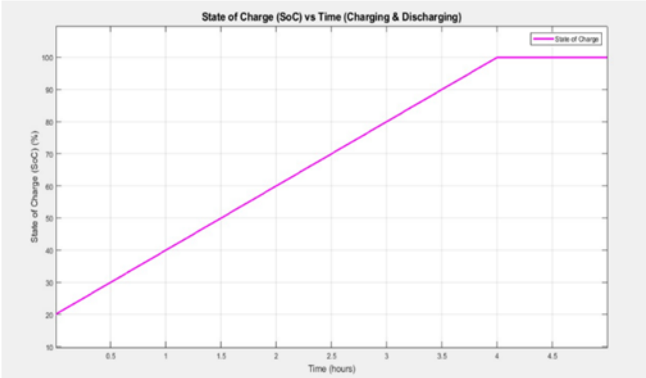

Fig. 2. State of charge of battery from 20%

Fig.2 image shows the amount of current stored in the battery and the amount of voltage discharged from the battery will be inferred.

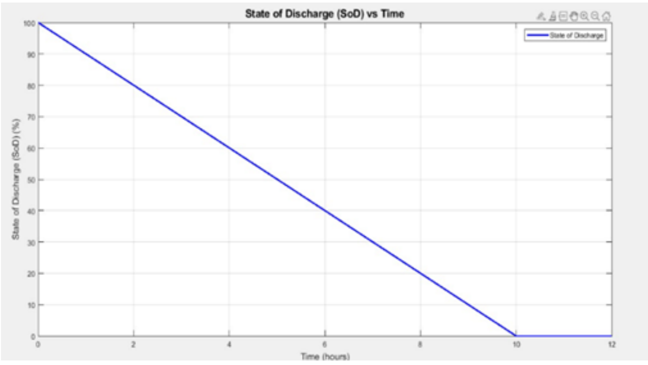

Fig. 3. Voltage discharge from battery at 25°C

In Fig.3 graph, the amount of voltage discharged from the battery when the vehicle starts moving will be measured and monitored.

When the temperature ranges from 25°C to 50°C, the controller, equipped with a coolant fan, carries out the control action. This action is initiated once the temperature reaches 25°C or higher. It is considered the most effective cooling method within this temperature range**.**

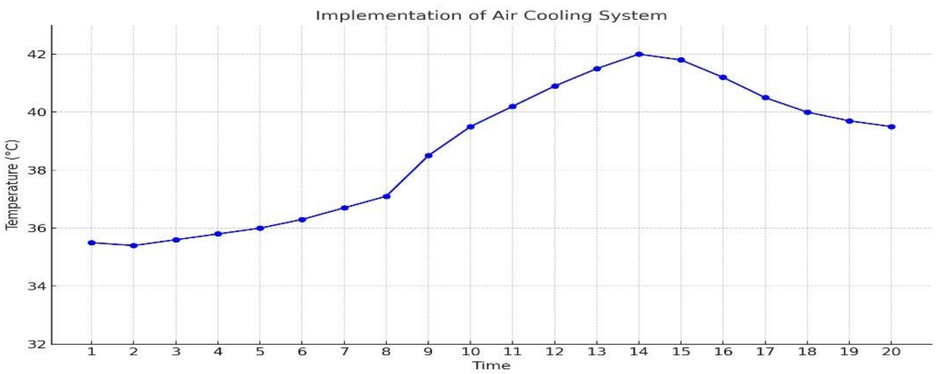

Fig. 4. Implementation of Air-Cooling System

The Fig 4 is the graph which represents the temperature of the battery which will be kept in the state of charge. The battery temperature is increasing from the optimal room temperature once it reaches above 30°C the controller will enable the air-cooling system.

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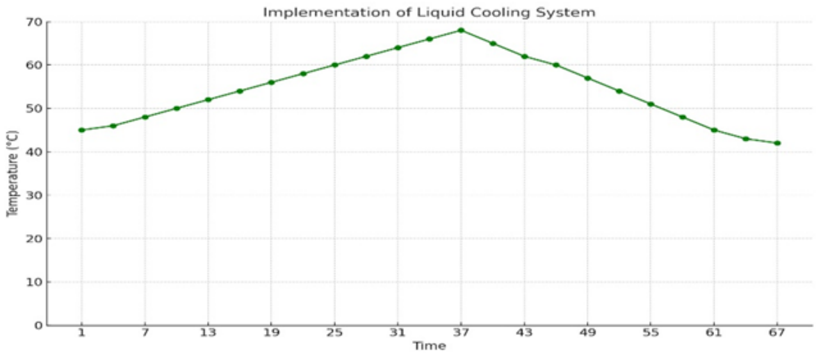

Fig. 5. Implementation of Liquid Cooling System

The Fig 5 is the graph which represents the temperature of the battery which will be kept in the state of charge. The battery temperature is increasing from the optimal room temperature once it reaches above 45°C the controller will enable the liquid-cooling system.

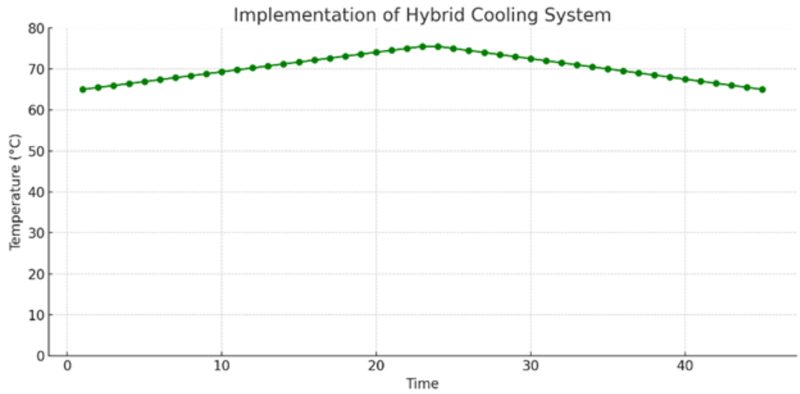

Fig. 6. Implementation of Hybrid Cooling System

The Fig 6 is the graph which represents the temperature of the battery which will be kept in the state of charge. The battery temperature is increasing from the optimal room temperature once it reaches above 45°C the controller will enable the Hybrid cooling system. The hybrid cooling system is the combination of the air-cooling System and the Liquid Cooling System.

Table 1 Comparison Summary Table of the hybrid cooling system

Temperature Range	**Control Mechanism**	**Purpose**	**Efficiency (%)**
0 °C to 25 °C	Thermoelectric Generators (TEGs)	Heat generation and maintenance	85
30 °C to 45 °C	Air-cooling system	Heat dissipation	75
45 °C to 65 °C	Liquid cooling system	Efficient temperature reduction	90
Above 65 °C	Air + Liquid cooling	Rapid temperature reduction	95

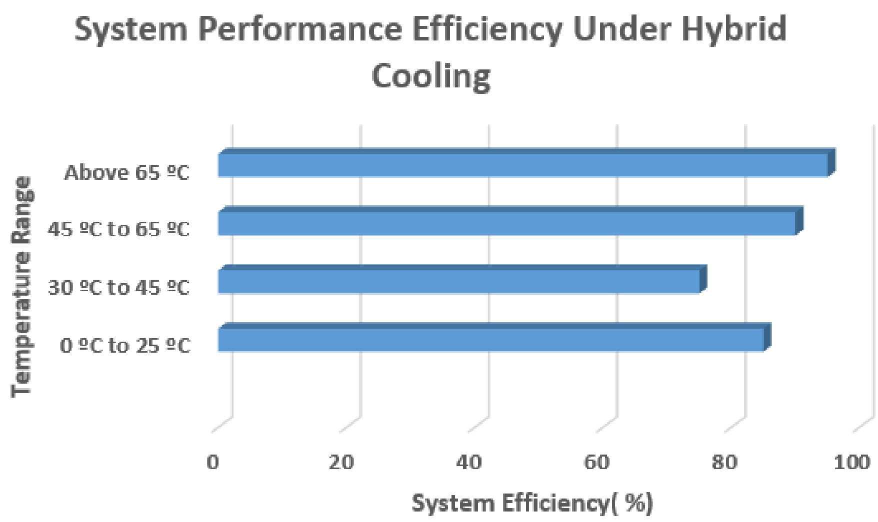

Fig. 7. System Performance Efficiency Under Hybrid Cooling

This Table.1 and Figure 7 comparative analysis demonstrates the effectiveness of various thermal management techniques in ensuring the optimal operation of the battery. By implementing the appropriate cooling or heating mechanisms, battery life can be extended, and safety risks can be minimized.

CONCLUSION

The implementation of an advanced cooling system for electric vehicle (EV) battery packs is recognized as a significant advancement in EV technology, allowing for efficient temperature control, improved battery performance, and enhanced safety. By integrating various sensors, microcontrollers, cooling mechanisms, and speed control, the system ensures that the battery is maintained within optimal temperature ranges during discharging, protecting both the battery and the EV's operation. This innovative approach underscores the ongoing commitment to sustainable and reliable electric mobility while addressing critical challenges associated with battery thermal management. This innovative approach will reduce the space complexity in an electric vehicle. The optimal temperature of a battery is 25ºC to 30 ºC, and when the temperature ranges above or below these temperatures, it will result in an issue of reducing the battery efficiency. For the first stage, When the temperature ranges from 30°C to 60°C, an air-cooling system is applied to lower the battery temperature. For temperatures between 60°C and 90°C, a liquid cooling system is utilized to decrease the heat. If the temperature exceeds 90°C, both cooling technologies are implemented simultaneously to effectively reduce the high temperature. The temperature below the optimal level will also result in a loss of efficiency to overcome the Thermo-electric Generators are used to maintain the optimal temperature. The future direction of this project includes linking the controller to the cloud, enabling remote battery temperature monitoring via a mobile device. This will help maintain the battery at an optimal temperature for improved efficiency. Additionally, a speed control module can be incorporated into the system to minimize the risk of explosions caused by high temperatures. Whenever high temperature is measured for a few minutes the speed control module will cut off the supply to the motor to improve the safety.

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