International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

A Review of Battery Management Systems for Lithium-Ion Batteries of Electric Vehicles

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ABSTRACT—

Lithium-ion batteries are a top choice for electric vehicles, but they can overheat and cause serious problems when charged or discharged quickly or in extreme temperatures, puzzling researchers. To prevent this, effective thermal management is essential. Single cooling methods are not enough, so multiple methods are needed. Phase change materials (PCMs), both organic and inorganic, are key components in these systems due to their exceptional heat absorption and release properties. To enhance heat dissipation, PCMs are combined with graphite powder, nanomaterials, and metal structures to create composite PCMs. These advanced materials, coupled with intelligent control strategies, significantly improve battery thermal performance. Researchers are also exploring the use of PCMs as flame retardants to mitigate thermal runaway propagation.

Despite progress, challenges persist. Developing cost-effective, compact, and efficient thermal management systems with minimal energy consumption remains crucial for widespread EV adoption. This review aims to provide a comprehensive overview of integrated battery thermal management solutions using composite PCMs, guiding future research and development efforts towards safer and more sustainable electric vehicles.

Keywords— battery classification and application, Lithium-ion battery, Thermal runaway battery thermal management, Integration of liquid cooling and phase change materials.

Introduction

The increasing interest in EVs, with 6.6 million units sold across the world in 2021, steers the subsequent need for optimizing the performance of thermal management systems for battery durability and safety. These include air, liquid, PCM-based cooling and thermo-electric element cooling. Indoor air cooling is cheap, yet it yields low performance in conditions of high thermal load. Liquid cooling is still one of the most efficient solutions but they are expensive in comparison to air cooling. As distinct from standard liquid systems, PCM-based ones utilize phase changes for heat control but their thermal conductivity is low and needs boosting. Thermo-electric systems are very accurate with temperature control but are costly. Cooling is important as charge and discharge cycles are reduced by temperature variations especially high temperatures [1]. The progress and potential problems of EV battery and management systems need to be understood in order to drive the progression of sustainable mobility. There are: lithium-ion, lithium-metal, and post-lithium batteries that have different features, advantages, and disadvantages. The article acknowledges the notion of utilizing electrothermal models with data-driven information and paradigms such as move-and-charge, and Wireless power technologies to minimize battery dependency. Advanced interests are expected to converge information and energy internet concepts in reinforcing data and energy distribution in electric mobility [2]. Concerning safety, the automobile industry has stepped up its technologies, but the increase in the number of cars has complicated air pollution in urban areas. Transportation is the leading source of GHG emissions at 27% of which 70% are from transportation. Electric vehicles (EVs) are now recognized for their potential to bringdown emissions of GHGs and thereby curb global warming. For EVs battery management systems (BMS) are essential offer high energy density, long cycle life and low self-discharge rates. Indeed, temperature and aging impacts batter performances. To be effective, BMS must measure such features as temperature, charge and the ability to detect faults [3]. Specifically, consumers have displayed a lot of interest in owning EVs because of the high fuel prices and the issues of the Green House. EVs were first considered in the 18th century but then they gone out of focus because of IC engines due to cheap and easily accessible fuel. In recent years, sport initiatives such as India's National Electric Mobility Mission Plan (NEMMP) and the Faster Adoption and Manufacturing of Electric Vehicles (FAME I and II) plans to push higher EV acceptance level. Excellent energy and power density of lithium-ion batteries are the crucial components of EVs as they allow long range at constant velocity and powerful acceleration. Proper battery control and particularly SOC plays a significant role in the overall performance of EV [4]. Even today, automobiles consume 25% world energy and rechargeable batteries provide a remedy to swap gasoline driven vehicles for EVs. It also finds application in portable computing and communications devices, home appliances and renewable energy technologies. Battery management systems (BMS) aim at providing safety, optimizing the functionality, as well as reliability. Two main approaches to BMS modeling exist: Ekachan offers recommendations on choosing the variety of models used: electrical equivalent circuit models (EECMs) and electrochemical models, while EECMs are applied mostly because of their simplicity. Major issues present are; thermal runaway, charging and discharging efficiency and balances in cell placement. The BMS algorithms concern charging, state-of-charge (SOC) estimation, and battery-pack configuration. Battery reuse brings new questions, since conventional BMS architectures do not apply well to reused batteries. This paper analyses these challenges and the solutions provided by the authors [5]. The second-generation hybrid and electric vehicles are driving the change from traditional gasoline and diesel vehicles and battery management system (BMS) are an essential component of these vehicles and renewable energy storage devices. This review looks into the opportunities and threats associated with batteries specifically battery management system: battery modeling, state estimation, and charging. It also describes the electric, thermal, and electro-thermal battery models and methods for the state of charge and health estimation. The paper also looks at various cell balancing methods, charging process, and optimization approaches, their advantages, disadvantages and the existing literature gaps in BMS [6]. EV lithium-ion batteries have certain thermal issues such as risks of runaways, calling for a hybrid thermal management system. Thermal energy storage using PCMs containing graphite, nanomaterials, or metal foams increases the material's thermal conductivity and reduces heat spread. Machine learning based solutions augmented with hybrid systems are promising; however, these must be cost effective, compact, and green to promote widespread usage of Electric Vehicles [7]. Lithium-ion batteries, desired for their compactness and better cycle efficiency in the EVs, are temperature dependent and need thermal control. This paper reviews heat generation and thermal issues, categorizing Battery Thermal Management Systems (BTMS) into two types: Cabin air systems Compression systems are those that include cabin air, liquid, and two-phase cooling, whereas non-compression systems include PCMs, heat pipes, and thermoelectric cooling. It introduces a new BTMS that addresses the shortcomings of individual systems, thus achieving the best battery performance and durability [8]. LIBs, which are widely used in HEVs and BEVs in terms of their energy density and life cycle, are sensitive to heat and require sophisticated thermal control. This paper also discusses heat generation problems and divides the Battery Thermal Management Systems (BTMS) into vapor compression type including air, liquid and two-phase and non-compression methodologies involving PCMs, heat pipes. In view of the drawbacks of the individual approaches, a novel BTMS is devised to improve both battery performance and lifetime. [9]

Literature Review

Air-cooled, liquid-cooled, phase change material and thermoelectric-based Battery Thermal Management Systems (BTMS) are critical systems in electric vehicles. Their strengths and weaknesses are discussed and direction for further studies is given, with emphasis on the fact that it is crucial to employ multiple strategies to improve the safety, efficacy and durability of batteries under different thermal conditions [1]. A discussion of EV battery technologies and their evolution and future scope is carried on with an outlook to lithium-ion and post-lithium advancements. Key areas consist of boosting the energy density, safety issues and charging time. AI advancements in the battery management systems together with wireless charging, cloud integration is also highlighted as well [2]. A detailed technical analysis of technical strengths of smart battery management technology for electric vehicles with focus on state estimation, fault diagnosis, and thermal management is given. It presents research directions, improvements, and algorithms, in addition to future development suggestions for enhancing the battery's safety, dependability, and efficacy [3]. BMS in electric vehicle mainly targets cell balancing, thermal regulation, cell age modeling and utilization. provides methods for controlling battery parameters for safety and performance purposes based on various charging strategies for the continual operation of electric vehicles [4]. Battery management systems are responsible for safety, efficiency and reliability by means of SOC/SOH estimation functionality, optimal charging, cell balance functionality and tracking algorithms [5]. The battery management systems of electric vehicles therefore extend to estimation of voltage, SOC/ SOH, fault detection as well as cell balancing for safety, durability and efficiency [6]. Advancements in BMS include battery modeling, SOC/SOH estimation, thermal management, optimization, charging strategies, fault diagnosis, and cell balancing [7]. Converging on the arch of propulsion, battery and thermal management, power electronics, climate impact, as well as efficiency improvement through methodologies and comparisons [8]. The Battery Thermal Management System (BTMS) for electric vehicles has two groups: those who use the Vapor Compression Cooling (VCC) system and those who do not [9]. Li-ion batteries are compared with other types of batteries focusing on safety concerns, environmental impacts, and performance differences [10].

Methodology

A Battery Management System (BMS) is one of the key features that allow controlling the safety and efficiency of the battery-powered devices regardless of the industry, from electric vehicles, renewable energy storage to portable electronics and industrial applications. BMS is critical in its capability to monitor, control, and enhance battery packs as they are normally composed of several cells that must collectively deliver the needed power. This is through use of monitoring systems of electrical parameters including voltage current and temperature within battery packs as well as the environmental settings for the battery packs with the help of various sensing system integrated within battery packs. These measurements are the primary information base of the BMS's work, in the form of an analysis of which data is immediately transmitted to various controlling algorithms to manage and protect the battery. Another critical operation of BMS is the management of charge and discharge cycles using a protection relay with a primary role of maintaining safety by not allowing conditions such as overcharging and over discharge, short circuiting, and high temperatures. These conditions if not arrested lead to permanent detriment in the battery resulting in shortening of cycle life or worst creating thermal runaway where a battery catches a fire and burns and there is no stoppage.

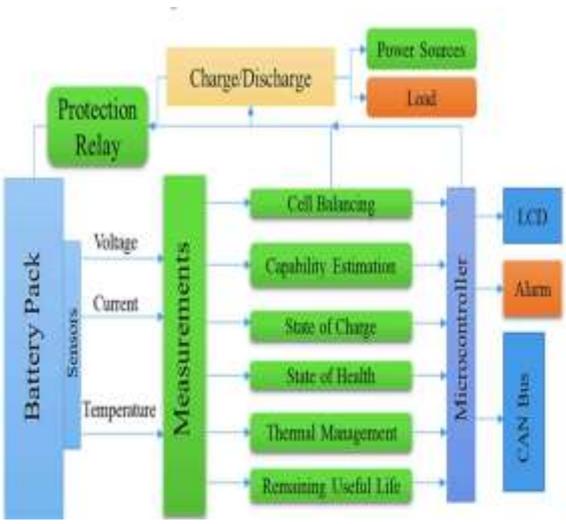

fig1 Battery Management System

Apart from safety control, the BMS also has several functions to control and monitor the performance and durability of the battery in at least two other ways. Among them, cell balancing is that, a method to bring each cell of a battery pack to a common voltage and SoC. This function is important much more when used in larger battery systems because any equalization that is less than 100% will cause performance to degrade as well as reduce the capacity needed. All cells can easily be overcharged or over discharged if balancing is not well done hence making the overall pack to have a short life span. The BMS also constantly carries out capability estimation which is the ability to ascertain actual power capabilities of the battery in real-time. This estimation is important in the control of energy since it can be used to predict the amount of power available in applications such as electric vehicles where range information is critical to the usability and safety of the vehicle. The second major tasks of the BMS are to calculate the state of charge (SoC) and the state of health (SoH) of the battery. The SoC determines the quantity of energy in the battery with reference to its total capacity so that accurate energy control could be done while the SoH gives an estimation of the general health of the battery, to include the capability to store and deliver power as expected. By constantly recording these signals, the battery management system guarantees that the battery is within the most favorable working conditions hence the durability and reliability.

The core of a BMS is its control center: the microcontroller that takes inputs from the sensors and processes this data along with the complex software that controls the safety and efficiency of the BMS. This microcontroller plays a dual role: it not only is directly related to cell balancing, thermal and charge control for internal needs, but also acts as a signaling center and serves as a working interface with other systems and devices. Using communication standards like CAN Bus, the BMS transfers

information with other subsystems or with external displays connected, for the useful life of a battery, the state of charge, and any alarms regarding possible safety issues. This communication is necessary for the battery system to be incorporated into more extensive applications like electric vehicles where it is essential for real-time efficiency feedback of the battery pack and information on the range capability of the electric vehicle as well as the vehicle systems in general. The microcontroller also regulates the thermal system, and the battery's temperature should not go beyond the limits. One of the biggest threats to batter durability is heat since it causes rapid chemistry changes on the cells, eventually leading to failure. The thermal management is managed by the microcontroller that controls the temperature of the battery and can turn on the cooling options or control the rate of charging and discharging. Combining these safety, optimization and communication functions the BMS represents the core of modern battery technology offering safe, reliable and maximized energy storage solutions for various applications and the vehicle's onboard systems.

Results and Discussion

Optimization of Battery Life and Safety through Advanced BMS Techniques

One of the major conclusions of the review is that Battery Management Systems (BMS) extend the lifecycle, reliability, and efficiency of lithium-ion batteries avoiding operating unwanted situations like overcharging, over-discharging and thermal runaway. Various methods such as the passive balancing, and the active cell balancing are employed to prevent cell balancing and to ensure equal or nearly charge across the cell and hence reduce the rate at which it loses its capacity. Extended Kalman filters and Coulomb counting are used for state of charge SOC estimation important for preventing an over-discharge of batteries that might result in permanent battery damage. Likewise, new state-of-health (SOH) estimation algorithms have enhanced the capability of machine learning models, which can accurately estimate the degradation trends of batteries by using earlier data information. They help extend battery life, increase vehicle and range reliability not only by having the ability to diagnose different issues. Moreover, adaptive control design BMS algorithms that can change some of its parameters according to the operational conditions have been implemented more often, which makes EV batteries less susceptible to environmental and operating variations.

Table 1: Comparison of different battery types based on key parameters

Parameter	Lithium-Ion (Li)	Nickel-Metal (NIMH)	Lead-Acid	Solid-State	Sodium-Ion
Energy Density (Wh/kg)	150-250	60-120	30-50	300-500	100-150
Cycle Life (Cycles)	1,000-3,000	500-1,000	300-500	5,000+	2,000+
Charging Time	1-2 hours	4-8 hours	8-10 hours	1 hour	2-4 hours
Thermal Management	Required (Cooling Systems)	Less sensitive to heat	Minimal management	Requires robust management	Moderate management
Safety Concerns	Risk of thermal runaway	Safer, low fire risk	Prone to leakage	Safer, but tech evolving	Stable, less reactive
Cost per kWh (USD)	120-200	300-500	150-200	Projected 80-150	100-150
Environmental Impact	Limited recycling options	Easier to recycle	Toxic materials(lead)	Improved recyclability	Low toxicity

Thermal Management and Energy Efficiency

Another major concern that BMS has to solve is controlling the battery temperature within its normal limits to avoid capacity aging and thermal runaway. Recent research brought out the benefits of a new concept of dual thermal management systems (DTMS) and hybrid thermal management systems (HTMS) which employs air liquid and phase change material (PCM). While more complicated than air-cooling, liquid cooling provides significantly improved cooling for densely packed EV batteries and, in general, systems of greater capacity. It also allows for better thermal management since the integration of the system into BMS guarantees good battery performance under both conditions, fast charging and maximum load, increases battery life. Studies for thermal management claim that heat and cold losses drop by up to 15 percent and battery efficiency by about 10-12 percent over the life cycle of a car. However, there are issues of cost and complexity of these methods which are hard to overcome for vehicle makers targeting the popular segments of the market. To address this, OEMs are opting for a sonic and flexible BMS structure that combines thermal control to minimize system size and expense.

Emerging Trends and Challenges in BMS Implementation

Currently, the development of BMS technology is wireless BMS (wBMS), cloud monitoring, and predictive analysis. As with the wired connections, Wireless BMS does not require the complicated wiring that would add on the vehicle mass and also restrict the flexibility of the system when incorporated into a moving vehicle, while at the same time allowing for faster installation at the time of manufacturing the vehicles. In addition, cloud-based platforms make it possible for the fleet operators and individual clients to monitor the vehicles, and conduct predictive maintenance on them. These systems employ BDA/ML to yield precise real time SOC/SOH readings due to which maintenance expenses cut down up to 20%. However, untrained and immature these new technologies are, they bring out new issues such as, security risks and compliance to safety rules. Since data transmission has shifted to the core business processes of BMS, protection of transmitted data comes into question. In addition, the regulatory formations are actively striving to set the standards for BMS that will allow understanding how new-generation BMS in electric vehicles are compatible and can intersect. Even though the technology behind BMS has improved in recent years to overcome the drawbacks of lithium-ion batteries, technology development must be on-going to meet the new demands of users, manufacturers and policymakers.

Conclusion

The necessity to apply Battery Management Systems (BMS) for the lithium-ion batteries (LIBs) usage in electric vehicles (EVs) as well as for their protection, stable operation and durability is underlined. BMS also plays an important role in electrical control and safety of important data such as SOC, DOD, SOH, SOP and thermal control. Cell balancing techniques are embedded to ensure battery health, avoid any imbalance and also decrease degradation. Recursive control algorithms such as predictors improve the efficiency of BMS since they predict battery states in real-time to achieve safe operation. Thermal management is highlighted as one of the critical issues for LIBs since temperature differences between cells cause capacity loss, and pose the potential risk of thermal runaway. The review also highlights the point that air, liquid, and phase change material utilizing hybrid thermal management systems (HTMS) gives better solutions to temperate control in severe condition. Liquid cooling, having a higher specific heat capacity than air cooling, has received significant attention, but it complicates the system's design and increases its cost. PCMs are promising for passive cooling applications, particularly NePCMs, but the latter has drawbacks, including low thermal conductivity and flammability. Scientists are also experimenting with compact modular designs as the means to incorporate cooling solutions better in terms of efficiency and cost. Details of the future BMS technologies have been highlighted in this review as including BMS, cloud-based monitoring, and Honeywell's analytics. These will lead to minimization of the wiring system, facile maintenance through system diagnostics and increased flexibility of operation. However, some other issues, including security concerns like cyber-risk and compliance issues, make integrated solutions for satisfactory implementation. The reliance on hybrid cooling systems will also become more important with increasing ambient temperatures and the need for higher cooling performance EVs.

Therefore, in order to address the inherent demands of the market, improvement of BMS technology is needed constantly. An improved and safer BMS will make car performance better, and at the same time contribute to sustainable growth since it has the backing of climate change, and the change traffic to green energy. Strengthening the economically efficient, compact and lightweight BMS for wider use of electric vehicles will be important challenges and directions for success in the long-term automotive market development.

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