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Research Article

Enhancing battery safety and performance through advanced cooling solutions for electric vehicles

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ABSTRACT

The increasing stipulation of electric vehicles underscores the critical requirement for effective thermal management in lithium-ion battery systems, particularly during high-rate charging. Overheating and Capacity Degradation remain a primary challenge, as it impact battery safety, lifespan, and performance. The study examines a thorough evaluation of cooling techniques to improve battery packs' thermal management under situations of fast discharge. A comprehensive analysis of heat generation and dissipation mechanisms within the battery cells has been conducted to identify critical factors influencing thermal performance in battery packs. This paper has been focused on battery pack temperature and state of charge analysis at different atmospheric conditions.

The air cooling technique is evaluated through simulation studies to determine the effectiveness of maintaining an optimal temperature range. The result demonstrates significant improvement in thermal regulation, exploring the benefits and limitations of the proposed cooling strategy. Simulation studies highlight the impact of air cooling on temperature control by using an auto-tune Propotional-Integral-Derivatives controller, revealing significant improvements in thermal stability, battery lifespan, and overall efficiency by 13.11%. In addition to improving battery performance and longevity. It has been evaluated on the OPAL-RT real-time simulator's test bench. The proposed strategy enhances the overall safety and efficiency of high-power battery systems. For the creation of efficient heat management techniques in the future of battery technologies, the study offers valuable suggestions.

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INTRODUCTION

Numerous automobile manufacturers are introducing electric cars as a more advantageous and ecologically friendly option to internal combustion engine automobiles. Throughout the next few years, the number of EVs will increase rapidly [1]. Electric vehicles (EVs) are cutting-edge and difficult substitutes for conventional automobiles. They are advantageous to the environment since they have minimal running costs and may use renewable energy sources. The flourishing popularity of EVs has created problems with the management of load and effective charging infrastructure [2]. The most affordable energy storage technology for EVs at the moment is lithium-ion batteries because of their massive specific energy, high specific power, low self-discharge rate, high voltage, very long lifespan, and remarkable recyclability [3, 4]. However, Li-ion battery performance will be influenced by operation and even storage temperature [5]. Studies indicate that temperature is the key contributor to battery aging which has an adverse impact on internal resistance and capacity [6].

In battery thermal management (BTM), the most modern advances are being implemented to address the expected problems and ensure battery safety. By using a heat transfer intensification technique, the BTM technology improves battery safety by ensuring battery operation performance derived from mechanical, electrochemical, and the battery's thermo kinetic characteristics under both typical and unusual operating situations. It's also critical to maintain the proper operating temperature and avoid overheating for safe operation in optimal temperature range i.e. 15°C to 35°C.as shown in Figure.1. Thus, creating a BTM system that is dependable and safe is an important research objective [7]. This study is important because it examines innovative battery thermal management system (BTMS) techniques. They are necessary to increase lithium-ion battery's lifespan and performance in automobiles that are electrically driven. The research offers helpful recommendations for creating efficient temperature management systems in battery technologies of the future [8].

Several studies have been explained on creating an accurate thermal management system (TMS) that enhances the lifespan of battery. performance is one of the key components in the building of an electric car [9]. In practice, this issue may contain some restrictions which turn it into a constraint optimization problem. Their benefit, meanwhile, is that they can handle complicated problems far better than numerical ones, particularly in current situations with a huge number of input factors [10]. One of the issues that manufacturers are now dealing is real-time battery heating. The temperature rise in battery is the main influencing factor as a Joule's heat. Instead of using dynamic loading, various techniques were used to predict the heat generation in battery at a fixed charge/discharge rate [11]. One crucial ability that has been applied extensively to power battery cooling and preheating is the TMS of the battery at a suitable temperature. It will guarantee the power battery operates steadily and safely. Author provided a summary of status of research on the TMS for power batteries, thoroughly comparing four distinct cooling system types Phase-change materials, heat pipes, liquid cooling, air cooling, and two kinds of heating system internal and external heating heating [12]. Combining several cooling systems as shown in Figure 2 based on the benefits and drawbacks of various cooling methods is now the main growth route for Lithium-ion battery thermal management technology as given in Table 1. An appropriate cooling techniques may be chosen and combined to satisfy various thermal management user requirements [13].

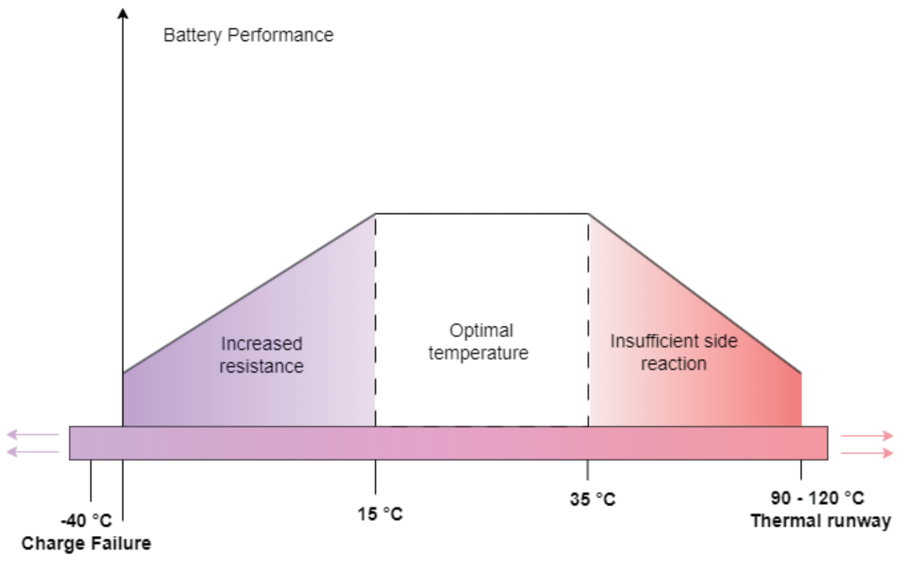


Figure 1. Temperature range of lithium-ion battery.

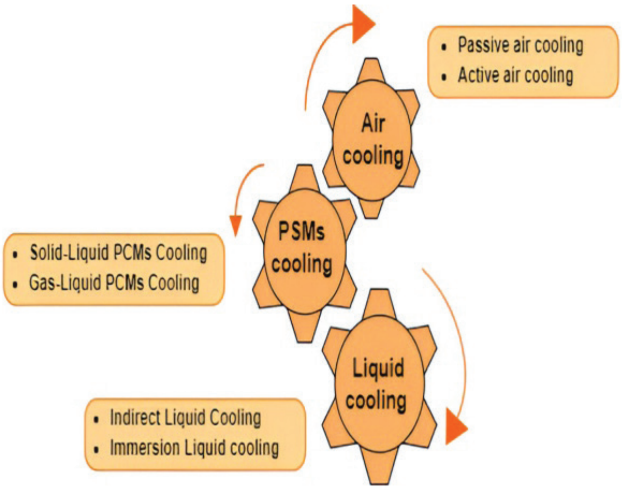


Figure 2. Different cooling technologies in BTMS.

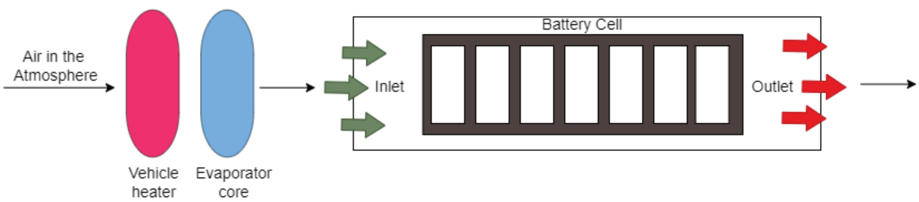
The air cooling mechanism is generally employed to decrease the temperature of battery packs. The Air cooling (AC) mechanisms are lightweight, compact scale, low viscosity, low maintenance costs, minimal expenditure, and direct and safe medium access. The principle of AC may be divided into two types: active and passive [14]. An active cooling system differs from a passive one in that the former requires a powerful motor, such as a fan to circulate air as seen in Figure 3.

Effectual heat regulation of Li-ion batteries is necessary since at what temperature they determine their performance attributes and safe operation. A number of barriers prevent the widely used cooling techniques from achieving the intended heat regulation of balanced temperatures, powerful battery distribution, and a permitted maximum temperature [15]. Efforts are being made to find cutting-edge cooling techniques that might overcome the drawbacks of existing techniques and be used in battery thermal management systems of the future [16].

Given the layout constraints of automobile batteries in Figure 4, thermal management is crucial thus, a design approach for efficient cooling should be precisely chosen [17]. In the automobile sector, in particular, forced air cooling has been seen as an affordable alternative [18]. New battery pack concepts, creative cooling channel designs, and creative thermally conductive materials significantly increase air-cooling

Table 1. The evaluation of the benefits and drawbacks of various cooling systems

Types of cooling	Thermal Conductivity	Uniform Temperature	Cost	Structure	Compactness	Weight
Air cooling	Medium	Low	Low	Low	High	Low
Liquid cooling	High	Medium	Medium	Medium	Low	High
PCM cooling	Low	High	High	High	Low	High



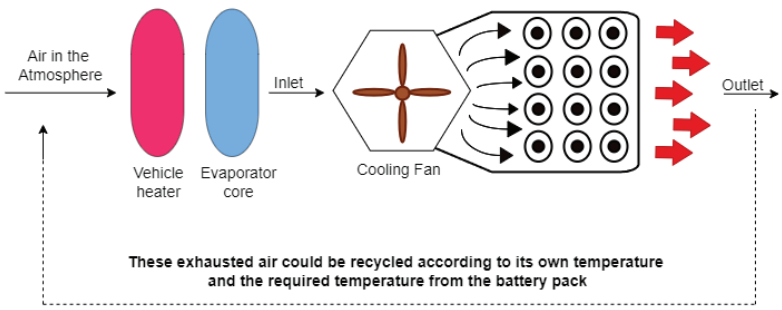


Figure 3. The air-cooling BTMS schematic design shows a) passive air cooling and b) active air cooling.

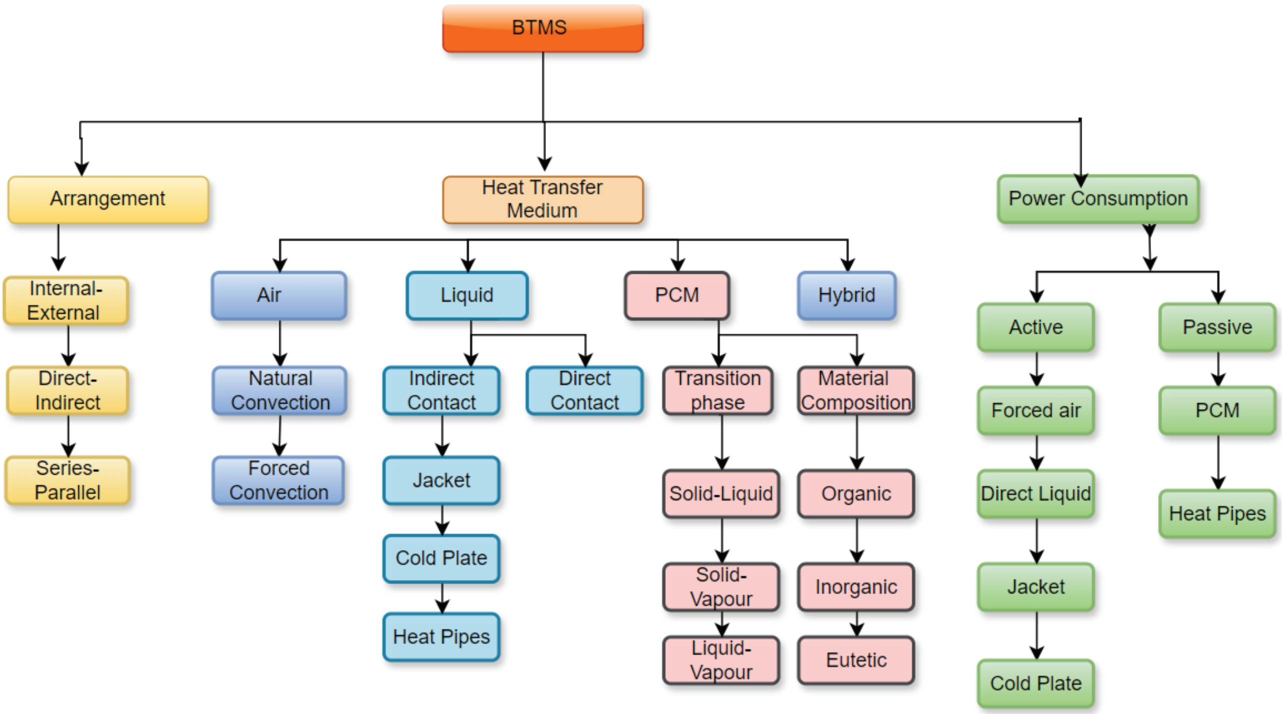


Figure 4. Classification of Li-ion battery thermal management techniques.

Table 2. Summery of cooling methods, key references and research gap

Cooling method	Research gap
Air Cooling Systems [14]	Limited suitability for high-capacity batteries.
Heat Pipe Systems [15]	Performance limitations under dynamic loads, manufacturing, and integration complexity.
Liquid Cooling Systems [16]	complex structure, larger energy consumption, heavier overall weight, liquid leakage,
Phase Change Materials (PCM)[17]	Low thermal conductivity, slow heat dissipation, integration challenges with active systems.
Hybrid Cooling Systems [21]	Increased design complexity, higher production cost, and scalability issues for large EV fleets.
Direct Refrigerant Cooling [22]	High initial cost, complex system architecture, refrigerant safety, and environmental impact concerns.

efficiency, according to rigorous testing and sophisticated computational numerical models [19]. The heat production phenomenon of Lithium-ion batteries through the charge and discharge treatments is a reason for an increase in temperature is observed surrounding Lithium batteries. One of the main types of BTMS which are utilized to increase the safety and efficiency of electric power trains, is examined in this paper. To improve different BTMS design objectives, this study specifically examines It describes air-cooled BTMS methods (design parameter optimization (both passive and active)) and techniques (using algorithms or iteration) [20].

RESEARCH MOTIVATION

Existing BMS systems frequently use static or semi-static prototypes, which are insufficient to manage the complexity of actual battery consumption, where situations vary owing to shifting operating requirements, environmental factors, and battery aging processes. This system's limited ability to adapt dynamically to new inputs of data as well as modify its execution plan serves as a strong indicator of this problem. Maintaining battery cycle life and reducing safety risks requires efficient temperature management [21]. Battery heat regulation and a classification of lithium-ion battery heat regulation methodologies, as seen in Figure 4, are essential to preserving the battery temperature within a safe range [22]. As a result, there is a significant gap in using predictive analytics, which might stop issues before they start and decrease the risks of aging as well as battery failure [23]. To prevent thermal runaway initiation, an evolution of effective battery heat regulation technologies is required. These reactions raise the internal battery temperature sharply, which destabilizes and deteriorates the internal structures of the battery and ultimately results in battery failure [24]. An essential component of electric cars is the safety performance of lithium-ion batteries, which directly affects driving distance as well as safety. A battery thermal management system (BTMS) is crucial [25]. Techniques to control the temperature in cylindrical packs of lithium-ion batteries with a focus on optimizing efficiency, safety, and life. Primary concerns for the EV system manufacturer are the battery safety issues. Maintaining the ideal temperature is one of the most significant scientific problems. It has restricted the overall use of batteries [26].

Our work has addressed the direct air-cooling technology for temperature reduction in battery packs which significantly increases system efficiency. The BMS keeps an eye on vital indicators like voltage, current and internal ambient temperature when the device is being charged. The discharged cycle is a crucial part of maintaining these batteries. Historically, assessing these batteries' charge and discharge properties has involved laborious laboratory procedures requiring oscilloscope readings. Advanced cooling solutions are essential in EVs to improve battery safety, performance and longevity. By efficiently managing battery temperatures, these systems prevent overheating, reduce degradation, and ensure stable performance.

They play a pivotal role in preventing thermal runaway supporting fast charging by dissipating heat during rapid charging sessions, and enhancing the driving range. In autonomous vehicles, predictive thermal management boosts operational reliability, while commercial and industrial EVs benefit from robust cooling systems that handle prolonged use and heavy loads. A simulation model of the BMS has been created to overcome inefficiency and expedite the testing procedure. The curves showing different charge percentages and discharge rates at various ambient temperatures will be produced using the suggested model. Furthermore, by using the current simulation framework, further investigation into how temperature and state of charge SoC affect battery performance will be possible thanks to this model.

Table 2 shows the summary of cooling methods with references and research gaps observed. The contributions of the research paper are:

1. As per the author's knowledge from a literature survey, very few researchers have focused on battery pack temprmature analysis at different atmospheric conditions.
2. An applicability and proposed design method to investigate an improved performance of battery pack.
3. Comparison of performance via simulation studies and experimental tests conducted on the OPEL-RT 4510 simulator.

These main achievements of the study are the development of an extensive modelling framework that accurately depicts the complicated nonlinearities of Lithium-ion batteries as well as the proof that it is effective enough in enhancing energy management mechanisms. The remaining part of the study is covered in the second chapter, which also covers the mathematical formulation for the SoC formula and generic battery model. The methodology of the research is covered in the third chapter and outcomes and analysis are covered in chapter four. The fifth chapter holds a conclusion for the same.

PROBLEM FORMULATION

An electrical equivalent circuit representation of Lithium-ion cells created using the MATLAB/Simulink environment is presented in this article [27]. It is discovered that the battery temperature is primarily influenced by three factors: heat production, thermal diffusion and heat conduction [28].

Charge Model

The process of adding electrical charge to a rechargeable cell or battery is known as battery charging. There are a number of different charging techniques, including burp charging, float charging, trickle charge current-voltage-current (IUI) charging, random charging, pulsed charging, taper charging, and constant current and constant voltage. The charge model is represented in Eq. (1).

These equations are used in the model for Lithium-ion batteries.

Charge Model ($I^* < 0$)

$$f_{22}(It, I*I) = V_0 - K.\frac{Q}{It+0.1.Q}.I* - K.\frac{Q}{Q-It}.It + A'.\exp(-B'.It) \quad (1)$$

The ambient temperature as well as the battery pack unbalanced charge is caused by frequent charging and discharging. When an EV is in traction, this unbalancing charge is unable to supply the necessary power requirement and may possibly result in an explosion or fire [29]. However, the battery pack needs to be protected from any hazardous conditions by safety and protection requirements.

Discharge Model

During battery discharge, the positive ions of lithium from the cathode go in the direction of the anode, reducing the stored charge. The whole charge and discharge sustain time is taken into account with the required safe period since cell and pack voltages strongly depend on charging and discharging current rates [30]. The meanings of the symbols used in equations 1 and 2 in all mathematical expressions are shown in Table 3.

The discharge model is shown as

Discharge Model ($I^* > 0$)

$$f_{12}(It, I*I) = V_0 - K.\frac{Q}{Q-It}.I* - K.\frac{Q}{Q-It}.It + A'.\exp(-B'.It) \quad (2)$$

Table 3. Lithium-ion batteries charging and discharging Model parameters.

Nomenclature:	
V_0	Constant voltage (V)
exp (s)	Exponential zone dynamics (V)
K	Polarization constant (Ah−1) or Polarization resistance(Ohms)
I*	Dynamics of low frequency current (A)
I	current in the battery (A)
It	Extracted capacity (Ah)
Q	Maximum battery capacity (Ah)
A'	Exponential voltage (V)
B'	Exponential capacity (Ah)-1

SoC Estimation Using Coulomb Counting Method

Generally speaking, the SoC of the battery is determined by dividing its nominal capacity Q (n) by its current capacity Q (t). The nominal capacity, or maximum charge that the battery can withstand, is defined by the manufacturer.

SoC is represented as

$$SoC(t) = \frac{Q(t)}{Q_{(n)}} \tag{3}$$

High charging as well as discharging efficiency Lithium-ion batteries SoC estimation may be completed quickly using the coulomb counting method. According to an investigation of the charging and discharging properties, the coulomb counting method is a practical and precise How to calculate lithium-ion batterie's state of charge (SoC) [31]. Only in cases of forced convection with constant physical characteristics is Newton's law applicable. Several heat transmission theories are highlighted, along with their close relationships. The link between temperature differential and surface heat flow as a drivable force may also be used to categorize heat transfer events [32].

Battery capacity equation

The aim of battery is to maintain its temperature in order to capacity varies when the temperature deviates from reference temperature T_{ref}. In order to preserve capacity, BTMS increase their life. Within an acceptable range. While lower temperatures might temporarily impair capacity, higher temperatures may accelerate deterioration rate

$$Q(T) = Q_{nominal} * [1 - \alpha * (T - T_{ref})] \tag{4}$$

Where,

Q (T) - The temperature-dependent capacity of the battery.

$Q_{nominal}$ - The nominal capacity at a reference temperature Tref

α - Constant, α > 0

T - The battery's temperature-dependent efficiency.

T_{ref} - The reference temperature where the nominal capacity $Q_{nominal}$ is measured.

Battery efficiency equation

Temperature dependent efficiency of a battery is represented by

$$\eta(T) = \eta_{ref} * [1 - \beta * (T - T_{ref})] \tag{5}$$

Where,

η (T) - The temperature-dependent efficiency of the battery

η_{ref} - The reference efficiency at temperature Tref.

B - A constant that reflects how sensitive the efficiency is to temperature changes.

T and T_{ref} - As previously defined

Efficiency decreases when the battery temperature diverges from the optimal range.

State of charge (SoC) equation

$$SoC(T) = SoC_{initial} - \int \frac{I(t)}{d(t)} Q(T) * \eta(T) \tag{6}$$

Where,

SoC (T) - The state of charge at temperature T.

$SoC_{initial}$ - The initial state of charge.

I (t) - Current flowing over time.

Q (T) ×η (T) - The temperature-dependent capacity adjusted for efficiency.

In this instance, the discharge with varied discharging currents is always accurate, and the Coulomb counting method is helpful for measuring the battery's state of charge [33].

MATERIALS AND METHODS

Battery Configuration Development

MATLAB and Simulink were used to create a 3S4P (three series, four parallel) Lithium-ion battery stack model for the battery architecture. To get a minimal voltage of 11.1 V (3 x 3.7 V) and a total load of 10.4 Ah (4 x 2.6 Ah), this arrangement was used and specification of Lithium-ion battery are included in the Table 4. The model applied established electrochemical principles and battery dynamics using custom scripts and Simulink blocks to accurately represent battery activity. The framework as given in Figure 5 include modules for cell modelling, 3S4P cell connections, and the deployment of a BMS interface so we can monitor as well as control. To check out the performance of the battery pack under real-life conditions, it was made to simulate dynamic load situations, which represent the inconsistent urging frequently seen in renewable energy applications [23].

Table 4. Specifications of lithium- ion battery [34] [drawn by the author]

Normal capacity	2.6 Ah
Minimum capacity	2.5 Ah
Nominal voltage	3.7 V
Charging voltage	4.2 V
Discharge cut-off voltage	3.0 V
Internal resistance	0.014231 ohm
Standard charge current	0.52 A
Max. charge current	2.6 A
Max. discharge current	5.2 A

The following presumptions underlie the battery model that is implemented in MATLAB/Simulink [28]

1. The model's specifications, which are presumed to remain constant during the charging process, are defined by the discharge characteristics.
2. Self-discharge effects are excluded, and the battery is presumed to be memory-effect-free.
3. The battery is presumed to be memory-effect-free, self-discharge effects are excluded.
4. Internal resistance is viewed as constant during both charging and discharging cycles, staying unaffected by changes in current amplitude.
5. Temperature is incorporated into the model since it affects the system's overall behavior.
6. Even though vibration impacts might affect the model's performance, they are not taken into account.

Performance Evaluation

To assess the Lithium-ion battery model performance under various operating situations, a number of simulations were run. To replicate discharge cycles at constant loads throughout a variety of atmospheric temperatures (-20, -10, 0°C, 27°C, 30°C, 35°C, 50°C and 60°C), a simulation prototype was set up. Throughout these simulations, temperature and state of charge were tracked using the proper sensor blocks to document changes over time. To evaluate the battery stack's overall performance an effect of varying ambient temperatures on SoC distribution was examined.

Implementation of Air Cooling Method

This method describes the precise procedures for putting in place a cutting-edge cooling system for EV battery packs. In certain situations, air cooling systems may be less effective than liquid cooling; yet, they have benefits, including being lighter, simpler, and requiring less maintenance. For some EV designs, these features can make air cooling a viable option, especially where weight and space are concerns to be taken into account [35]. Maintaining optimal battery temperatures requires effective cooling technology, as shown in Figure 6. The flow chart for the suggested model shows the compleate cooling system design process.

Temperature Control and Optimization

To control fan operation based on battery cell temperature, a MATLAB control method was created. The Simulink model was included with temperature criteria for fan activation and deactivation. SoC and temperature were tracked as a function of time and load conditions in simulations

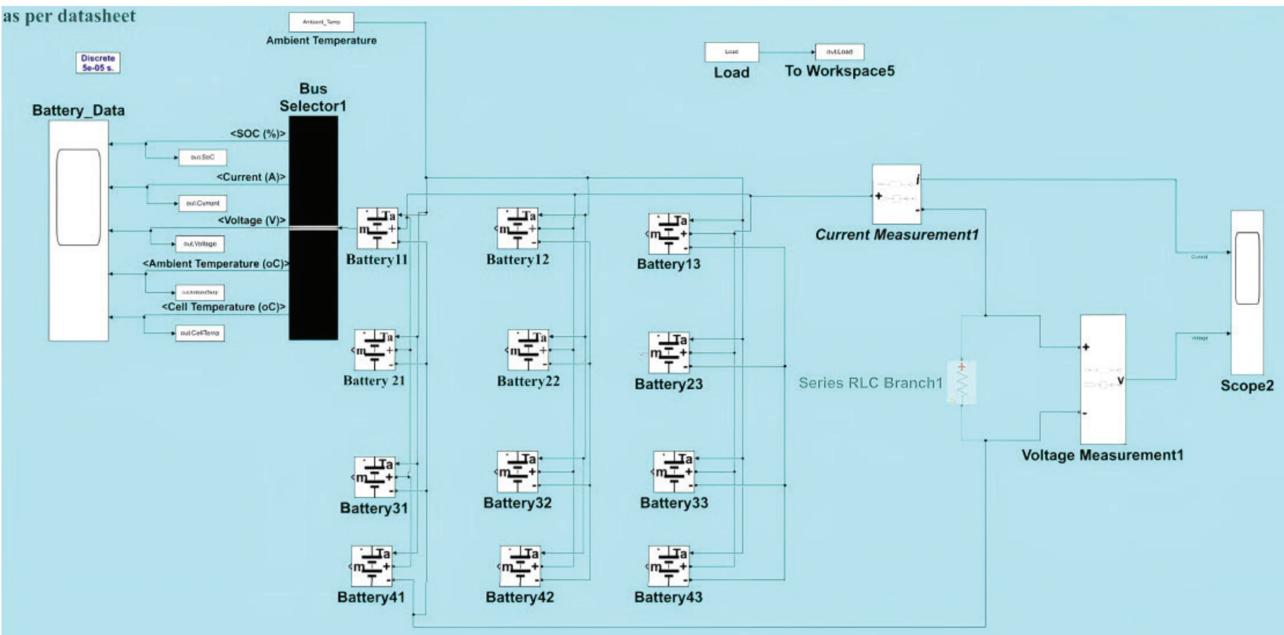


Figure 5. Simulation model 3S4P prototype battery pack.

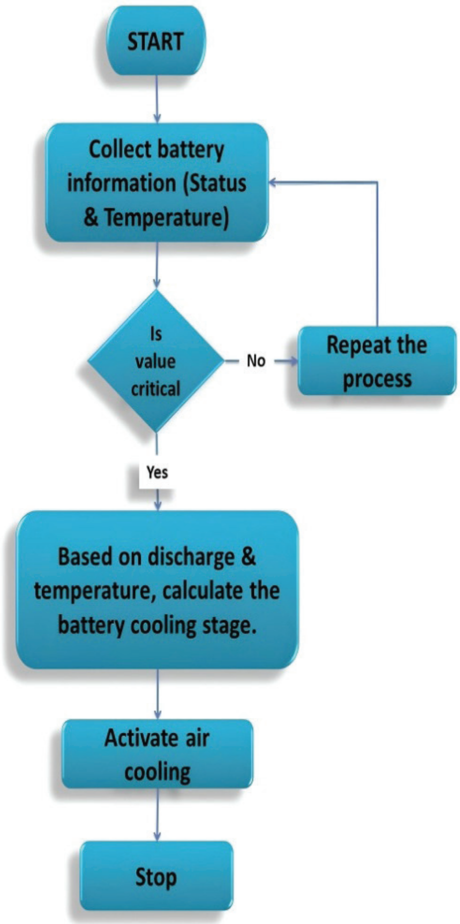


Figure 6. Battery pack without cooling mechanism.

that compared battery performance with and in absence of the cooling device as depicted in Figure 7.

PID Controllers

One of the best ways to guarantee adequate cooling and preserve device dependability is through Propotional -derivative –integral (PID)-based designs. In order to maintain the heat sink's uniform surface temperature, it turns on the cooling fan and controls its speed [36]. The PID control is well known for being a simple and efficient technique for temperature control applications as shown in Figure 8. According to statistics, the kind of control is used by more than 97% of industrial controllers [37]. This paper describes the method of creating a PID controller using MATLAB as an alternative to manually programming a micro-controller to regulate the desired temperature [38]. The time needed for controller design is greatly decreased by using this technique.

Throughout the simulation, voltage, current, SoC, and temperature data were gathered and examined using MATLAB's data logging features. Trends and connections between the distribution of SoC, temperature fluctuations, and the effectiveness of the cooling method were found using the statistical analysis tools in MATLAB.

RESULTS AND DISCUSSION

The modelling of battery pack performance for varying ambient temperatures over an hour is the primary objective of this section. The C-rate is a metric used in battery systems, especially electric cars that quantifies how quickly

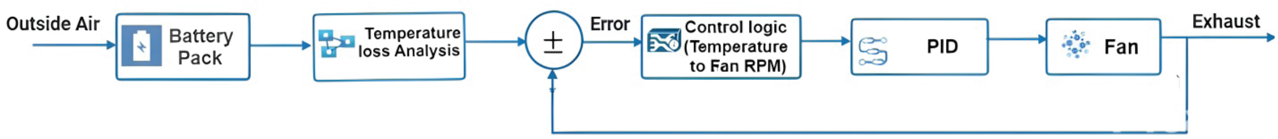


Figure 7. Battery pack with air cooling mechanism.

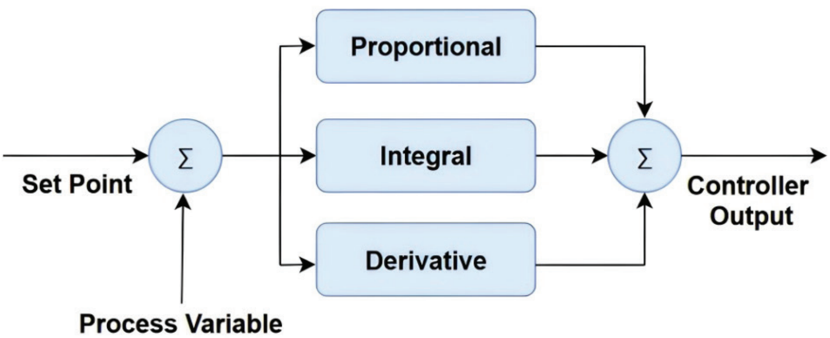


Figure 8. PID controller.

a battery charges or discharges in relation to its capacity. It impacts the relationship between voltage and ampere-hours (Ah). At low C-rates, the voltage drops slowly and the battery delivers nearly full capacity. At medium C-rates (1C), the voltage declines faster but still provides most of its capacity. At high C-rates, voltage drops sharply and the battery delivers less capacity due to inefficiencies and heat build-up. In this work, the model runs at a 0.2 °C rate, as at low °C rates, the voltage drops slowly so that temperature and SoC analysis will be fine.

Overall, the battery temperature gradually aligns with the ambient temperature of 30 C, impacting SoC, current, and voltage behaviour over time as shown in Figure 9. Similar relationships for current, voltage, and SoC can be generated at various ambient temperatures. The current initially remains high in both scenarios due to cooling demands in hot conditions and heating demands in cold conditions before gradually decreasing as the battery stabilizes. The voltage drops more quickly in high temperatures due to increased internal resistance, while in cold conditions, it remains stable initially but declines sharply at low SoC levels.

SoC and Temperature of Battery Pack Without Air Cooling

The primary interaction in this case is the temperature differential between the battery and atmospheric air. This type of evaluation is crucial because battery performance is significantly affected by temperature variations. Here is

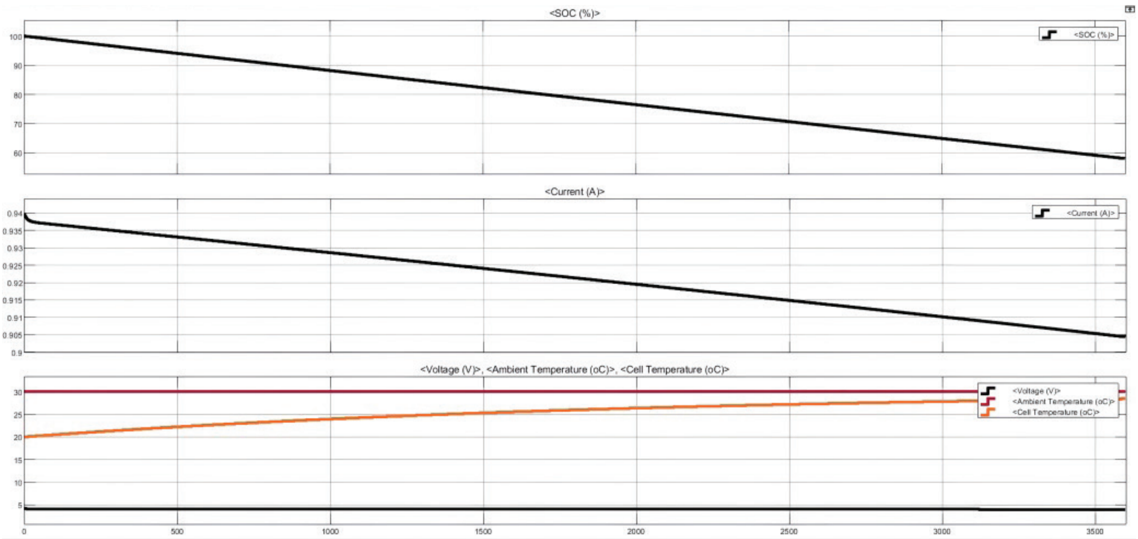
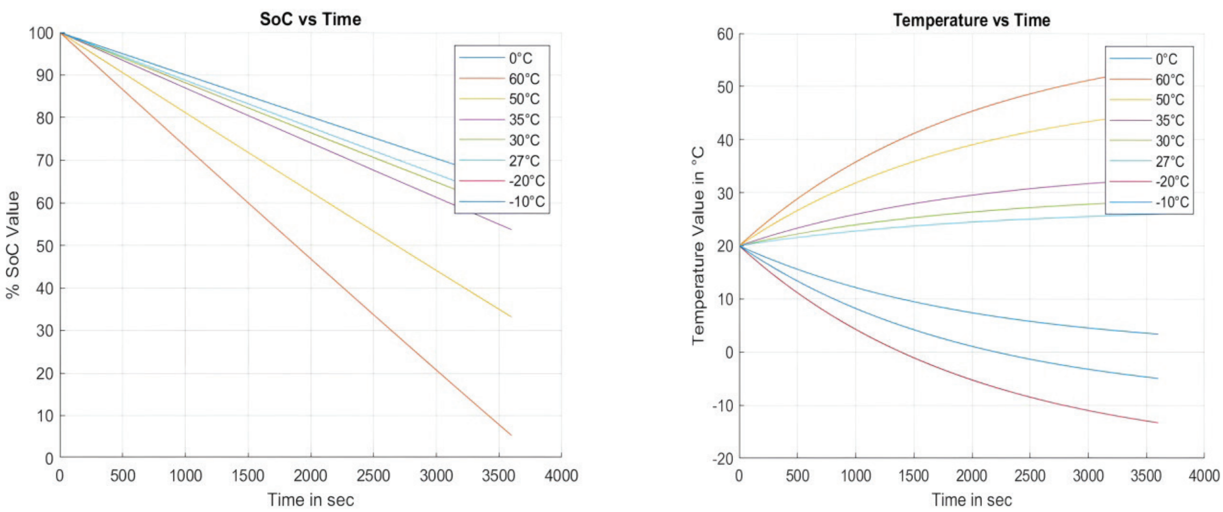
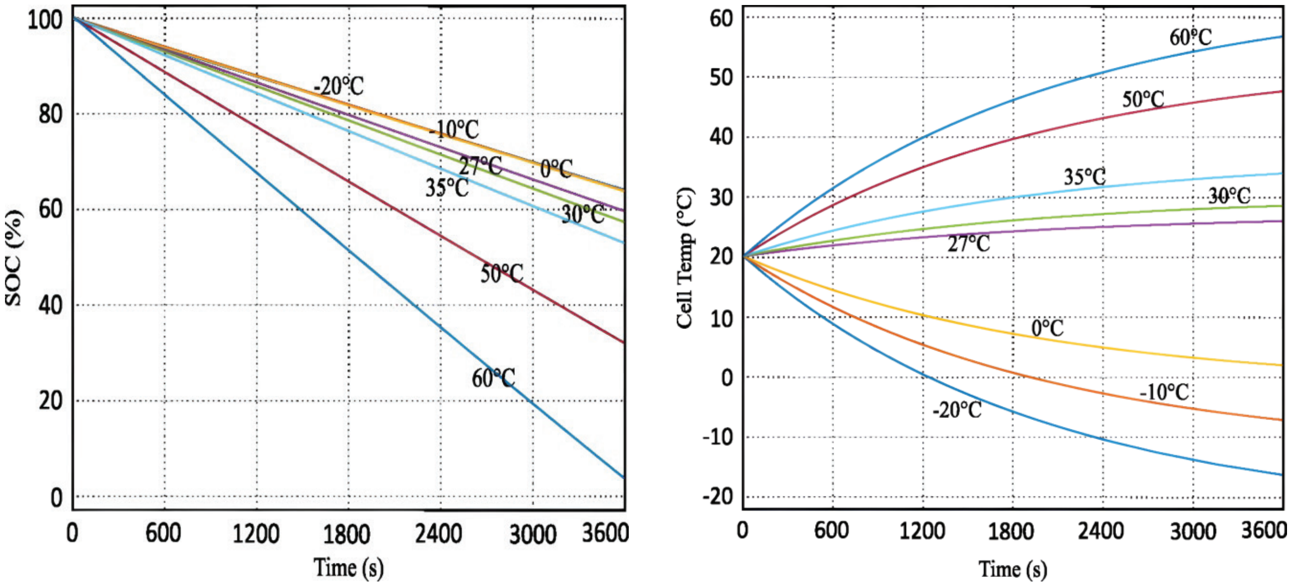


Figure 9. Voltage, current and SoC characteristics EV battery pack at ambient Temperature 30 °C.



(a) (b)

Figure 10. Simulated SoC and temperature at different atmospheric temperatures of battery pack.



(a) (b)

Figure 11. Real time SoC and Temperature at different Atmospheric Temperatures of battery pack.

a summary of the expected observations from Figure 10. based on common trends.

The SoC is a dynamic metric that varies significantly with changes in ambient temperature because of the battery's composition of chemicals and how the temperature management mechanism works. In high temperatures, faster SoC depletion occurs due to increased energy consumption and inefficiencies, while in low temperatures, the SoC may appear stable but is accompanied by a reduction in usable capacity and charging efficiency. The battery temperature tends to align with the ambient temperature over time. This is a natural process because the BTMS works to balance internal temperature changes with the external environment.

Real-Time Validation

The proposed model of the battery pack shown in Figure 5 is authenticated in the OPAL-RT 4510 real-time digital simulator (RTS). It allows moreover, accurate parallel evaluations in real-time, and the results are quite similar to the real system outcomes [39]. As depicted in Figure 12,

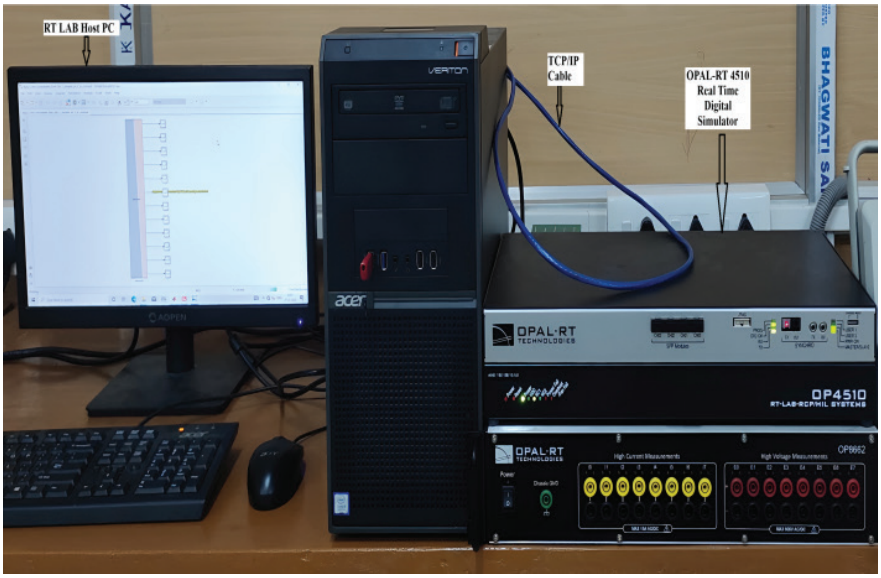


Figure 12. Real-time digital simulation platform installed in the lab.

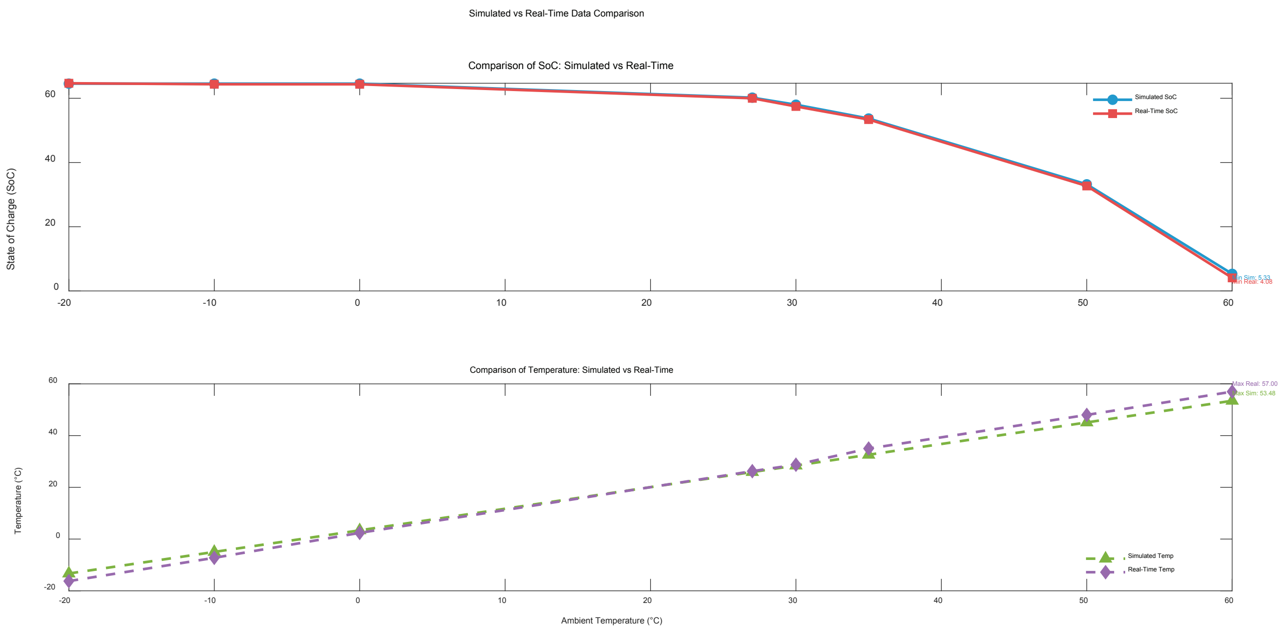


Figure 13. Comparative analysis of SoC and temperature

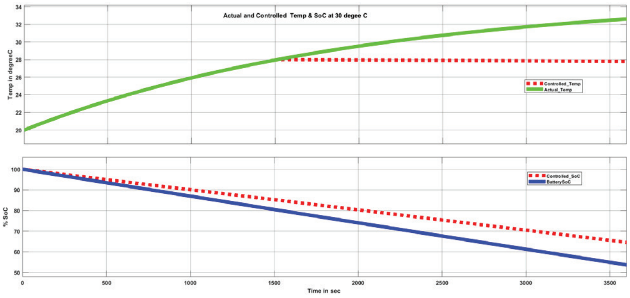
the laboratory setup with OPAL-RT arrangements comprises of MATLAB-enabled host PC with RT-LAB connections. Results from simulations and actual applications agreed. The performance of a system is successfully validated [40-41]. An interlink connecting the host PC and RTS is established by a TCP/IP cable. RT-LAB, which is already integrated with MATLAB, is used to immediately improve the proposed control strategy on a Simulink/MATLAB platform. The simulated result of SoC and Temperature of the 3S4P battery pack is validated in OPAL-RT as shown in Figure 11. The MATLAB simulations offer an idealized baseline for initial design while OPAL-RT provides real-world validation by accounting for factors such as temperature effects, dynamic behaviour and degradation.

In OPAL-RT, SoC might be lower due to inefficiencies, higher power demands, energy losses, and temperature might rise more than predicted especially under high load conditions due to thermal effects that are often simplified or not fully captured in MATLAB simulations. These discrepancies as given in Figure 13 emphasize the importance of refining the MATLAB model to account for real-world factors such as thermal dynamics and battery aging to achieve a more accurate prediction for the behaviour of the system, leading to more reliable performance validation.

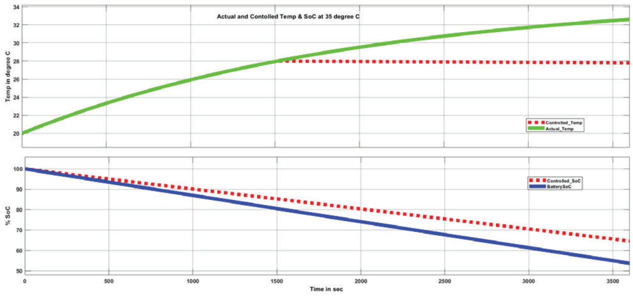
SoC and Temperature of Battery Pack With Air Cooling

Air cooling helps keep the battery cooler, improving charging efficiency and SoC, and extending battery life while preventing overheating. Without cooling, higher temperatures can reduce performance and degrade the battery faster. The cooling system's ability to manage temperature spikes during rapid discharge has been assessed by analyzing profiles over time at various temperature levels. Figure 14. compare battery temperature and SoC with and without air cooling for ambient temperature 30°C and more than 30°C as the set point is 28°C Without cooling (green colour), the battery overheats quickly, rising above the controller's set temperature due to inefficient heat dissipation. With air cooling (black colour), the battery temperature is better controlled, staying closer to the set point. The SoC behaviour without cooling (black colour), SoC drops more rapidly due to overheating and reduced efficiency. With air cooling (green colour), SoC depletes more slowly as the battery operates more efficiently at lower temperatures, improving overall performance and range.

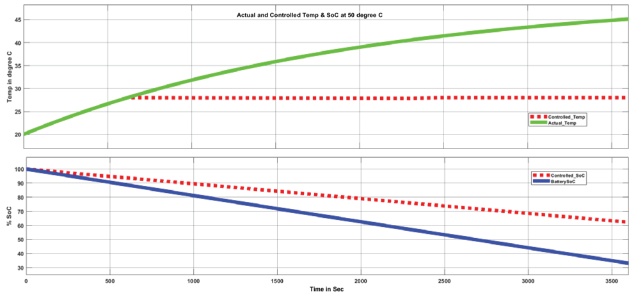
An auto-tune PID controller continuously adjusts its parameters based on system feedback to optimize performance. The 30°C is the ambient temperature from Table 5, PID controller has very significant role in regulating battery's temperature by controlling the cooling system. As the temperature exceeds target of 28°C, PID controller turns the fan on and adjusts its speed dynamically to maintain the battery temperature close to the set point ensuring optimal battery performance and longevity. The air cooling mechanism is activated in response to a noticeable rise in battery temperature, which would otherwise increase significantly beyond the threshold if left uncontrolled. Once the cooling system is engaged, the temperature is regulated effectively preventing the battery from overheating.



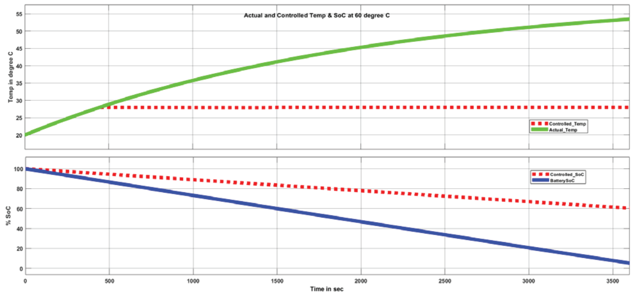
a. Atmospheric Temperature 30 °C



b. Atmospheric Temperature 35 °C



c. Atmospheric Temperature 50 °C



d. Atmospheric Temperature 60 °C

Figure 14. Battery calefaction and SOC with and without air cooling.

Table 5. SoC and Temperature analysis for with and without controller

Ambient temp °C	Simulated value		Real time value		Controlled SoC	Controlled tempeature	Improved efficiency
	SoC	Tempe-rature	SoC	Temperature			
	100	**20**	**100**	**20**	**100**	**20**	
-20	64.562	-13.3118	64.68	-16.25	64.562	-13.3118	0%
-10	64.5619	-4.9648	64.37	-7.25	64.5619	-4.9648	0%
0	64.5618	3.3822	64.36	2.40	64.5618	3.3822	0%
27	60.1962	25.9194	60.00	26.25	60.1962	25.9194	0%
30	58	28.4237	57.46	28.75	65.3258	27.95	7.86%
35	53.7	32.6	53.38	35	64.5813	27.79	11.20%
50	33.2	45.1	32..7	48	62.2096	28	29.50%
60	5.326	53.4768	4.08	57	60.3696	28	56.28%

When comparing real-time values with controlled values of performance at 27°C, when the cooling might not have been required or as successful, these gains are significant. The greater improvement shown at 30 °C can be ascribed to the data being recorded at precisely timed intervals when temperature regulation is more important. The benefits of air cooling at higher temperatures are reflected in the SoC and efficiency improvements. The air cooling assist the battery in retaining maximum performance by lowering thermal stress, enhancing energy retention and lowering power losses from overheating. This demonstrates how crucial active cooling systems are to preserving battery life and increasing its operating range particularly in hot weather.

After stabilizing the temperature, an improvement in SoC of about is observed in Figure 15, indicating that the battery is able to retain more charge when operating at a controlled temperature. Additionally, the efficiency of the battery improves by approximately 7.86% for 30°C, meaning that the battery delivers energy more effectively when air cooling is applied.

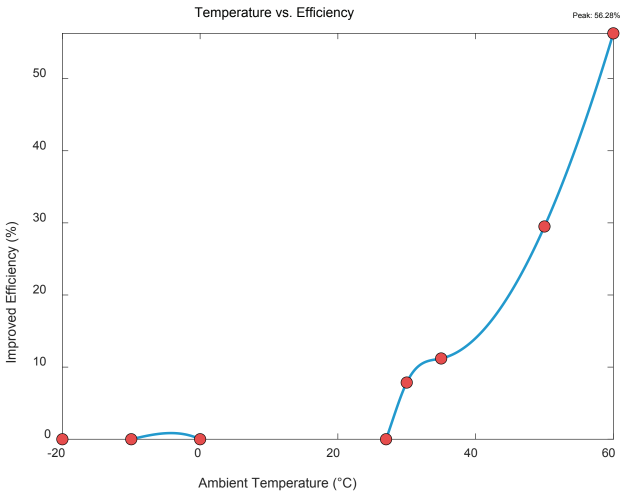


Figure 15. Improvement of efficiency due to PID controller.

CONCLUSION

The prime benefaction of this research is the incorporation of sophisticated computational models into Battery Thermal Management System frameworks, which shows how they may be used practically to enhance Electric Vehicle battery performance. The battery differential temperature has been measured and analyzed at different ambient temperatures via on OPAL-RT platform. A rapid simulator was deployed to operate both the suggested and conventional network designs, and a comparative analysis of simulation and real-time experimental results gives crucial information on how well the cooling mechanism maintains optimal temperature levels within the battery pack. The simulation studies highlight the impact of air cooling on temperature control, When reveals to the significant improvements in thermal stability and battery lifespan. The overall efficiency has been improved to 13.11%. Results show that the performance and safety of lithium-ion batteries in practical applications may be remarkably enhanced by the application of strong Battery Thermal Management System frameworks. When an economical direct air conditioning method is used for Electric-vehicles, the stability of a system increases.

For battery management systems, using an auto-tuner Proportional-Integral-Derivatives (PID) controller has several advantages, especially when it comes to temperature control and State of Charge stability. In comparison systems without auto-tuners, are more vulnerable to inefficiencies and quicker deterioration. It guarantees more efficient energy utilization, lowers battery wear, and prolongs battery life. Controlling the heat produced during charging and discharging helps to maintain safe and dependable battery performance by minimizing thermal degradations. In the future AI and Smart Thermal Management for the enhancement of battery performance, in which AI-driven cooling optimizes thermal regulation grounded on driving patterns while smart detectors cover and adapt battery temperature in real-time, may be studied.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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