

A novel approach to flexible BTMS for 2-wheeler electric vehicle to avoid fire accidents-an Indian perspective

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ABSTRACT

The Indian electric vehicles market share has significantly increased due to various government initiatives, increased fuel prices, and charging infrastructure. On the contrary, fire accidents of EV's in India are no rarer due to inappropriate BTMS and its inability to work with different environmental conditions prevailing in India, so it has become one of the major concerns. Two-wheelers, being one of the most used modes of transport, are dominating the Indian roads; it well deserves an innovative BTMS that suits local environmental conditions for preventing thermal runaways and maintaining better performance of the battery. As we get to see diverse environmental conditions at different parts of India, it will be good if we can develop flexible BTMS. Major challenges being faced in the development of suitable BTMS are space and cost constraints. This paper focuses on the development of BTMS for electric two-wheelers, suitable for various environmental conditions, which fits in the available space with low additional cost. It also provides flexibility to drop or add some of the features based on one's operational requirements or environmental conditions prevailing at the place of operation, which can be as easy as one can drop or choosing to have fog lamps, speakers, camera, and sunroof depending upon their requirement and budget.

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1. INTRODUCTION

A substantial portion of global energy usage can be attributed to the transportation sector, which accounts for more than 30% of oil consumption worldwide [1]. With rising global warming concerns due to automobile emissions, depletion of fossil fuels, and strict environmental regulations on greenhouse gas emissions, EV is gaining the interest of many. India's transition to electric vehicle (EV) mobility is propelled by pressing environmental concerns, energy security imperatives, economic advantages, and supportive government policies. Backed by initiatives, India aims to reduce its carbon footprint by 45% by 2030, aligning with the Paris Agreement and COP26 commitments. As per the report on "Forecasting Penetration Of Electric Two-Wheelers in India [2] by NITI Aayog in collaboration with TIFAC, in an optimistic scenario, the report forecasts 100% penetration of electric two-wheelers in the Indian market by FY 2026–27. Two-wheelers are the dominant segment when undergoing electrification, advancements in battery

technology enhance EV performance, range, and affordability, poised to make India a leader in EV manufacturing and innovation.

EV comprises a battery, the motor, the power electronic controllers, a few moving parts, a few complex gears, bearings, and other components that control the powertrain. The intricacy in placing control, monitoring, and integrating all parts of Electric vehicle have brought new challenges to the automobile industry. The heart of EV is a battery that provides the energy demanded as per the range of drive cycle, its configuration, and various ambient conditions. The electric vehicle battery cost significantly contributes to the overall cost almost 45% of the vehicle cost is due to the energy storage system. The type of battery, cell chemistry, cell arrangement, and their properties substantially influence the vehicle's safety, cost, reliability, and performance. Among various batteries used in EV's, Li-ion batteries have a low rate of self-discharge, a long life, and high-power, energy density, making it best suited for automobile purposes. But battery protection towards safety issues is degrading its performance, or else causing thermal runaway. To protect the battery from thermal runaway and to enhance its performance, a battery thermal management system suitable for varying/different ambient temperatures is the need of the hour. As per the available literature, the various types of battery thermal management systems (BTMS) implemented in 4-wheelers use air cooling technology, water cooling technology, phase changing materials, or any of these combinations to cool the battery, whereas for 2-wheelers, there is no specific BTMS designed. The various BTMS used in EV are shown in Figure 1. A BTMS that can maintain the battery temperature with safe range is said to be efficient. Yan *et al.* investigated that the battery temperature should not surpass 45 °C with ΔT of 5 °C for safe operation [3].

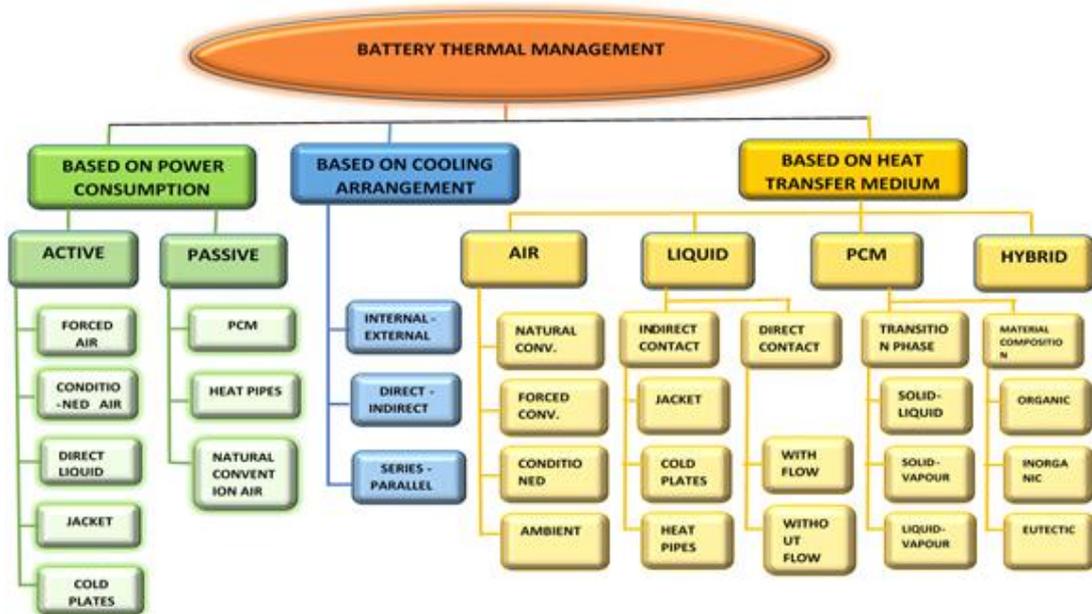


Figure 1. Battery thermal management systems

It is observed that extensive research is carried out by different authors to improve Li-ion battery module efficiency for different cooling methods pertaining to cell arrangement, spacing, charge-discharge rate, and type of cooling. Wang *et al.* conducted an experiment on a 1×24, 3×8, 5×5 cell module and summarized that Forced air cooling when cells are arranged in an axially symmetric structure with fan mounted on top of the battery cools effectively [4]. Kai *et al.* experiments with respect to the cell spacing deduced that the best performance is when the channels beside the inlet and outlet have airflow rates 0.7 times that of other channels [5]. Ouyang *et al.* studied the heat propagation in batteries and the effect of cell gaps in the battery pack, state of charge (SOC) of the battery, and phase change material (PCM), and concluded that with the battery spacing squared, the speed of failure propagation declined [6]. Panchal designed a water-cooling system using dual cold plates from 1 °C discharge rate to 4 °C with temperature boundary conditions of 5 °C, 15 °C, 25 °C, and 35 °C, respectively, and observed an increase in T_{max} and discharge rate with an increase in temperature boundary conditions [7]. Saw *et al.* used computational fluid dynamics (CFD) analysis to investigate the influence of and without aluminum foam on the thermal

conductivity of Li-ion battery and concluded that aluminum foam with a heat sink improved thermal performance significantly [8]. Song *et al.* proposed a thermoelectric device and PCM-based thermal management and noticed effective improvement in temperature uniformity of the battery module and prolonged thermal retention [9]. Wang *et al.* and Yang *et al.* reviewed a hybrid cooling arrangement (thermoelectric cooling (TEC)-based BTMS technology) and came to the conclusion that TEC increases the cooling efficiency and improves system stability by obtaining precise temperature control. TEC with air cooling increases the heat dispersion efficiency, thereby overcoming the disadvantage of uneven distribution of temperature among cells in the battery with air cooling alone [10], [11].

In India, different places have varying ambient temperatures ranging from very low in Ladakh and Kashmir to moderate in Bengaluru and high in Rajasthan. Most of the EV 2-wheeler fire accidents are taking place while charging [12]-[14], the ambient temperature at the place of accidents varies between 27 °C to 42 °C from the battery casing made from Mild steel. Comprehensive research is carried out on BTMS for 4-wheelers, and its literature is made available by different authors, but very little research literature is available on BTMS for electric two-wheelers that suit Indian roads and weather conditions. This is a potential research gap as these BTMS are restricted to only a few segments of EV and may practically not be used for 2-wheelers in India due to the different ambient temperature, cost, weight, and space associated with the cooling arrangement. This paper presents a novel flexible BTMS tailored for 2-wheeler electric vehicles that suit different climatic and load conditions to avoid the risk of fire accidents and thermal runaway. A flexible cooling system with 3-stage protection of battery packs proposed can mitigate the rise in temperature among cells by combining internal air circulation, forced air cooling, and a thermoelectric cooling arrangement within a finned battery casing made of aluminum, which will not only increase the battery life, but also facilitate fast charging and better cooling.

2. METHOD

2.1. Experimental set-up stage-wise

The heat generated while charging increases the battery temperature, and if it is not controlled, it can trigger thermal escalation or deteriorate the performance of the battery. The BTMS is said to be efficient if it can maintain the battery temperature within battery safety limits of 15–45 °C [3]. To check the feasibility of the proposed Flexible BTMS, the first step towards the novel approach is the fabrication of the EV Chassis and the assembly of wheels and suspension with the chassis, as shown in Figure 2. The available space in between the suspension units, rear wheel, and seating is then measured to appropriately design a battery pack along with a cooling arrangement that can fit into the available measured space, as shown in Figure 3.

To optimize the available space in a 2-wheeler and safeguard the battery, a battery pack of 1 kWh capacity, and its casing with a proposed cooling arrangement, is designed in CAD step-wise as shown in Figure 4 for hardware proceedings. For this, a cell holder having good mechanical strength and insulation properties is used, which tightly holds the cells in a fixed position and provides proper space for the circulation of air to avoid any short circuit [15]. The 112 Li-ion cells are then properly stacked in parallel and series to attain the desired battery capacity and spacing among cells for air circulation to facilitate proper cooling of the battery pack. Packing is done to cover the spot-welded nickel circuitry to avoid short circuits without blocking air circulation paths.

Battery casings are used to protect batteries from short circuits/damage due to water spillage, dust settlements, and physical damage. Heat dissipation/cooling efficiency of the battery cooling system depends on the casing material's heat transfer coefficient, air velocity, and temperature of the air. For naturally cooled battery cooling systems, ambient air will act like cooling air. At comparatively higher ambient air temperatures, the battery cooling becomes inefficient, and the temperature of the battery will rise beyond safe operation limits. In addition to that, if casing materials have a poor heat transfer coefficient and a lower cooling air velocity, then there will be higher chances of battery temperature rising to dangerous levels. Therefore, the finned casing of desired measurements made of aluminum is used as it is lighter and has thermal conductivity better than the conventionally used Mild steel casing. The battery module is then placed in an aluminum finned casing.

A well-designed BTMS is said to be efficient if it can maintain cell temperature within the safe range during different climatic conditions [16]-[19]. The hardware model of the hybrid thermal management system, thus proposed by combining internal air circulation (IAC), forced air cooling (FC), and TEC within the battery casing, is then designed. For IAC, the casing is provided with two internal fans assembled with heat sinks, one facing towards the battery at the rear end and one facing towards the casing at the front end, as shown in Figure 5. The system is facilitated with an internal air circulation within the battery casing to dissipate heat generated by cells to the heat sinks/casing. Internal air circulation also helps achieve temperature uniformity between individual cells [20], [21].

A forced air-cooling fan is provided at the front end of the casing for quick heat dissipation from the battery casing. It is a direct, most efficient, economical, and commercially used cooling method to manage heat generated inside the battery pack, particularly when design space is limited. The thermoelectric cooling arrangement is provided at the rear end of the casing to cool the battery under high ambient temperature conditions. Thermoelectric cooling (TEC) is used in this project as it is light, flexible, quiet, and can achieve temperature control with precision within the battery [22]-[25]. The TEC's are arranged outside the casing near the rear end in such a way that the TEC's cold side is facing towards the battery and the hot side is facing towards the ambient atmosphere. The heat sinks are placed on the hot plate of TEC so that the generated heat is dissipated into the environment without hitting back the casing, as in Figure 6, with all electrical connections as shown in Figure 7. The air flow within the battery casing with all cooling arrangements is as in Figure 8, which clearly depicts that the heat generated while charging is dissipated to the atmosphere through heat sinks and cooling arrangement there by allowing the battery temperature to be within a safe range [14]. The complete cooling arrangement with the battery is fitted in the vehicle for testing, with all electrical connections as in Figure 9.



Figure 2. Fabricated EV chassis, assembly of wheels, and suspension



Figure 3. Assessment of space to install a battery with a cooling arrangement

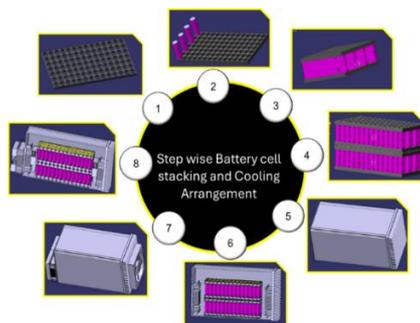


Figure 4. Step-wise -designing of holder, battery pack module, aluminum casing with fins, and all cooling arrangement within the available space in CAD

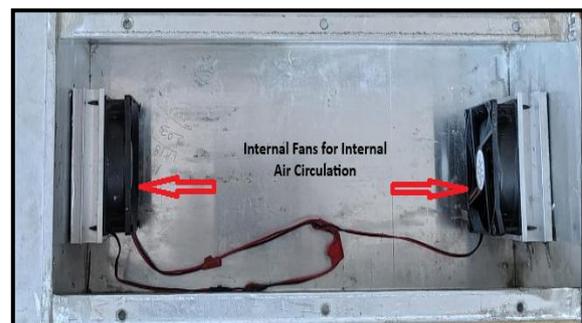


Figure 5. Aluminum finned battery casing with an internal air circulation arrangement



Figure 6. Aluminum finned battery casing with internal air circulation and forced air cooling arrangement



Figure 7. Aluminum finned battery casing with internal air circulation, forced air cooling and thermoelectric cooling arrangement with electrical connections

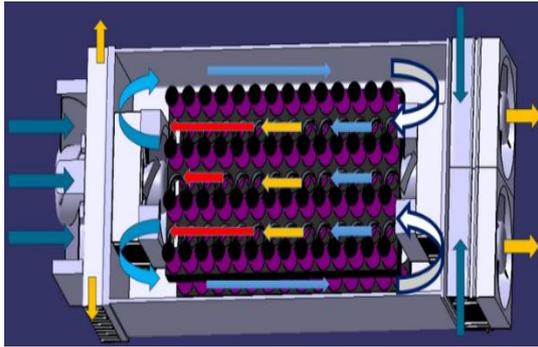


Figure 8. Air flow diagram with all cooling arrangements within the battery casing

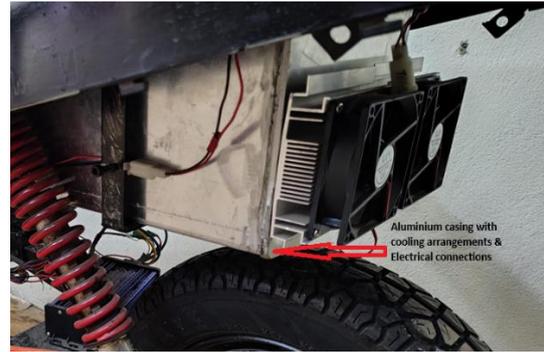


Figure 9. Aluminum finned battery casing with all cooling arrangements and electrical connections, fitted to the vehicle for testing

2.2. Testing and experimental results

Conventional BMS doesn't have any temperature controls. However, present-day BMS comes with a temperature-based cut-off feature to protect the batteries. While experimenting as per the experimental setup shown in Figure 10, we have fixed the BTMS power cut-off temperature as 70 °C to keep the system safe. To test the efficiency of each protection arrangement used in the proposed method, the charging system is tested at a fixed 1C charge rate and 35.7 °C ambient temperature. The first test is performed by placing the battery pack in a mild steel casing, as we have it in the conventional electric two-wheelers. The battery temperature with this arrangement rose beyond 70° C for 6 times in a single charge cycle and BTMS tripped every time as shown in Figure 11(a). After every trip, the BTMS allowed the batteries to cool down to less than 60 °C and restart. This clearly demonstrates that the temperature would have gone much beyond 70 °C if BTMS had not cut off the power, and the time taken for complete charge is 39 mins. When the charging is performed by placing the battery in an aluminum finned casing with internal air circulation, the maximum battery temperature is observed to be 46.9 °C, and the time for complete charge is 29 mins with a power consumption of 5 W due to fans used for internal air circulation, as shown in Figure 11(b). When the charging is performed by placing the battery in an aluminum finned casing with internal air circulation and forced air cooling, the maximum battery temperature is observed to be 44 °C, and the time for complete charge is 28 mins with power consumption of 16 W due to fans used for internal air circulation, forced air as shown in Figure 11(c). When the charging is performed by placing battery in aluminum finned casing with internal air circulation, forced cooling, thermoelectric cooling the peak battery temperature is observed to be 42 °C and time taken for complete charge is 27 mins with power consumption of 116 W due to fans used for internal air circulation, forced air cooling and thermoelectric cooling as shown in Figure 11(d).



Figure 10. Experimental setup during charging with all electrical connections and cooling arrangements

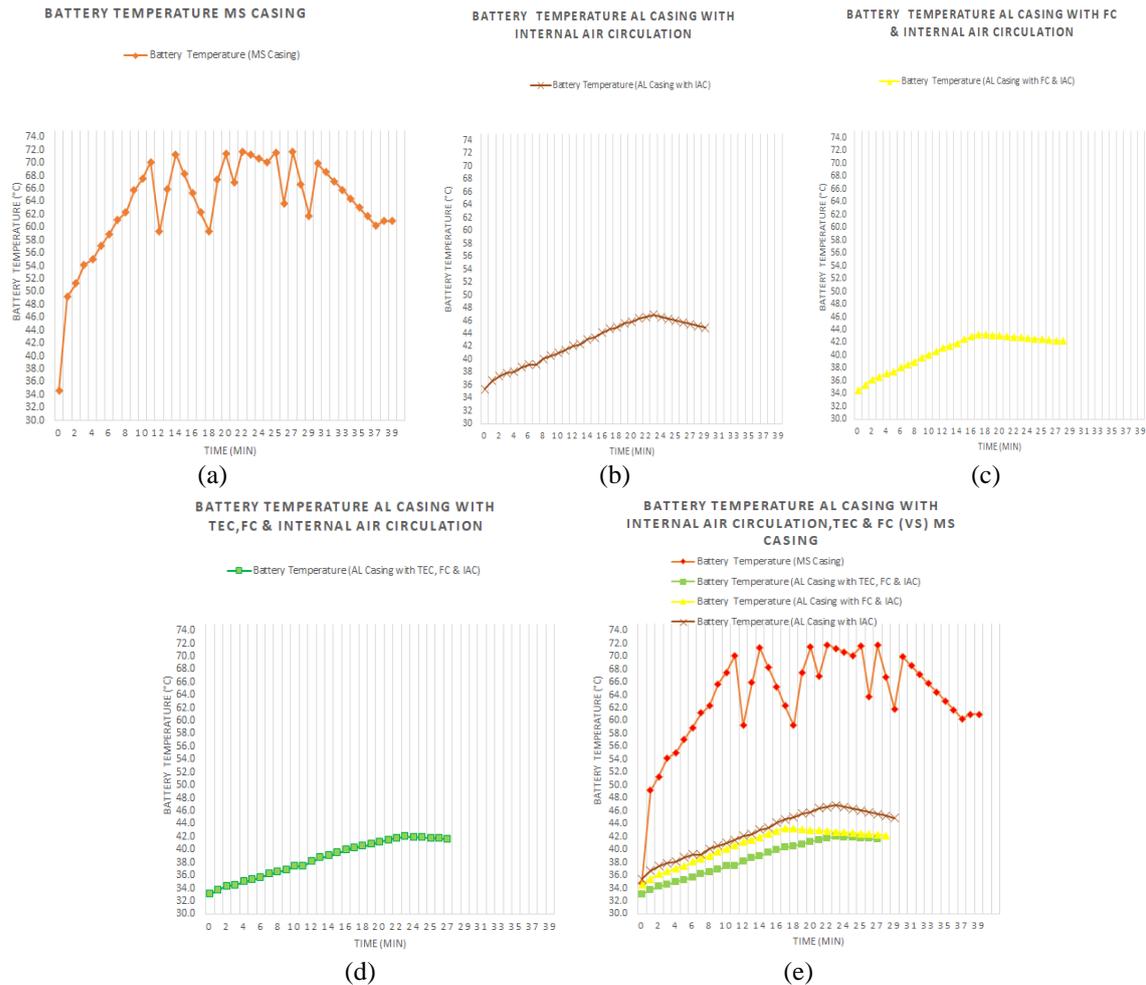


Figure 11. Time Vs battery temperature: (a) MS casing, (b) Al casing with IAC, (c) Al casing with IAC & FC, (d) Al casing with IAC, FC, & TEC, and (e) comparison of Al casing with IAC, FC, & TEC with MS casing

2.3. Comparative analysis

2.3.1. Based on thermal performance

On Comparing different cooling arrangements at Charge rate-1C and Ambient Temperature 35.7°C from 50% State of charge to 100% state of charge as listed in Table 1, it is found that the conventional mild steel battery casing is unsafe with maximum battery temperature crossing 70°C and was tripped off for around 6 times and it was allowed by BTMS to cool to keep the system safe. Battery cooling systems with IAC, FC, and TEC together were able to effectively cool the battery to a temperature below 42°C , which was the lowest among all cooling arrangements, but with an additional power consumption of 116 W of the battery [22].

2.3.2. Based on cost

With Mass production of the proposed system, the total additional cost will be approximately 15% of the battery cost or 7-7.5% of the vehicle cost. The cost analysis of the conventional verses present system is shown in Table 2. Instead of using all 3 cooling arrangements throughout the charging process, which otherwise would consume 116 W, stage-wise switching of different cooling arrangements can be initiated by monitoring the battery temperature using a triple protection control board, which will use extra power only when the temperature of the battery goes beyond prescribed operating limits, as shown in the flow chart Figure 13(a).

After several tests, an optimistic approach of 3-stage protection is derived to cool the battery while charging, in which two internal fans, which facilitate internal air circulation, are always kept ON. If the battery temperature goes beyond 35°C (T_{s1}), the forced air cooling will be initiated. For forced air cooling, a fan is provided on the front-end fins, which will accelerate the heat dissipation from the battery casing. If the temperature exceeds the battery safety threshold despite forced air cooling and internal fans working together, and it increases beyond 40°C (T_{s2}), TEC will be initiated. If the battery temperature goes beyond

45 °C (T_{s3}), the triple protection control board will cut off the charging and wait for the battery temperature to drop down and appropriately select the cooling system. This approach keeps the battery temperature under safe limits without consuming much energy. The control circuit of this approach is shown in Figure 13(b).

Table 1. Comparison of different cooling arrangements with MS/aluminum casing at charge rate-1C and Ambient Temperature 35.7 °C

Casing/type of cooling	Mild steel/no cooling	Aluminum casing/ internal air circulation	Aluminum casing/internal air circulation + forced air cooling	Aluminum casing/internal air circulation + forced air cooling +thermoelectric cooling
Maximum battery temperature	above 70°C	46.9 °C	44 °C	42 °C
Time for 50-100% charge	39 Mins	29 Mins	28 Mins	27 Mins
Power consumption	—	5 W	16 W	116 W
% of battery power used with different cooling arrangements	—	0.5%	1.6%	11.6%

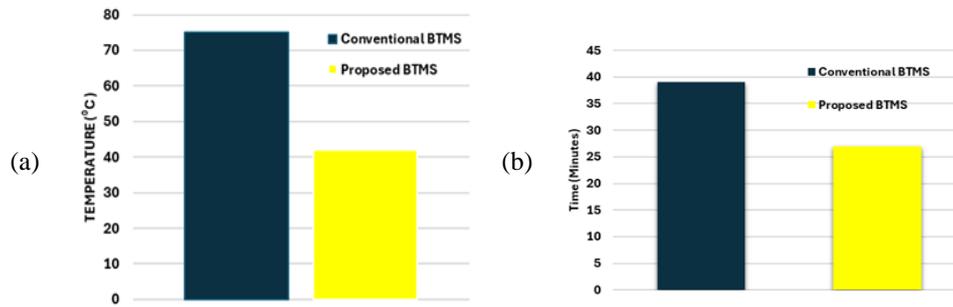


Figure 12. Conventional BTMS Vs proposed BTMS: (a) maximum battery temperature and (b) charging battery time

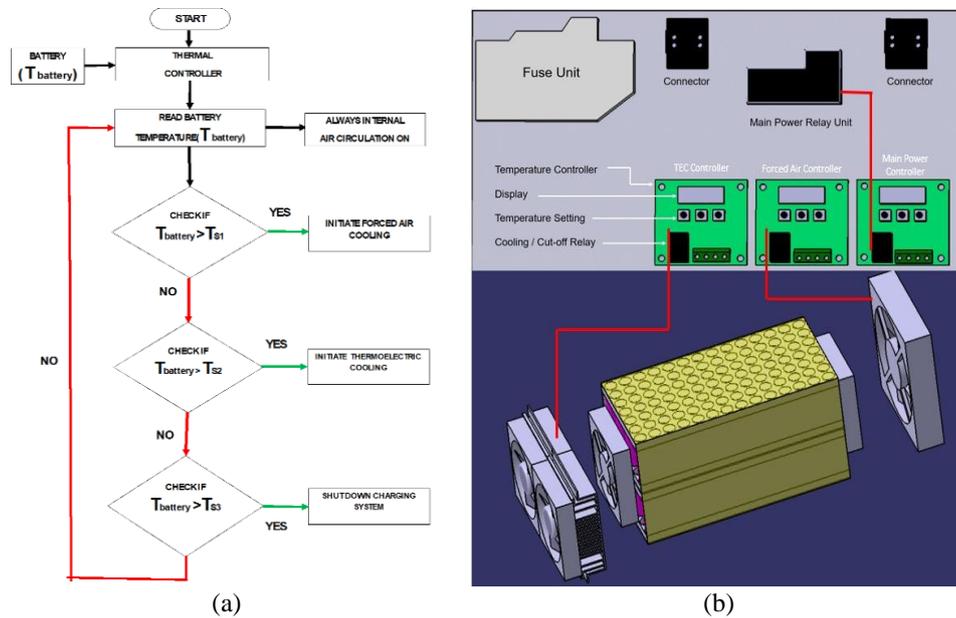


Figure 13. Three-stage protection: (a) flow chart and (b) control circuit

Table 2. Cost comparison of different cooling arrangements in a finned aluminum casing with a mild steel casing

Type of casing/cooling arrangement	In terms of % of the battery cost
Mild steel casing	5%
Finned aluminum casing	12%
Internal air circulation	1%
Forced air cooling	2%
Thermoelectric cooling	5%

3. CONCLUSION

In contrast to the conventional BMS used in electric two-wheelers, the present design uses a finned Aluminium casing with three types of cooling arrangements (Internal air circulation, forced air cooling, and thermoelectric cooling) to protect the vehicle from thermal runaways and maintain the performance of the battery pack. Along with Internal air circulation and forced cooling, the thermoelectric cooling is chosen to keep the system lighter and compact. A lighter battery thermal management system means less energy waste and compactness, which will make it best suited to fit into two-wheelers.

The experiment showcases that while charging, the proposed BTMS for 2-wheeler EV with all cooling arrangements within a finned aluminium casing has cut down the peak battery temperature by 28 °C and achieves fast charging by reducing the charging time by 12 Minutes when compared to conventionally used Mild steel casing within the available space with additional cost of just 15 to 20% of the battery cost.

India has varied climatic conditions, and the cooling requirements of BTMS will be different for various locations. That means battery thermal management requires chillers along with forced cooling, where the temperature is too hot, it requires forced air, where it is moderately hot, and at some other places where it is relatively cool, natural cooling will be sufficient. Therefore, the 3-stage protection for the battery provides flexibility to select or drop some of the components of BTMS depending upon operational conditions. The present design allows dropping of the thermoelectric chiller or forced air cooling, or both if not necessary at the place of operation.

Providing a thermal management system that can suit every condition may lead to increased cost as it requires several components or a drop in energy efficiency due to the load of components or both. As the proposed system is flexible (detachable), we can customise cooling arrangements only to the requirements so that it consumes very little energy and cost. The present model, being one of the low-cost cooling cum safety arrangements, can easily penetrate the Indian market. (benefiting both buyers and sellers).

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AUTHOR CONTRIBUTIONS STATEMENT

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Mahmooda Mubeen	✓	✓		✓	✓	✓	✓	✓	✓	✓				
Gangishetti Srinivas					✓	✓				✓	✓	✓	✓	✓

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that supports the findings of this study are available from the corresponding author [MM], upon reasonable request.

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