A Comprehensive Survey of EV BMS with Fire Protection and Charge Monitoring

Akruthi M K, Shreena M, Spoorthi S, Vyshnavi K Y, and Om Prakash Yadav

Department of Electrical and Electronics Engineering, PES Institute of Technology and Management, Shivamogga, Karnataka, India
email:akruthiakruthi123@gmail.com
vvyshnavinitin@gmail.com
shreena15102@gmail.com
spoorthideepthi34@gmail.com
omprakashelex@gmail.com

Abstract. The integration of battery energy storage systems (BESS) in various applications has increased due to advancements in renewable energy, electric vehicles, and grid stability solutions. However, safety concerns, particularly fire incidents, have gained attention. This article reviews existing literature on battery management systems (BMS) and fire protection mechanisms, identifying current trends in BMS technology to mitigate fire risks. It discusses thermal management strategies, state-of-charge monitoring techniques, fault diagnosis algorithms, and fire suppression methods. The review also examines challenges, limitations, and future research directions in enhancing fire safety within BMS. This review is valuable for researchers, engineers, and policymakers working on BESS development and deployment.

Keywords: Battery Management Systems (BMS) · Thermal Manage- ment · State-of-Charge Monitoring · Fire Protection · Fire Safety.

1 Introduction

The ever-growing popularity of electric vehicles (EV) is reshaping the automo- tive landscape, with an increasing number of consumers embracing the transition to cleaner and sustainable transportation. Central to this paradigm shift are the lithium-ion batteries powering these electric vehicles, serving as the heartbeat of their propulsion systems. EVs are increasingly recognized as a promising solution to combat greenhouse gas emissions from transportation. They operate on elec- tric power generated by batteries, offering bidirectional power flow during both acceleration and braking. The EV’s battery system, managed by sophisticated

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Battery Management Systems (BMS) technology, includes power converters to efficiently transfer energy between the battery and the motor. This process not only enables efficient energy use but also reduces emissions [6][15][25]. However, these batteries are not without challenges, and addressing concerns related to temperature management and fire protection is of utmost importance.

Electric Vehicle Battery Management Systems (EVBMS) play a pivotal role in ensuring the safety and optimal performance of electric vehicle batteries. Functional blocks for the EVBMS is shown in Figure 1.

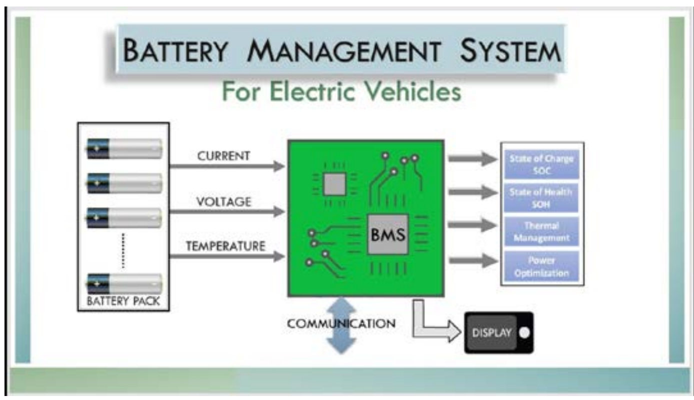

Fig. 1. Basic Architecture of Battery Management System

The details about the working of the EV-BMS can be obtained from [4][13]. Among the critical aspects addressed by these systems, temperature and fire protection stand out as paramount concerns. This paper explores the significance of incorporating robust temperature and fire protection features within EVBMS, delving into the challenges, solutions, and advancements in this dynamic field.

Managing temperature is crucial for optimizing the performance, lifespan, and safety of lithium-ion batteries. Elevated temperatures can accelerate chemical reactions within the battery cells, leading to degradation, reduced capacity, and, in extreme cases, thermal runaway. The EVBMS, equipped with sophisticated thermal management algorithms, serve as the guardian against these adverse effects. By continuously monitoring and regulating the temperature of individual battery cells, the BMS ensures that the operating conditions remain within the optimal range [17][6].

Another vital role of a BMS is to maintain the battery within a safe temperature range. Should the battery temperature rise excessively, the BMS may reduce the charging rate or even deactivate the battery to avert damage. Conversely, if the battery temperature drops too low, the BMS may elevate the charging rate to facilitate warming up the battery. In essence, the BMS is indispensable for ensuring the safe and efficient operation of rechargeable battery systems, thereby enhancing their longevity [17][3].

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EV batteries commonly utilized are 2-cell lithium-ion (Li-ion) batteries, which should ideally exhibit a voltage of approximately 6.0V when fully depleted and a maximum charge voltage of around 8.4V. During the charging process, a balancing charger monitors each cell's voltage and adjusts the charge rate as needed to ensure uniform charging across all cells. The charging process ceases automatically once the battery reaches full capacity. It is imperative to exercise caution during the charging of Li-ion batteries, as overcharging may lead to malfunctions, potentially resulting in fire or explosion hazards. Therefore, careful monitoring of the charging process is essential, and it is crucial to never leave the battery unattended while charging [6].

The integration of advanced cooling and heating systems within EV BMS allows for precise temperature control. Passive cooling methods, such as heat sinks and thermal insulation, work in tandem with active cooling systems, including liquid cooling or air cooling, to maintain the batteries within the desired temperature range. This multi-layered approach not only safeguards the battery against overheating but also enhances its overall efficiency and performance [18].

Fire protection is another crucial aspect addressed by EVBMS, considering the potentially catastrophic consequences of a battery fire as shown in the Figure 2[12]. Lithium-ion batteries, while offering high energy density, can pose fire risks due to factors such as thermal runaway, manufacturing defects, or external damage. The EVBMS acts as a vigilant sentinel, employing a suite of measures to mitigate these risks and ensure the utmost safety for both the vehicle and its occupants.

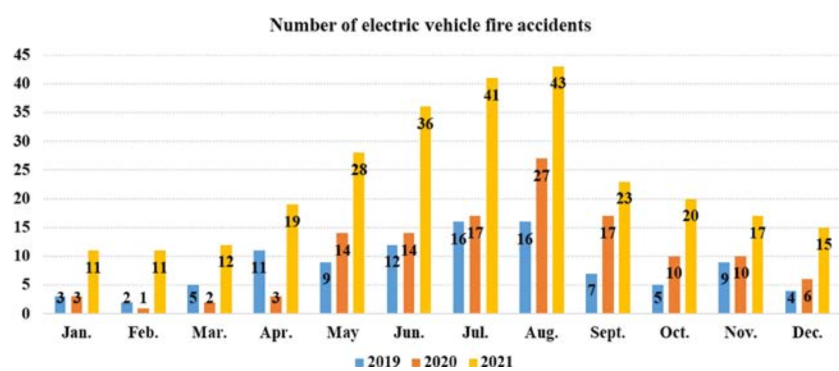

Fig. 2. Estimation graph of Fire accidents from EV vechiles

Moreover, the EVBMS is equipped with advanced software algorithms capable of detecting abnormal battery behavior that may signal potential fire hazards. These algorithms continuously analyze multiple parameters, including voltage, current, and temperature, in real-time to detect any deviations from normal operating conditions. If a potential threat is detected, the BMS can promptly activate protective measures, such as isolating the affected battery module or initiating emergency cooling systems, to mitigate the risk of escalation.

2 Battery Management Systems (BMS) Overview and Challenges

Linru Jiang et al. investigated critical systems pertaining to battery manage-ment, highlighting inefficiencies in current battery charge monitoring systems.To tackle this issue, establishing an advanced charging safety database and refin- ing a more precise and dependable charging fault diagnosis model are imperative. Additionally, research efforts should be directed towards charging safety protec- tion technology to counter power quality fluctuations, while the development of an early fault monitoring system based on electric load remains crucial. Further studies are warranted to effectively confront and surmount the aforementioned challenges[14].

In [1], the authors delved into the intricacies of managing batteries for EVs and highlighted the associated challenges. The scope of the exploration encom- passed critical factors such as battery lifespan, safety, cost considerations, and temperature issues, with a comprehensive analysis of BMS. The research un- derscored six pivotal aspects concerning the equilibrium of battery cell charges within BMS. Challenges identified included the imperative for real-time moni- toring of battery charge and health, optimization of charging processes, thermal management, and effective recycling strategies.

Shi et al. in 2023 proposed potential trends in Battery Management Systems (BMS), advocating for the integration of smart algorithms, universal designs, efficient prototyping methods, enhanced predictive capabilities, and virtualiza- tion techniques. Despite the adoption of advanced methodologies, the study ac- knowledged persistent challenges faced by BMS. The successful integration and widespread adoption of Electric Vehicles depended on effectively addressing these issues and advancing BMS technologies to cater to the evolving needs of EVs. The research findings provided valuable insights and recommendations intended for vehicle engineers and EV manufacturers [23].

3 Safety and Performance Enhancement in Battery Management

Q. Wang et al. discussed the primary challenge associated with the utilization of large lithium-ion batteries (LIBs) in applications such as electric vehicles and en- ergy storage: safety concerns [26]. The review emphasized that the heat generated from short circuits and chemical reactions within the battery can pose significant risks, potentially leading to hazardous situations. These reactions may release flammable gases, which, when combined with oxygen, can result in fires. The pa- per noted that different types of batteries may fail in distinct ways, and the level of risk depends on factors such as the battery’s condition and usage patterns. To address these safety concerns, researchers are employing advanced technologies like X-ray tomography to gain a better understanding of battery failures. However, accurately assessing the risk of LIB systems remains challenging at present. Nonetheless, the paper underscored that testing and the development of safer materials are crucial steps towards enhancing safety standards in the future of battery technology.

Sun et al. discussed the increasing risk of EV fires attributed to factors such as driving demands, accidents, and the rising energy density of batteries. With the expanding market share of EVs, the authors anticipated a corresponding increase in fire incidents. They highlighted the limited availability of full-scale EV fire tests, which had shown comparable heat release rates to traditional vehicles but with the potential release of more toxic gases. Suppression of EV fires presented challenges due to battery re-ignition and difficulties in cooling. While water remained the most effective suppressant, it required a significant amount for effective mitigation. The review underscored the pressing need for enhanced fire-protection systems in buildings and parking spaces with a higher concentration of EVs to mitigate these risks effectively [24].

In 2020, Ghosh et al. delved into the potential of electric vehicles (EVs) in mitigating carbon emissions within the transport sector [10]. The review underscored the advantages of battery electric vehicles (BEVs) as genuine zero-emission options, highlighting their role in combating environmental concerns. However, the paper also brought attention to several challenges faced by BEVs, including the weight added by batteries, the necessity for efficient energy storage and management systems, and the limited availability of fast charging infrastructure. Additionally, the review emphasized the critical influence of government incentives in driving EV adoption, alongside the impact of consumer willingness to pay and socio-economic factors on purchasing decisions. To bolster the adoption of EVs, the authors suggested that manufacturers should prioritize the creation of diverse and appealing EV models to stimulate sales and accelerate the transition towards sustainable transportation.

In 2022, D Sahitya Devi et al. highlighted the critical role of charging meth- ods and precise State of Charge (SOC) approaches in maintaining an efficient EVBMS [5]. With a focus on reducing greenhouse gas emissions, the review emphasized the importance of optimizing power performance. The paper sug- gested that selecting an appropriate charging method and prioritizing model-based methods, particularly those emphasizing statistical performance, could significantly enhance BMS effectiveness. Moreover, advancements in technology,such as the utilization of neural network methods, were introduced to maximize the effectiveness of various approaches, further contributing to improved BMS performance and overall sustainability in the realm of electric vehicle technology.

Pavan Kumar et al. emphasized the indispensable role of Battery in BMS in ensuring the safe and efficient operation of energy storage systems [19]. They highlighted key functionalities such as temperature monitoring and fire protec- tion, which played a vital role in preserving battery durability and reducing the severity of potential damage. Temperature tracking was particularly crucial for lithium-ion batteries commonly used in residential energy storage, as they were sensitive to temperature fluctuations. Elevated temperatures could accelerate battery degradation, reduce capacity, and potentially lead to fires or explosions.

Furthermore, even though there is no intrinsic risk associated with lithium-ion batteries, fire safety is still a top priority. The early identification of possible fire threats is made easier by a BMS with fire protection capabilities. This activates safety mechanisms that isolate concerned battery modules, turn on fire suppression systems, and notify emergency services or homeowners. These actions considerably

lower the possibility of fire-related mishaps, protecting both assets and people. For domestic energy storage systems to operate effectively and securely, a strong BMS must be integrated with capabilities for temperature monitoring and fire safety. When renewable energy storage technologies proliferate in residential settings, ongoing monitoring and early detection not only maximize battery performance and lifespan but also help to ensure a safer transition.

Khaled Laadjal et al. [16], in their paper, reviewed strategies for estimating the State of Charge (SoC) in electric vehicle batteries. They emphasized the challenges posed by complex electrochemical reactions and varying efficiency, particularly with the increasing demand for electric vehicles and diverse battery technologies. The paper highlighted approaches for optimizing voltage drift and suggested employing machine learning methods to train models using real-world data. Internal resistance was identified as a critical parameter affecting battery performance and lifespan. Furthermore, the analysis discussed the impact of temperature on battery life and proposed early detection methods for temperature-related changes. The paper concluded by underscoring the importance of considering various factors for accurate battery status assessment and suggested future research directions, including the integration of different models and methodologies for enhanced predictive efficiency under diverse conditions.

Miao et al. [20] offered a comprehensive overview of lithium-ion batteries within the realm of energy storage for electric vehicles (EVs). The paper extensively covered various aspects, including diverse electrode materials, electrolyte types, and the physical setup of Li-ion batteries. Through a detailed comparison of these elements and insights into battery management systems, the paper underscored the crucial role of material and thermal characteristics in determining the performance of lithium batteries, with particular emphasis on electrode-generated heat. Furthermore, it highlighted the pressing need for further research in cooling methods and electrode design to enhance battery life and capacity. Additionally, the paper explored repurposing and recycling strategies for EV batteries at the end of their useful life, reflecting a holistic approach to sustainable energy storage solutions.

4 Advancements and Trends in Battery Technology

An embedded battery monitoring system for electric vehicles (EVs) was presented by B.V. Manikandan and co-authors in [7]. This system enabled real-time

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monitoring of battery performance degradation, achieved through the integration of sensors and LCS technology. The system included an embedded user interface and hardware components designed for battery monitoring purposes. Notably, the system could identify coordinates and display them within the Google Maps application, providing users with essential information such as location, battery life, and time. Additionally, the authors introduced a smartphone application aimed at facilitating remote battery monitoring for users, thereby enhancing the overall efficiency and reliability of EVs.

In their 2014 paper, Rezvanizaniani et al. offered a comprehensive review of various methodologies for predicting and managing battery health in electric vehicles (EVs) [22]. The paper outlined three primary approaches: physical models, data-driven techniques, and a combination of both. Physical models utilized an understanding of battery operation to forecast remaining lifespan, although they might overlook intermittent issues. Data-driven approaches, conversely, focused on diagnostics in the absence of specific information, requiring training data for accurate predictions. A fusion approach, integrating elements of both methodologies, provided enhanced predictive capabilities. The paper highlighted challenges such as managing uncertainties in mobility, durability, and safety throughout battery life, emphasizing the necessity of addressing these challenges to advance battery health management in electric vehicles.

The paper authored by Ghiji et al. provided a comprehensive review of Lithium-ion Batteries (LiBs), highlighting their advantageous features such as high voltage, energy density, and extended lifespan [9]. However, the review also underscored significant safety concerns associated with LiBs, particularly regard- ing thermal runaway and fire incidents under abusive conditions. The paper em- phasized the imperative of prioritizing safety considerations in battery selection processes. Despite the existence of battery management systems, safety incidents still occurred, prompting a comprehensive review of safety techniques at various levels. The paragraph proposed the utilization of water mist with additives asa promising approach to extinguishing and cooling LiB fires, particularly given limitations with other extinguishing agents. Additionally, the review stressedthe importance of further research aimed at establishing effective extinguishing guidelines to enhance overall battery safety standards.

In their 2021 paper, Nitika G. Panwar et al. comprehensively reviewed BMS from 2006 to 2020, with a focus on recent trends [21]. The review meticulously examined BMS functions, including cell balancing, thermal management, and protection measures, alongside state-of-charge and health estimation techniques, and recent advancements. Additionally, the paper identified gaps in current BMS technology and explored emerging areas such as digital twin technology, self-configurable batteries, and recycling methods. Proposing a methodology for developing future BMS that would be comprehensive, compact, and efficient, the authors emphasized the critical role of skilled talent in battery technology, particularly in the rapidly evolving electric vehicle landscape. They underlined the necessity for continuous skill development and expertise in battery technology to meet the demands of this dynamic industry.

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SectionComprehensive Reviews and System Modeling

Hossam A. Gabbar et al.'s publication [8], which was released on April 11, 2021, included a thorough analysis of battery management systems (BMS) and emphasized the importance of this essential part of electrical energy storage systems. The research emphasized the significance of guaranteeing BMS safety in order to efficiently operate an electrical system, acknowledging that BMS interacted with both internal and external occurrences. The report covered a wide range of topics, including testing, components, functions, topology, operation, architecture, and safety considerations. It delves into the complex intricacies of BMS for both electrical transportation and large-scale (stationary) energy storage applications. The research noted that, although acknowledging the various configurations that BMS may take on based on the application, the core operating objective and safety feature of BMS remained constant:

The paper authored by Balasingam et al. provided a comprehensive review of key technologies within the Battery Management Systems (BMS) of Electric Vehicles (EVs), focusing particularly on battery modeling, state estimation, and battery charging. Battery modeling, coupled with accurate estimations of internal states and parameters, was highlighted as crucial for understanding the holistic operating status of batteries in EV applications. Once these key states were identified, appropriate battery charging approaches could be devised to safeguard against damage, enhance energy conversion efficiency, and prolong battery lifespan. However, the review noted that many of these key technologies were developed and validated under specific test conditions, which may not accurately reflect real-world applications or worst-case scenarios. Consequently, there was a need to explore the limitations of these technologies and develop confidence intervals to address this challenge effectively [2].

In their paper, Hariprasad et al. delved into the challenges and solutions concerning EVBMS, laying the groundwork for future research endeavors [11]. The paper underscored the significance of continually upgrading and optimizing BMS performance to suit specific operational contexts. It concluded by advocating for the development of a comprehensive system model for BMS in EVs, encompassing control parameters such as voltage, current, state of charge, state of health, state of life, and temperature. Emphasizing the critical role of BMS maintenance in ensuring battery reliability and safety, the paper highlighted the importance of optimizing power performance within electric vehicles. Ultimately, the authors suggested that achieving a reduction in greenhouse gas emissions is feasible through the effective implementation of battery management systems.

5 Conclusion

This comprehensive survey highlights the critical importance of integrating robust fire protection mechanisms and precise charge monitoring techniques within

EVBMS. With the rapid proliferation of EVs and battery energy storage systems, ensuring the safety and optimal performance of lithium-ion batteries has become paramount. Through an in-depth review of existing literature, this survey synthesizes key findings and identifies current trends in EVBMS technology aimed at mitigating fire risks and enhancing overall system reliability. Thermal management strategies, state-of-charge monitoring techniques, fault diagnosis algorithms, and fire suppression methods integrated into EVBMS designs are crucial components in safeguarding against potential hazards. While advancements in technology have significantly improved the safety and efficiency of EVBMS, challenges and limitations persist, underscoring the need for continued research and development in this dynamic field. By addressing these challenges and em- bracing emerging trends, stakeholders can contribute to the advancement of EVBMS technology, ultimately promoting the widespread adoption of electric vehicles and sustainable energy storage solutions.

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