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Review

Review of Battery Management Systems (BMS) Development and Industrial Standards

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Abstract: The evolving global landscape for electrical distribution and use created a need area for energy storage systems (ESS), making them among the fastest growing electrical power system products. A key element in any energy storage system is the capability to monitor, control, and optimize performance of an individual or multiple battery modules in an energy storage system and the ability to control the disconnection of the module(s) from the system in the event of abnormal conditions. This management scheme is known as "battery management system (BMS)", which is one of the essential units in electrical equipment. BMS reacts with external events, as well with as an internal event. It is used to improve the battery performance with proper safety measures within a system. Therefore, a safe BMS is the prerequisite for operating an electrical system. This report analyzes the details of BMS for electric transportation and large-scale (stationary) energy storage. The analysis includes different aspects of BMS covering testing, component, functionalities, topology, operation, architecture, and BMS safety aspects. Additionally, current related standards and codes related to BMS are also reviewed. The report investigates BMS safety aspects, battery technology, regulation needs, and offer recommendations. It further studies current gaps in respect to the safety requirements and performance requirements of BMS by focusing mainly on the electric transportation and stationary application. The report further provides a framework for developing a new standard on BMS, especially on BMS safety and operational risk. In conclusion, four main areas of 1) BMS construction, 2) Operation Parameters, 3) BMS Integration, and 4) Installation for improvement of BMS safety and performance are identified, and detailed recommendations were provided for each area. It is recommended that a technical review of the BMS be performed for transportation electrification and large-scale (stationary) applications. A comprehensive evaluation of the components, architectures, and safety risks applicable to BMS operation is also presented.

Keywords: energy storage safety; control

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1. Introduction

The electrical power system is one of the only supply networks where the product—electricity—is consumed instantaneously after it is generated. It is mainly because a safe and reliable means to store electrical energy has been missing. The evolving global landscape for electrical distribution and use created a need for energy storage systems (ESSs), making them among the fastest-growing electrical power system products.

The maturity of electrical energy storage technologies can be divided into three categories: deployed, demonstrated, and early-stage technologies. Pumped hydro, compressed air energy storage, battery, and flywheel are examples of the deployed electric energy storage system. The demonstrated energy storage technologies include flow batteries and advanced Pb-acid, superconducting magnetic energy storage, and electrochemical capacitor. The early stage energy storage technologies are adiabatic compressed air energy storage (CAES), hydrogen, and synthetic natural gas. Among all the above-mentioned technologies, batteries and capacitors are susceptible to risks and safety issues [1].

A battery is an electrical energy storage system that can store a considerable amount of energy for a long duration. A battery management system (BMS) is a system control unit that is modeled to confirm the operational safety of the system battery pack [2–4]. The primary operation of a BMS is to safeguard the battery. Due to safety reasons, cell balancing, and aging issues, supervision of each cell is indispensable. Moreover, BMS ensures the preset corrective measures against any abnormal condition at the system infrastructure. Besides, since the system temperature affects the power consumption profile, BMS also confirms the proper procedure to control the system temperature.

In [5], authors discussed the battery management systems in electric and hybrid vehicles. The paper addresses concerns and challenges related to current BMSs. State evaluation of a battery, including state of charge, state of health, and state of life, is a critical task for a BMS. By reviewing the latest methodologies for the state evaluation of batteries, the future challenges for BMSs are presented, and possible solutions are proposed. In [6], authors discussed the battery management system hardware concepts. It focuses on the hardware aspects of battery management systems (BMS) for electric vehicles and stationary applications. In [7], it presented an enhanced multicell-to-multicell battery equalizer based on bipolar-resonant LC converter. Mathematical analysis and comparison with typical equalizers are provided to illustrate its high balancing speed and good efficiency.

In [8], it dealt with the susceptibility to electromagnetic interference (EMI) of battery management systems (BMSs) for Li-ion and lithium-polymer (LiPo) battery packs employed in emerging electric and hybrid electric vehicles. A specific test board was developed to experimentally assess the EMI susceptibility of a BMS front-end integrated circuit by direct power injection (DPI) and radiated susceptibility measurements in an anechoic chamber. In [9], the paper proposed a novel method for accurate hysteresis modeling, which can significantly improve the accuracy of the SOC estimation compared with the conventional methods. The SOC estimation is performed by using an extended Kalman filter (EKF), and the parameters of the battery are estimated by using an auto regressive exogenous (ARX) model and the recursive least square (RLS) filter.

In [10], it presented the battery management system demonstrator board design using EMC system simulation. The paper explains how EMC system simulation is used to find the root cause and optimize the board design quickly. In [11], it illustrated a specific test board developed to experimentally assess the EMI susceptibility of a BMS front-end integrated circuit by direct power injection (DPI) and radiated susceptibility measurements. Experimental results are discussed by highlighting different EMI-induced failure mechanisms observed during the tests.

Kang et al. presented and studied a battery pack's thermal behavior under the power demand [12]. The proposed thermal prediction model is categorized based on Joules heating with equivalent resistance, reversible heat, and heat dissipation. The equivalent resistances are controlled by the state of charge intervals using the hybrid pulse power characterization. In [13], it studied the detailed models of high-power charging impacts and limitations of batteries by the optimization techniques. It presents an optimal operation of the power distribution from the power sources.

Arnieri et al. proposed an efficient management strategy that allows maximizing the overall energy efficiency of grid-connected storage systems considering the actual relationship between the efficiency and the charging/discharging power of the storage system [14]. Lee et al. proposed a method for estimating pulse power performance according to pulse duration. This method is applied for power generation systems in the application of energy storage and transportation electrification [15].

Uno et al. proposed a novel cell voltage equalizer using a selective voltage multiplier. By embedding selection switches into the voltage multiplier-based cell voltage equalizer, the number of selection switches can be reduced compared to that in conventional topologies, realizing the simplified circuit. A prototype for twelve cells was built, and an equalization test using Li-ion batteries was performed [16]. Lee et al. presented a regression analysis of the peak point in the incremental capacity (IC) curve from the new state to a 100-cycle aging state. Moreover, the State of Health (SOH) of the considered retired series/parallel battery pack was estimated using a regression analysis model. The error in the SOHs of the retired series/parallel battery pack and linear regression analysis model was within 1%, and hence a suitable accuracy is achieved [17].

Currently, there is no specific BMS standard for large-scale applications, small appliances, or electric transportation. Considering the importance of BMS and its functionality in the safe operation of ESSs, the scope of this report is to provide a technical review of BMS for applications in transportation, electrification, and large-scale (stationary) applications, with a focus on standardization. This report also performs a comprehensive evaluation of the components, architectures, and safety risks during the BMS operation. Besides, it reviews technical standards relevant to the BMS to assist in new standard development.

2. Battery Management System

The definition of BMS varies from application to application. In general, BMS refers to a management scheme that monitors, controls, and optimizes an individual's performance or multiple battery modules in an energy storage system. BMS can control the disconnection of the module(s) from the system in the event of abnormal conditions. It is used to improve battery performance with proper safety measures within a system. In a power system application, BMS is introduced to monitor, control, and deliver the battery's power at its maximum efficiency (battery life is also considered here). In automobile applications, BMS is used for energy management in different system interfaces and ensures the system's safety from various hazards. BMS consists of distinct functional blocks. The functional blocks of BMS are connected to batteries and all other units related to the structured system as controllers, a grid, or other distributed resources, presented in Figure 1. Proper architecture, functional blocks, and advanced circuitry can extend the system battery life. Several commercial BMSs are available in markets. For example, NUVATION Energy provides a flexible, module, reliable, and UL 1973 recognized BMS for mobile and stationary energy storage applications [12].

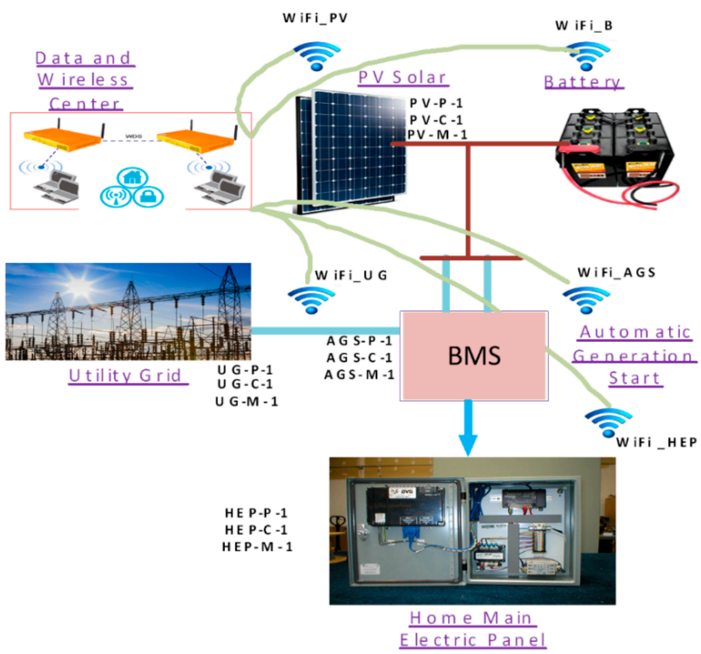

Figure 1. Battery Management System (BMS) connections and integrations [5].

2.1. Components and Topology

A BMS cannot be used as a standalone within a system infrastructure. It is integrated with other system modules to accomplish the system objectives. For example, an intelligent energy automation system includes a battery management module (BMM), battery interface module (BIM), battery units, and battery supervisory control. The system protects the battery pack, extends the battery lifetime, manages the power demand, and interfaces with the different network [13].

There are three implementation topologies—centralized, distributed, and modular—available in the BMS market. In a centralized topology, a single control unit and battery cells are put together through multiple wires. For distributed topology, each control unit is dedicated to each battery cell by a single communication cable. Lastly, in modular topology, multiple numbers of control units deal with a particular battery cell, but the control units are interconnected [14]. The centralized BMS is the most economical and least expandable. The distributed BMS is the costliest, but it is the easiest among the three to install and offers the cleanest assembly. The modular BMS includes more hardware and programming effort and makes a confrontation between the features and problems of the other two topologies. Figure 2 shows BMS implementation topology.

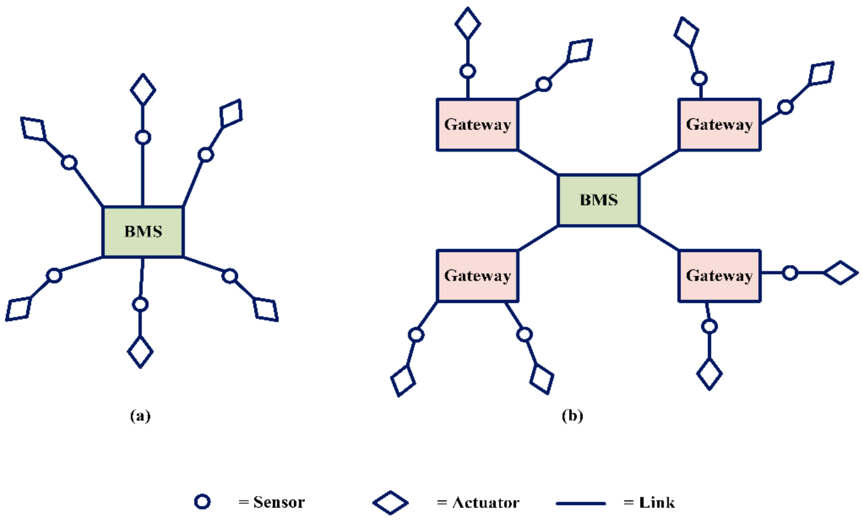

Figure 2. BMS implementation topology: (**a**) centralized, (**b**) distributed.

2.2. Software Architecture

BMS software architecture offers multi-tasking capabilities. Previously, it was not possible to continue different tasks simultaneously; one task was postponed to carry on the other task. Now, in new BMS software architecture, various tasks can be carried out together without any interruption. A BMS software architect's initial tasks, such as voltage/current measurement, over current/voltage protection, temperature measurement, and protective relay actuation, must be performed promptly to ensure BMS safety. The real-time operating system (RTOS) is introduced in BMS software architecture to perform the real-time functionalities. Figure 3 shows the architecture of BMS software [15].

2.3. Functionalities

BMS deals with battery packs that are connected internally or externally. It calculates the battery quantities, with typical measurements performed for cell voltages, pack current, pack voltage, and pack temperature. BMS uses these measurements to estimate state of charge (SOC), state of health (SOH), depth of discharge (DOD), and the operational key parameters of the cells/battery packs. The measurements also help to increase battery life and keep pace with the demand requirements of the original power network.

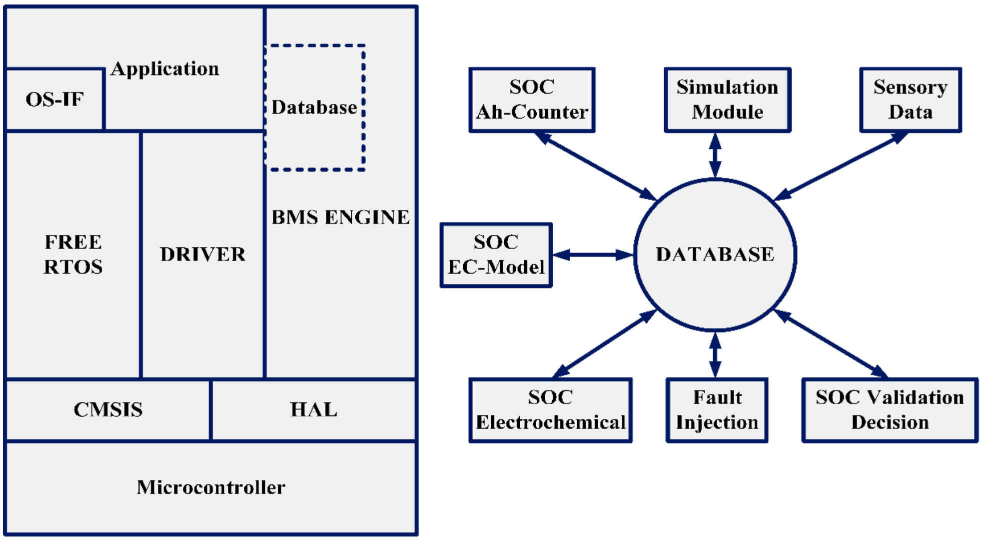

Figure 3. BMS software architecture.

BMS is built using functional unit blocks and design techniques. Battery requirements for different applications will help to indicate the appropriate architecture, functional unit blocks, and related electronic circuitry to design a BMS and BMS charging scheme. Battery life can be optimized based on the following features [16]:

– Energy management system with a user interface to control and examine battery systems' performance in different system blocks.
– Battery pack performance and safety features.
– Resiliency among the system units in different accident scenarios.
– Advanced technologies that integrate batteries with conventional/non-conventional energy sources.
– Internet-of-things (IoT), which monitors and controls the energy management system.

BMS will investigate the following significant capabilities and functions: automatic charging/discharging, protection, monitoring, and stability and resiliency. The following figure provides a functional tree of BMS.

Furthermore, BMS has efficient impacts related to accuracy and battery life. It leads to increased battery life with accurate operation measurements and control. BMS applies different methods for accurate modeling, which can provide a significant improvement in terms of the accuracy of the SOC estimation. Additionally, the accuracy of cell balancing is another benefit of BMS functions in the service of energy performance optimization. It is used to improve battery performance with proper measures within a system. BMS is able to control the power of the battery at its maximum efficiency with extended battery life. The system will protect the battery pack, extends the battery lifetime, manages the power demand, and interfaces with the different network.

On the scale of the accuracy, it calculates the battery quantities, with typical measurements performed for cell voltages, pack current, pack voltage, and pack temperature. BMS uses these measurements to estimate state of charge (SOC), state of health (SOH), depth of discharge (DOD), and the operational key parameters of the cells/battery packs. The measurements also help to increase battery life and keep pace with the demand requirements of the original power network.

Battery life can be optimized based on the energy management system with a user interface to control and examine battery systems' performance in different system blocks. The charging and discharging management significantly impacts battery life. The economic advantages of BMS are extensions of battery lifetime, increasing the accuracy, and lowering the cost. Figure 4 shows the functions of BMS.

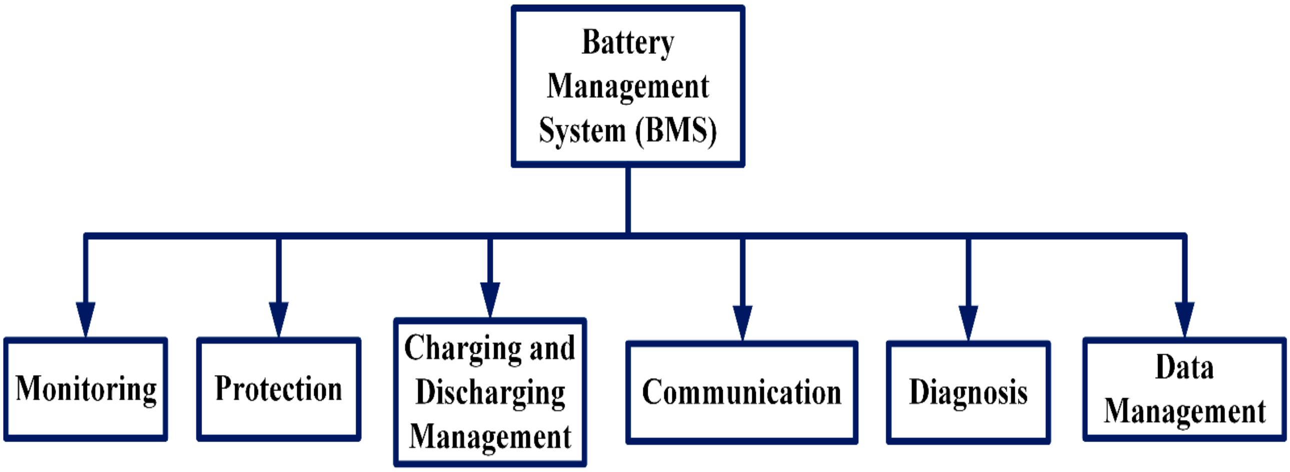

Figure 4. BMS functionalities.

BMS has significant impacts on batteries' operation and performance, especially on reducing the environmental impact of battery systems. BMS can protect the battery system from external events since the battery pack's external environment causes changes in the cell/pack parameters. Two types of temperatures—electrochemical reaction temperature and battery environment temperature—can be controlled in the battery pack for BMS safety. BMS can ensure control of these two types of battery temperatures within their safety limit. BMS is capable of handling the potential hazards related to the operation within battery systems. It allows protection of loss of air conditioning and battery cooling and protects the loss of battery heating controls (BSS).

Kokkotis et al. discussed the electrochemical means of EES systems such as batteries. The authors represented the caused damage to humans and the environment from batteries and other energy storage systems. The paper also covered a short review of the small-scale energy storage systems based on their environmental impacts. Besides, this paper explained the causes of soil and water pollution and endangered wildlife. Cadmium can cause damage to soil micro-organisms and affect the breakdown of organic matter. Other chemicals used in modern electrochemical batteries and any protective means of safe utilization with minimum environmental impact are also discussed in the paper [18].

A preparatory study on eco-design and energy labeling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619- Lot 1 is highlighted in [19]. It confirmed the European Union (EU) directives to describe the prospective boundaries or definitions to address the eco-design performance improvement. The main objective of requirements is to reduce the carbon footprint per functional unit modeled its projected useful lifetime. The standard IEC 62620 for industrial Li-ion batteries (from cell to system level) can be considered a valid base. The cycle-life test in IEC 62620 seems too different from the envisaged applications. In general, extending the lifetime of EV battery application by offering environmental and economic benefits reduces the need for primary resources. The criterion will create the conditions for more efficient management of batteries.

Moreover, BMS can control the charge and discharge cycles to avoid overloading the power and thermal impact that may reflect the environment. These actions can reduce the emissions from the power plants and the utility grids, which effectively reduces air pollution and enhances the human health measures and impacts.

Table 1 presents and summarizes the BMS issues on environmental impact, the efficiency, and the other operational parameters.

Table 1. BMS impacts.

Environmental Impact	Technical Efficiency Impact
Reduction in CO_2 emissions: Reduction in CO_2 emissions by a rate of 40% is possible when a battery is controlled by BMS to store off-peak clean electricity to serve peak demand.	**Real-Time State of Health Estimation:** BMS enables precisely to predict the state of health (SOH) of a battery. It has positive impact on the safety and quality of the operation and performance.
Greenhouse gas (GHG) benefits: The greenhouse gas (GHG) benefits of batteries could be doubled using BMS and better use of clean off-peak electricity.	**Optimal Charging:** The target is less time-consuming, highly efficient, safer, and optimal solutions based on the design parameters.
Metal depletion impacts BMS can be efficient in controlling the charging/ discharging cycles and the operation frequency. It impacts the comprised materials that have high environmental and energy impacts.	**Fast Characterization:** BMS enables the SOC and SOH characterizations. SOC is modeled using one complete cycle of data, whereas SOH characterization is done based on the number of cycles of data.
Temperature control impacts Two types of temperatures—electrochemical reaction temperature and battery environment temperature—can be controlled in the battery pack by BMS.	**Self-Evaluation:** BMS enables an evaluation based on mathematical models to represent the complex features of a battery, such as power, capacity, temperature effects, and hysteresis effects.

2.3.1. Monitoring

BMS mainly focuses on monitoring the battery pack voltage, current, cell voltage, temperature, isolation, and interlocks. A faulty battery charging system or voltage regulator can cause overvoltage in the battery system. An overvoltage or overcurrent may cause permanent damage to the battery system, while the overcharge causes cell venting. As vented gases are flammable, it creates a severe safety concern. Similarly, a low voltage or current significantly affects battery performance. Isolation of the central battery system is an essential task for BMS, especially for a high voltage system. If a human body comes into contact with a faulty high voltage battery system, the current will flow through the body and cause death. Temperature control is another crucial task for BMS. High temperatures create heat and other abnormal issues that negatively impact the battery system [17].

2.3.2. Protection

A BMS must ensure protection against any battery system hazards. The BMS safeguard includes (among others) detecting the operating mode, setting fault criteria, authenticating, and identifying the system, predicting the pack/cell overvoltage and overcurrent, predicting the isolation fault, and detecting the high/low temperature. A BMS must protect the battery system from the external event since the external environment of the battery pack causes the changes in the cell/pack parameter.

2.3.3. Charging and Discharging Management

The state of charge (SOC) has a significant impact on battery life. Each battery has a specific number of charging and discharging cycles, and the battery life reduces with the increased number of charging and discharging phenomena. BMS must confirm the efficient way for charging and discharging procedures. Additionally, a BMS must maintain the proper SOC so that the battery lifetime will be maximized. To ensure management in this area, BMS performs the following tasks: control the charger current, turn on/off active switches between the pack and load/charger, run the pre-charge sequence, set dynamic power limits, and conduct active and passive balancing.

2.3.4. Diagnosis

BMS estimates and predicts the depth of discharge (DOD), state of charge (SOC), battery capacity, cell temperature, state of fitness (SOF), available energy, charging time, remaining useful life (RUL), remaining runtime, and the inner impedance of cell and current capability to ensure efficient battery performance. BMS is also responsible for detecting faults, such as fires, thermal runaways, explosions, and minimizing the consequences of fault effects. Therefore, fault diagnosis is an important functionality for BMS [11].

The DOD calculation is essential to estimate the effective battery cycle. Sometimes the higher DOD will reduce the battery lifetime. For example, lead-acid batteries show less lifetime if the DOD is more than 50%. So, the DOD should be maintained in BMS to avoid unexpected hazards. The SOC is an alternative form of the same DOD measurement. Battery capacity indicates the amount of energy that can be extracted from the battery. Typically, the battery capacity measures the stored charge (in ampere-hours). Battery capacity is related to cell temperature. Batteries perform best at room temperature. The decreased temperature raises the internal resistance of the battery, which decreases battery capacity. Whether excess heat or excess cold, both reduce the C-rate of the battery. Along with other testing, the SOF determines the capability of the battery to be matched with the system.

2.3.5. Components and Topology

The communications between internal and external BMS and between BMS and the primary system are vital for the battery system's performance optimization. BMS can predict the battery's future states and direct the main system to perform and prepare accordingly. Sometimes, its main system structure may need to change the working strategy according to the battery's performance. In such a case, BMS is the only thing that can communicate with the main system and inform the predicted BMS results of the battery pack.

2.4. Testing

There are two types of BMS: functional and non-functional testing, which include the battery's lifecycle, research and design, validation, verification, and manufacture. Functional testing focuses on the performance and operational parameters of BMS. It uses software and hardware or platforms to test the functional requirements such as voltage level, current capacity, and consumed power. This testing is required to ensure the BMS's operation quality based on the performance and safety indicators. Non-functional testing is carried out to fulfill the non-functional requirements of the system. BMS's functional testing focuses on BMS operation procedure rather than certain-defined characteristics of that BMS. It tests all low-level details related to software and hardware, or both, that can be tested either globally or separately, such as the programming code for charging scenarios. Non-functional testing combines software and hardware to fulfill the system requirements and has no impact on BMS's function.

A list of testing related to BMS is presented in Table 2 [20–26]. An example of functional testing from Table 2 is current, voltage, temperature sensing, while examples of non-functional testing are dynamic charging and isolation monitoring.

Table 2. BMS test cases.

No.	Test Case	Description	End-of-Test Criteria
01	Idle or Stand-by	BMS is configured and the fault criteria are defined in the BMS. The subsequent functions are evaluated in idle mode.	The whole process is evaluated in steady state.
02	Current, voltage, temperature sensing	The sensors are supposed to checked and calibrated. Then, the full-range accuracy test is carried out by keeping the BMS at various conditions.	All conditions tested.

03	Dynamic discharge	The battery pack is totally discharged at ambient temperature by considering a real dynamic discharge scheme.	BMS stops discharging to avoid over-discharge.
04	Overvoltage during regenerative braking	The battery pack is fully discharged during experiencing a high regenerative current. The battery is discharged by considering a real dynamic discharge scheme.	The BMS interrupts the regenerative charging current.
05	Over-temperature during discharge	The battery pack is fully discharged at high temperature considering a real dynamic discharge scheme.	Battery pack reaches the maximum temperature and BMS stop the discharge.
06	Short circuit	Short circuits are placed at different locations in the battery pack: Event I: Internal or external short circuit adjacent to the cell's tabs. Event II: External short circuit through fuses or shunt resistor. Event III: External short circuit through fuse and switch box.	Short circuit current is zero.
07	CC-CV * charge	Conventional CC-CV charging with active/passive balancing.	End of charge.
08	Charge test at low temperature	A charge is enabled, and battery temperature is kept below the threshold of charging. The temperature starts to increase gradually due to the heating system.	When the pack temperature reaches over the limit, charging starts.
09	Diagnosis	Event I: Emulate SOC vs BMS estimated SOC during real dynamic discharge scheme. Event II: New events based on the BMS diagnosis features.	End of charge or discharge.
10	Isolation monitor	Single isolation fault is introduced on the positive or negative terminal of the battery pack.	Isolation fault detected.
11	Global power consumption	Event I: Battery pack is fully discharged using a dynamic discharge scheme followed by CC-CV charge. Event II: Test on idle mode for a specific time span.	BMS power consumption is evaluated at all conditions.

* CC-CV = constant current constant voltage.

2.5. Advantages of Using BMS

The technical advantages of using BMS prevent damage from over/under voltage and cell balancing with limited charge current. The operational benefits include safety, reliability, and dual-purpose. BMS minimizes the occurrence of a thermal runaway for high-voltage batteries. BMS also identifies the faulty cells connected in series and parallel (dual-purpose). The economic advantages of BMS are extensions of battery lifetime and lowering the cost. For example, BMS shares only 8% of the total battery pack cost for a 22 kWh mid-size EV battery pack [27].

2.6. Drawbacks of Current BMS

Current BMSs have limited data logging functions. This provision helps to develop the SOC model of battery packs. Current commercialized BMSs also lack SOC and state of life (SOL) estimations. SOC and SOL are critical features for BMSs since both ensure scheduled operation and reliability of battery replacements. Besides, each battery unit has its own BMS, and it is quite impossible to develop a new BMS from existing BMS components [28]. However, cloud BMS and the digital twin technology could be potential solutions for limited data logging functions. It improves data storage capabilities and computational power by cloud computing [29].

3. BMS for Electric Transportation

Around the world, electric mobility is being widely accepted as the future of mobility. With global concern heightened for emission reduction to fight climate change, there is greater support for increasing electric transportation use while phasing out fossil fuel-driven vehicles. As more and more battery-powered vehicles are deployed, attention must be given to the standardization of BMS products for transportation electrification applications to ensure public safety, transportation reliability, and manufacturing regulations [30]. Standardization of BMS for EVs and proper implementation of the standards in EVs can reduce risks and hazards associated with BMS significantly.

3.1. Operation

BMS has a significant role in safe operation, energy usage optimization, charging functionality, and overall control of an electric vehicle (EV). Figure 5 shows the powertrain system structure of the battery-powered EV. The single source of power is the traction battery, which has a large capacity and high power. It has two main operating modes: charging and discharging. In discharge mode, it powers the electric motor that converts the electrical energy to mechanical energy. The mechanical drive transmits the rotational energy to the wheels of the vehicle. The battery also satisfies the remaining onboard power requirements, such as air-conditioning, sensing, communication, infotainment facilities, etc. [31]. Several powertrain configurations and design component of hybrid powertrain have been discussed in [32].

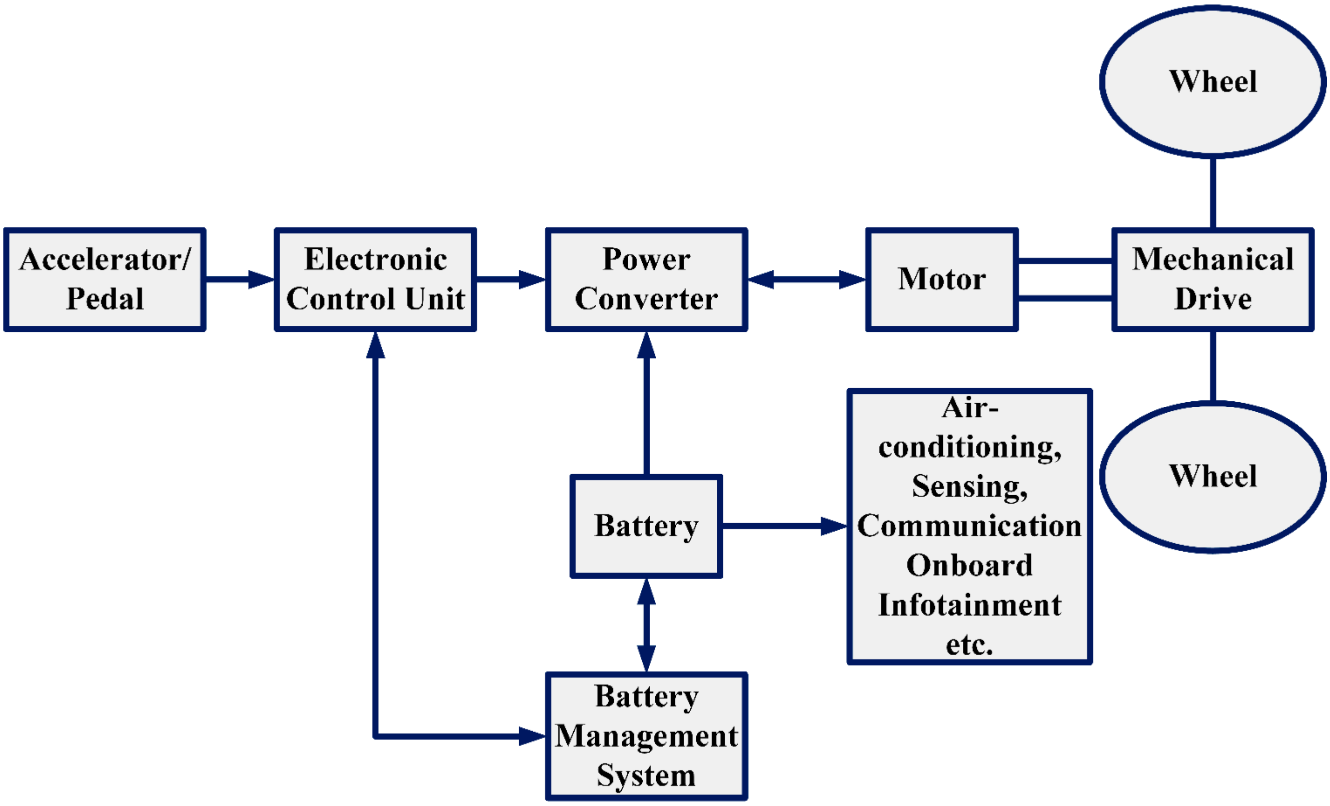

Figure 5. BMS operation inside Electric Vehicle (EV).

3.2. Architecture

Typical BMS architecture for electric transportation applications is master-slave architecture, where there are central control and distributed sub-controllers. Master-slave architecture is a new asymmetric control process and communication hub, where one procedure controls multiple processes. Figure 6 shows the modular BMS architecture's topology and the communication architecture between the cell management unit (CMU) and BMS unit. Each slave board monitors and controls a group of cells. A master control board interfaces with the slave boards via serial interfaces to control the functionality of the system [25].

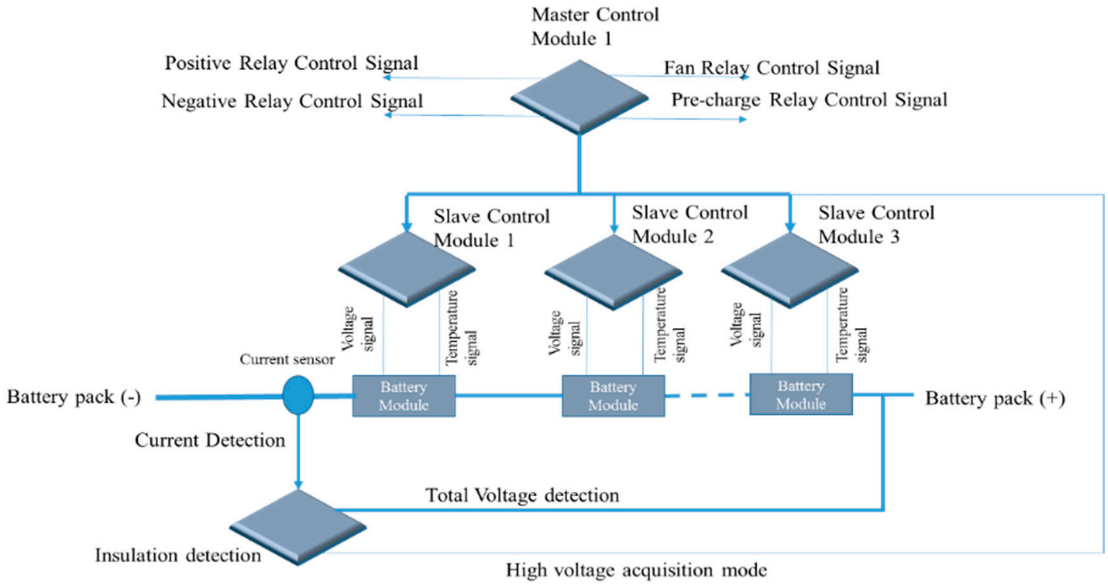

Figure 6. Master-slave architecture of BMS.

3.3. Safety Aspects

BMS safety is one of the most elevated concerns in the battery industry. Several numbers of codes and standards are prepared and followed for different applications to ensure battery safety. However, although batteries are the most convenient form of energy storage, accidents are continuing to happen in battery infrastructure [26]. As a result, all design basis scenarios must be considered to eliminate the risks.

BMS must control battery systems to ensure that it stays within BMS's operational limits via bus communication. BMS should maintain the on/off requirements for the main contactors, voltage, current, and temperature profiles in compliance with the corresponding safety procedure requirements.

Unless otherwise specified in the manufacturing procedure, BMS supports battery systems via BMS controls for technical, operational, and safety criteria. If an external power source provides energy to BMS, this energy must be recorded and included in the safety functions.

The behavior of BMS should be thoroughly tested for overcharge/over-discharge in order to validate the performance with integrated passive circuit protection devices operational. BMS active charge control function is inhibited during this process, and BMS interrupts the overcharge/over-discharge current through an automatic disconnect of the main contactors. In addition, cell overheating with an inhibited battery pack cooling control function should be secured. The objective is to validate the BMS functionality of cell overheating protection with the disconnection of power contactors and the potential start-up of safety battery support systems (e.g., fire extinguisher). Battery simulation system (BSS) or BMS safety function is key to ensuring that any BMS safety function failure (e.g., frozen sensor value) is detected within a controllable period.

To ensure safe integration and operation by end-users, every BMS should have a user manual that explains all the BMS safety constraints. This manual should align with relevant standards and codes (they will be covered in Section 5), provide specifications for every function, identify the hardware, software, or both configuration of the BMS, and address limitations on BMS usage by analyzing assumptions on its behavior or failure rates.

Chemical characteristics are one of the most dominant causes of battery accidents. Hazardous scenarios may include as follows: under SOC, over SOC, charging/discharging profile of the battery over the battery safety C-rate, and over-voltage (cutoff). Temperature is also a key factor in battery safety. Two types of temperatures—electrochemical reaction temperature and battery environment temperature—must be controlled in the battery pack for BMS safety. BMS must ensure control of these two types of battery temperatures within their safety limit [33].

BMS development has stemmed from the emergence of lithium-based batteries, which unlike conventional nickel-based batteries, do not tolerate any overvoltage and may require secondary functions to work safely (e.g., heating). Two relevant functions for a BMS are noteworthy:

i. Overvoltage protection, a safety-related battery protection action.
ii. Accurate cell balancing, a function in the service of energy storage performance optimization.

Table 3 presents the potential hazards related to BMS operation within battery systems.

BMS hazards can be caused by people, the BMS environment, and internal and external equipment. The following hazard analysis divides potential risks into two classes:

i. Chemical, electrical, and environmental hazards resulting from the operation of the BMS.
ii. Hazards resulting from the BMS operating within the battery system.

Table 3. Operational BMS hazards.

Potential Hazards Related to BMS Operation within the Battery System
1. Loss of air conditioning and battery cooling (BSS—battery support system).
2. Loss of battery heating controls (BSS).
3. Loss of battery voltage control function (BMS/EMS).
4. Over-discharge of cells due to a ground fault or control function loss (BMS/EMS).
5. Overcharge due to control function loss, data drift or software error (BMS/EMS).
6. Over-current due to control function loss or shunt calibration error (BMS/EMS).
7. Short-circuit in control and diagnostic cabling on the battery (BMS).
8. Loss of communication between control systems (BMS/EMS).
9. Loss of BMS/BSS functionality.

Once the hazard analysis is performed on BMS, the following two steps should be taken: selecting the hazard type to be mitigated by BMS action and estimating the risks associated with the above-mentioned hazards based on their quantified probability and severity. This stage depends on battery technology, planned mode of battery operation, environment, etc. Therefore, it should be carried out in close collaboration with the battery manufacturer, battery system developer, and future integrator or operator.

The quantitative and semi-quantitative techniques are applied to measure and relate safety integrity levels (SIL) to risks. Risks estimated through preliminary analyses should be compared to evaluate their tolerable rates of occurrence (THR). These rates determine the SIL attribution to corresponding safety functions.

Though people are more concerned about cold-induced battery issues, heat is the most sensitive issue that affects battery performance [34]. Excessive heat evaporates the electrolyte's liquid and reduces the battery performance significantly or permanently damages the battery. Heat speeds up the chemical reaction, while the cold reduces the speed of the chemical reaction. Thus, to get the battery system's optimized performance, it is necessary to ensure a sufficient amount of heat [35]. If the operating voltage is below the rated minimum value or above the rated maximum value, battery performance will be significantly damaged. Batteries may even burn out due to overvoltage. Overcharging is another issue of concern. If a battery is overcharged, the additional current will flow through the battery and decompose the water in the electrolyte. It will cause premature aging of batteries. Similarly, undercharge causes low current flow through batteries, and the chemical remains in the battery plate, causing a significant amount of capacity loss. A short circuit is a common phenomenon for battery damage. If the positive and negative side of a battery is connected via a low resistor or conductor, then a considerable amount of current will flow through the path. It will generate a large amount of heat, which causes battery damage. The loss of communication between the control units also causes failure in BMS since the control units are interconnected among them.

4. BMS for Large-Scale (Stationary) Energy Storage

The large-scale energy systems are mostly installed in power stations, which need storage systems of various sizes for emergencies and back-power supply. Batteries and flywheels are the most common forms of energy storage systems being used for large-scale applications.

4.1. BMS for Energy Storage System at a Substation

Installation energy storage for power substation will achieve load phase balancing, which is essential to maintaining safety. The integration of single-phase renewable energies (e.g., solar power, wind power, etc.) with large loads can cause phase imbalance, causing energy loss and system failure. Accordingly, it is better to take proper precautions to minimize the phase imbalance scenario [34].

The appropriate design criteria for sizing the energy storage systems will boost line voltages and eliminate undesired voltage drop cases. The energy storage system stores energy from surplus energy production and delivers the energy to the load when the main power source is unavailable. Therefore, the combination of an energy storage system and main power supply is sufficient to maintain a constant power demand and will not increase the rating of the main power supply [35,36]. Figure 7 shows the effect of energy storage for controllable power flow.

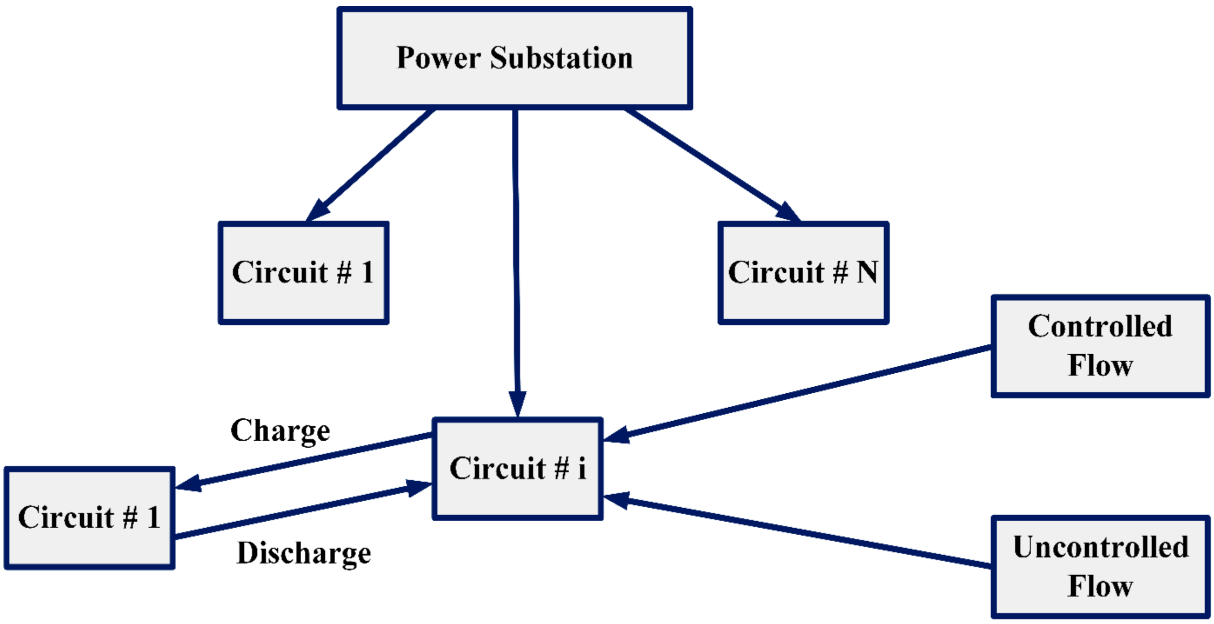

Figure 7. Effect of energy storage for controllable power flow.

4.2. Risk Analysis

The BMS risk analysis includes analyzing hazard scenarios, identifying system protective relay operations, and identifying the mode of connected loads during normal and abnormal operations. This assessment will also satisfy current constraints and capture the effect of those constraints on both repairs and maintenance. The objective is to determine system safety and reliability for normal functionality and emergencies [37].

Fire safety is the most significant safety issue for stationary BMS. Tests for technical batteries are done to reduce fire or explosion occurrences and the risk of injury to people. It is advised to examine user-lithium batteries periodically for admissibility if a cell contains more than 1.0 gm or if a battery contains more than 4.0 gm of metallic lithium. For technician-lithium batteries, the battery should not contain greater than 5.0 gm of metallic lithium [33,38].

Prevention of fire and shock hazards are primary concerns for any BMS operation. Basic principles of protection for safety include large sections of the International Electrotechnical Commission (IEC) Standards. For example, IEC 60364-1:2005 (*Low-voltage electrical installations—Part 1: Fundamental principles, assessment of general characteristics, definitions*) addresses the procedure for design, construction, and verification of electrical equipment installed in different sites (stationary and mobile) and applications.

There are storage systems that include hazardous and flammable battery chemicals. They are used in different industries, including the automotive industry. However, there are currently no legal regulations or requirements to store this type of battery. Certification organizations, fire consultants, and fire brigades have been working with energy storage consultants to find viable solutions. Even so, companies are generally reluctant to speak openly about their experiences with lithium-ion batteries, making it difficult to form an industry consensus [39]. Despite this issue, the rest of the requirements that are generally understood and respected: "safe zone", "operation boundary", and "damage zone" of the battery must be specified by the manufacturers on the specification sheet [40].

The risks related to lithium-ion batteries are as follows: When a lithium-ion cell reaches high temperatures or experiences overcharging, the physical composition of metal oxides is destroyed. This damage is exothermic and results in high energy release and production of oxygen. Consequently, the electrolyte fluid will boil, producing highly flammable gas. If the temperature rises to the flashpoint, thermal runaway takes place (defined below). Extinguishing such fire is difficult because the lithium-ion cells produce oxygen by themselves. When combined with water, lithium produces an aggressive acid that is hazardous to the environment. The dissolving lithium-ion cells produce a mixture of gas, such as carbon monoxide, methane, hydrofluoric acid, hydrogen, nitrogen oxide, oxygen, hydrocarbonates as ethene, ethine, and benzole. Flammable gas is then generated with a potentially explosive effect. After ignition, there is a massive increase in volume. Each cell bursts upon ignition, which ignites the neighboring cell; this is called thermal runaway. The process is like a chain reaction, and it increases in speed. Once all the cells burst, the remaining material burns at high temperatures.

Given the risk associated with lithium-ion batteries, certain precautions should be considered for their storage, as outlined above. For example, it is necessary to allow internal pressure relief using an explosion relief hatch, a mechanism designed to prevent the forced opening of doors. During an explosive chain reaction, the relief hatch will open with significantly lower pressure than that which occurs in forced door openings. After the explosion, the hatch is closed again. It is able to withstand fire for up to 120 min [41].

The battery pack is designed with BMS supplementary installation to ensure its highest safety. Battery designers prefer to apply more 'external measures' to stop battery fire. However, BMS is dedicated to measuring the current, voltage, and temperature of the battery pack; BMS serves no purpose if BMS hazards are caused by other issues. Therefore, both proper BMS functionality and the battery pack's external measures must be checked to eliminate the risk of battery fire [42,43].

Several BMS functions exist, such as safety functions are generally based on applied design to protect the battery pack from human and asset-related hazardous events (e.g., explosion, electric shock, emission of toxic substances, etc.). A safety integrity levels (SIL) process cites and uses IEC 61508 (*Functional safety of electrical, electronic and programmable electronic (E/E/PE) safety-related systems*) for corresponding normative requirements, where safety is defined as the protection of persons and assets. This function can be implemented through sensors, logic, and actuator hardware.

The safety function entails monitoring the battery pack state to measure battery cell and pack voltage, battery cell and pack temperature, and battery pack current flow. It is further used to detect battery system leakage currents.

The measurement of battery voltage and temperature characteristics is transmitted via BMS sensors, which then transfer the information to the BMS processor unit. For high safety achievement with validated SIL that is targeted, the design should be optimized based on BMS parameters, installation, circuits, and others. Similarly, BMS sensors indicate the measurement of current flow for battery packs and transfer the information to the BMS processor unit. Its overcurrent protection function can be handled automatically by electronic components, such as a fuse or circuit breaker. The measurement of battery-electric insulation resistance is based on the intensity of battery leakage currents in applications like vehicle traction. The risks associated with leakage currents may either be tolerable or mitigated by overcurrent protection devices. The safety functions of the BMS feature effectively address the various causes for lithium-ion battery fires. The most common are summarized in Table 4 [2,44].

Another safety function entails estimating the potential need for battery pack (dis)connection to determine the acquisition of battery pack status (at least voltage and temperature), the comparison of these measures with configured critical thresholds, and the elaboration of power contactors control in line with threshold exceeding specifications. This function also ascertains the management of the BMS operating mode and elaborates power contactors control in line with mode management specifications.

The obtainment of master unit control data, which was communicated to BMS, indicates the transfer of power contactor controls from the BMS processor unit to power contactors and actuators and demonstrates power contactors' effective action. It further shows the transfer of battery system configurations from the BMS processor unit to the master unit in the event of a (dis)connection order. To maintain safety, the BMS serves as a monitoring system, signaling the transfer of battery system configurations from the BMS processor unit to the operator when a (dis)connection order occurs.

Table 4. Causes of battery fire as part of BMS safety functions analysis.

1. Faulty electrical and mechanical design
2. Production quality deficiency issues with the cells
3. Flawed or no battery monitoring
4. Defective charging/discharging process
5. Lack of test for battery and BMS
6. Bad cell/pack level testing
7. Cycle life (charge/discharge cycling)
8. Cycle life (simulated drive/usage profiles)
9. HPCC (hybrid pulse power characterization)
10. Overcharge
11. Short circuit
12. Mechanical shock
13. Thermal/humidity cycling
14. Thermal shock
15. Altitude
16. Simulated environment: vibration, temperature, humidity
17. Failure analysis
18. BMS simulation and monitoring
19. Connector/service disconnect cycling and durability

Safety requirements for BMS hardware and software architecture and design are covered with express directives given for BMS hardware components, architecture, and software module design. Information technology hardware (e.g., electrical circuits and electronics), design, and architecture are addressed in IEC 60950-1:2001 (*Information technology equipment—Safety—Part 1: General requirements*) to reduce the following risks:

- Electric shock,
- Energy-related hazards fire,
- Heat-related hazards,
- Mechanical hazards,
- Radiation,
- Chemical hazards.

For the compatibility and safety of communication protocols between BMS internal and external controllers, designers should refer to IEC 61850 (*Interoperability for Advanced Protection and Control Applications*) requirements. Finally, BMS developers should consult the standard IEC/TS 61000-1-2 (*Electromagnetic compatibility (EMC)—Part 1-2: General—Methodology for the achievement of functional safety of electrical and electronic systems including equipment with regard to electromagnetic phenomena*) to learn the safety functions for electromagnetic compatibility. They can be summarized as listed below:

1- Protect the battery pack.
2- Monitor the battery pack state.
3- Measure battery cell and pack voltage.
4- Measure battery cell and pack temperature.
5- Measure battery pack current flow.
6- Detect battery system leakage currents.
7- Determine battery pack critical state.
8- Manage operating modes.
9- Receive information from the master control system (EMS, VMS…).
10- Control the battery pack (dis)connection.
11- Control the (dis)connection of the electric line of charge.
12- Control the (dis)connection of the electric line of discharge.
13- Inform master control system (EMS, VMS…) of battery pack (dis)connection status.
14- Inform operator (HMI) of battery pack (dis)connection status.
15- Optimize battery lifetime and energy availability.
16- Monitor and control battery pack state of charge (SOC) and state of health (SOH).
17- Manage cell balancing.
18- Monitor and control non-safety battery support systems (BSS).
19- Diagnostic—record battery life history log.

4.3. BMS Safety Recommendations

BMS includes battery cells, power electronic equipment, controller and monitoring units, and energy management units. Therefore, any abnormality or accident can cause a BMS-related accident. It is critical to take appropriate precautions as a rule for every BMS component. Indeed, BMS safety is essential for both external and internal equipment of BMS. The external safety procedures, along with technical safety measures, are necessary to ensure complete BMS safety. However, it should be noted that procedural safety measures are more important than technical safety measures.

Today, rechargeable batteries use a combination of energy storage systems, such as the flywheel and supercapacitor. Therefore, BMS safety is essential not only for the stand-alone battery pack but also for combined energy storage systems. By considering all potential factors related to BMS, a comprehensive list of safety actions is recommended below [1,45,46].

4.3.1. Recommendations for BMS Structure

1. A non-flammable and solid barrier should be used between the two electrodes of batteries. The barrier must be made of insulation material, and electrodes should never come into contact with each other, even if an accident occurs. The barrier ensures the internal short circuit of batteries.
2. Since battery is one of the inputs of BMS, flame retardants can be used in the electrolytes of batteries to prevent fire. The flashpoint of retardants must be higher than the electrolytes [42]. However, measures should be taken to prevent battery performance and the electrochemical reactor from being hindered.
3. In a battery, the combustion process includes a series of chemical reactions, which may cause a fire. To prevent this, fuel, oxidizer, and control unit must be chosen in such a way that the battery is not exposed to fire or any abnormality.

4.3.2. Recommendations for BMS Parameters

1. Two well-known safety strategies are available in the lithium battery: current interrupt devices (CID) and positive temperature coefficient (PTC). The PTC protects batteries from an external short circuit. In abnormal cases, the PTC will heat itself, increase its resistance, and block the excess current. The CID prevents current flow in an abnormal condition, which may cause gas generation [1]. It is highly recommended to implement these techniques for ensuring BMS reliability.
2. A new solvent with a higher flash point than the existing solvent is recommended to use in batteries for fire resistance. As battery is a part of the BMS, the development of a new solvent will reduce the probability of a BMS fire.
3. A gas sensor is capable of tracking volatile organic compounds (VOC) from leaked electrolytes. Hence, gas sensors can be a cost-efficient way to enhance the safety of BMS [45,46].

4.3.3. Recommendations for BMS Integration

1. All BMS units must be separated physically so that any abnormal issue within a BMS unit will not spread to other units.
2. There should be more than a minimum number of nominally identical equipment or subsystems in the fault detection, control, and communication unit of the BMS. If one component or subsystem fails, the other can perform as a backup for a random failure; this is called "fail-safe philosophy." The "fail-safe philosophy" includes safety vents, thermal fuses, and shutdown separators. Safety vents reduce the excess pressure inside the battery and prevent the rise of battery temperatures. Fallback protection, in particular, is exceptionally vital. If the primary protection system fails, then the secondary option will retain viability to prevent further problems.
3. The battery cell must not be discharged below the minimum specified SOC.

4.3.4. Recommendations for BMS Installations

4. The equipment rating and marking instruction must be strictly followed. Before the battery is put into operation, the normal case, worse case, and abuse case conditions of the battery must be evaluated.
5. The way BMS control unit interacts with humans should be checked for each unit of the BMS. If any modification or replacement is needed for part of the unit, an extensive investigation must be carried out to evaluate whether the existing unit is compatible with the proposed change.
6. Since the manufacturer and design fault is one of the most dominant causes for BMS failure, third-party verification is recommended to ensure safety.
7. If an accident occurs with a battery bank, it is recommended to remove and replace all of the battery bank and to avoid using a battery that has had contact with fire, no matter how minimal the contact.

8. Different types of batteries containing liquid electrolytes should not be combined for any extended use. If two male ends become connected to each other and they come into contact with flammable material, the impact will cause a fire explosion.
9. Every battery must be charged by a specifically rated charger; otherwise, there is a possibility of overheating, which will damage the battery.
10. It is recommended not to place that battery storage systems in high-temperature environments.
11. Safety reviews should be conducted regularly for each BMS unit and be recorded in safety review reports to assess the changes and required modifications of the BMS unit.

5. Technical Standard Relevant to BMS Development: Standard Landscape

The relevant technical standards for energy storage systems are reviewed to identify the current landscape in the BMS performance analysis and safety assessment. For each identified document, its scope and relevancy to the BMS are explained. Standards are presented and discussed for transportation electrification (Table 5) and stationary (Table 6) applications.

Table 5. Relevant standards/guidelines for transportation electrification.

No.	Standard/Guidelines	Scope and BMS Relevancy
01	ISO 6469-1:2019 Edition 3.0—Electrically propelled road vehicles—Safety specifications—Part 1: On-board rechargeable energy storage system (RESS)	This standard specifies requirements for the on-board rechargeable energy storage system for electrically propelled vehicles such as hybrid-electric vehicles, battery electric vehicles, and fuel cell vehicles. It mainly discusses climatic, electrical, functional, and simulated vehicle accident requirements. It also does not comprise motorcycles or other vehicles which are not designated as electric vehicles such as fork-lift trucks. The document does not consider the safety procedure for manufacturing, maintenance, and repair personnel.
02	ISO 6469-3:2018, Electrically propelled road vehicles—Safety specifications—Part 3: Electrical safety	This standard specifies electrical safety requirements of voltage class B electric circuit of electric propulsion systems and electrically propelled road vehicles. It specifies electrical safety requirements for protection of persons against electric shock and thermal incidents. However, it does not explain the safety measures for maintenance, manufacturing, and repair personnel.
03	ISO/TR 11955:2008, Hybrid-electric road vehicles—Guidelines for charge balance measurement	These guidelines explain the charge balance measurement procedure of hybrid electric vehicles (HEV) with batteries. The document does not consider any test for fully electric vehicles (EV). The “charge balance” term refers to the capacity of the battery.
04	SAE J2289_200807—Electric-Drive Battery Pack System: Functional Guidelines	These guidelines describe the electrical, physical, environmental, safety, and labeling requirements with product description, and shipment characteristics of the battery system for vehicles; these vehicles use a rechargeable battery to recapture the traction energy. They also explain the abnormal condition of the battery system.
05	SAE J2288_200806—Life Cycle Testing of Electric Vehicle Battery Modules	This standard describes a test method to determine the life cycle of EV battery modules. By using a set of nominal or baseline operating conditions, the expected degradation in electrical performance as a function of battery life is determined and possible failure mechanism is identified.
06	SAE J1798—Recommended Practice for Performance Rating of Electric Vehicle Battery Modules	This standard covers general test and verification methods to determine EV battery module performance. It provides the required performance in order to identify basic and minimum performance specification of EV battery modules.

07	UL 583, Standard for Electric-Battery-Powered Industrial Trucks	This standard addresses the requirements for electric-battery-powered industrial trucks, such as fork-lift trucks, tractors, platform-lift trucks, and other industrial application-specific vehicles in accordance with three most important risks: fire, explosion, and electric shock. However, there are also some other risks that are involved in this kind of equipment, such as corrosion, acid spill, and acid splash, are not discussed in the document.
08	ISO 18300:2016(E), Electrically propelled vehicles—Test specifications for lithium-ion battery systems combined with lead-acid battery or capacitor	This standard discusses the combination of lithium-ion battery with lead-acid battery or electric double-layer capacitor. The series combination of rechargeable chemical battery and double layer capacitor is an excellent solution for EV fast-charging station; however, the current and voltage spikes, during energy transfer between battery and electric double-layer capacitor, may reduce the system performance. In addition, the standard only addresses low voltage battery pack (e.g., 12V, 48V); design, test procedures, and safety requirement for high voltage battery are not covered in the document.

Table 6. Relevant standards/guidelines for large scale applications.

No.	Standard/Guidelines	Scope and BMS Relevancy
01	IEEE 1679.1—IEEE Guide for the Characterization and Evaluation of Lithium-Based Batteries in Stationary Applications	This standard provides guidance for an objective evaluation of lithium-based energy storage technologies by a potential user for any stationary application. It is to be used in conjunction with IEEE standard 1679. Section 5.8 (active management requirement) describes BMS as active management for the battery system and defines its function (cell balancing, disconnect devices, thermal fault handling) and provides a BMS block diagram.
02	UL 9540, Outline for Investigation for Safety for Energy Storage Systems and Equipment	This standard covers the energy storage system that only takes electric energy as input, stores the energy in any form (e.g., chemical, mechanical, thermal, electrochemical), and delivers the energy as electrical form. The standard also includes only the standalone mode and parallel mode operation of the energy storage system.
03	UL 2054 Household and Commercial Batteries	This standard only deals with the rechargeable batteries which produce electrical energy from chemical energy by chemical reaction. The standard is not applicable if the battery is used with other product as a combination. Moreover, the standard is not appropriate for the battery having a very high-capacity rating. The standard also does not cover the toxic risk resulting from the battery.
04	UL 1973 Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications	This standard covers the battery system requirement of the stationary application (e.g., PV, wind turbine) and other electric vehicles. The document does not evaluate the performance and reliability of the devices with the battery system.
05	IEC 61508, Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems	This standard addresses the hazards during the failure of system's safety function. The standard discusses the approaches to reduce the potential risks to an acceptable margin. BMS should regard these types of approaches to minimize risks.
06	IEC 61850: Communication networks and systems	In power substations, BMS should consider the standard for communication signal and networks as the monitoring-controlled data can be transferred to/from BMS through communication channels and protocols.
07	IEC 62619—Secondary cells and batteries containing alkaline or other non-acid	This standard specifies requirements and tests for the safe operation of secondary lithium cells and batteries used in industrial applications including stationary applications. It covers stationary application and motive application such as forklift

	electrolytes—Safety requirements for secondary lithium cells and batteries, for use in industrial applications	truck, golf cart, auto guided vehicle, railway and marine, excluding road vehicle. In Section 8.2, the requirements for a BMS are discussed.
08	NAVSEA S9310—Technical Manual for Navy Lithium Battery Safety Program Responsibilities and Procedure	This document describes safety guidelines for the selection, design, testing, evaluation, use, packaging, storage, transportation, and disposal of lithium batteries devices used in navy application. In Section 4.4.4, a definition for BMS and information on the performance, cycle-count, age, and condition of the battery during charging and discharging provided.

5.1. Transportation Electrification

Recently, several numbers of accidents are listed in high-energy batteries of EVs. It is also reported that the accidents are responsible for inadequate fire safety measures in BMS [39]. There are also other factors, which cause risks in EV batteries. This section investigates the scope and relevancy of different available standards/guidelines required to study to develop BMS standards. The standards/guidelines associated with energy storage systems of transportation electrification are listed in Table 5.

5.2. Large Scale (Stationary) Application

There are some specific safety aspects, such as overvoltage protection and cell balancing, mentioned in this report and must be included in all BMS documentation. Table 6 represents the list of reviewed standards for large-scale applications. Furthermore, Table 7 summarizes the main performance and safety tests for stationary applications that discussed in different standards or guidelines presented in Table 6.

Table 7. Performance and safety tests for BMS in stationary application.

Testing Requirements	Standards/Guidelines
Over-charge control of voltage (V)	IEC 62619 UL 1973, UL 9540 NAVSEA S9310
Over-charge control of current (A)	IEC 62619 UL 1973, UL 9540 NAVSEA S9310
Over-discharge	UL 1973, UL 9540 NAVSEA S9310
Overheating Control	IEC 62619
Cell Balancing	IEEE 1679.1
Disconnection	IEEE 1679.1
Cell Operating Range	IEC 62619 UL 1973, UL 9540 IEEE 1679.1
Temperature Range	IEEE 1679.1
Thermal Management	IEEE 1679.1 UL 1973, UL 9540
Heating and Cooling	IEEE 1679.1
Thermal Fault	IEEE 1679.1
Short Circuit	NAVSEA S9310
Functional Safety	IEC 62619 UL 1973, UL 9540

6. Conclusions

The main objective of this report is to hold a comprehensive discussion on BMS and BMS safety for various applications. The article consolidates and analyzes the current standards landscape and recommends, where needed, the technical and safety measures for the new BMS standard.

BMS is one of the basic units in electrical energy storage systems. Since BMS reacts with external and internal events, a safe BMS, on both fronts, is key to operating an electrical system successfully. In this report, the details of BMS for electrical transportation and large-scale (stationary) energy storage applications are discussed. The analysis includes different aspects of BMS for energy storage systems such as testing, components, functionalities, topology, operation, architecture, and safety aspects.

Depending on the application, the BMS can have several different configurations, but the essential operational goal and safety aspect of the BMS remains the same—i.e., to protect the battery and associated system. The report has also considered the recent BMS accident, investigated the causes, and offered feasible solutions. Guidance is provided for building the standard to ensure safe operation.

The current standards related to BMS are also studied to find the gaps within the current standards. The report provides recommendations on BMS safety aspects, battery technology, current market, and regulation needs. Additionally, a framework for building new BMS standards, especially for BMS safety and operational risk, is provided.

The BMS behavior should be fully validated in the test procedure for overcharge/over-discharge to improve the performance with operational and protective capabilities. During this process, the BMS active charge control function is inhibited, and the BMS interrupts the overcharge/over-discharge current through an automatic disconnect of the main contactors.

As well, cell overheating with an inhibited battery pack cooling control function should be secured. The objective is to validate the BMS functionality of cell overheating protection with the disconnection of power contactors and the potential start-up of safety battery support systems (e.g., fire extinguisher). Loss of the battery simulation system (BSS) or BMS safety function is key to ensuring that any BMS safety function failure (e.g., frozen sensor value) is detected within a controllable period and that the outputs of the degraded BMS place the battery system in a safe state.

Compatibility between the various systems and corresponding safety functions must be checked before operation. The BMS and battery should undergo test runs using the test modes implemented in the BMS and communicate with the test bench via common communication buses.

It is recommended that a technical review of the BMS be performed for transportation, electrification, and large-scale (stationary) applications. This report conducted a comprehensive evaluation of the components, architectures, and safety risks applicable to BMS operation. In addition, a review of technical standards relevant to BMS is provided as part of the more significant effort to develop the new standard for BMS. The report affirms support for these standards as outlined. In particular, the operational BMS must comply with the standards of CSA, IEEE, UL, NEC, and IEC to ensure validation and adherence to safety requirements.

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