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Battery Management System

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Abstract

This review of the literature delves into the changes, structure, and the latest BMS (battery management systems) technologies implemented in electric vehicles, smart grids, and energy storage, respectively. The studies emphasize the need for accurate battery modeling, advanced estimation algorithms, robust hardware design, and safety regulations. Artificial intelligence based forecasting methods, distributed and modular BMS architectures, and cloud-connected monitoring platforms are among the recent technological advancements transforming conventional BMSs into intelligent, adaptive systems with predictive analytics and optimized decision-making capabilities. These developments enable improved performance, enhanced fault tolerance, and more efficient energy utilization. Nevertheless, despite significant advancements, researchers still face challenges in accurate battery health prediction, early fault detection, and effective thermal management under varying operating conditions. The research describes how contemporary BMSs perform integration of modeling, monitoring, control, cell balancing, and diagnostics to facilitate safe and energy-efficient use of the battery. Present innovations such as AI-based forecasting, distributed architectures, and cloud-connected monitoring are enabling BMS to become intelligent, adaptive systems. So far, scientists are struggling to solve the questions of battery health prediction, fault detection, and thermal management issues that comprise a great area of potential for new technological solutions.

Keywords: Active balancing, battery management systems, electric vehicles, energy storage systems, lithium-ion batteries, smart grids

INTRODUCTION

Rechargeable batteries, with a particular emphasis on lithium-ion (Li-ion) batteries, are the primary energy carriers of the future. This is because more people want technology that saves power and helps the Earth. These cells now provide power for many things. They help run cars that use only power and cars that use both gas and power. They also help store green power from the sun and the wind. Phones, tablets, and large power kits also utilize these cells. These cells are key power sources for many things all over the world. The question of how their performance can be safely, reliably, and efficiently ensured has been raised as a result of technological advancements and the widespread use of batteries.

The question is how to ensure that the performance of these batteries is safe, reliable, and efficient because of technological advances and the widespread use of batteries [1]. There has been a significant increase in the use of batteries and technological developments, which raises the issue of safety, reliability, and efficiency of their performance. The one who should take this burden is the Battery Management System (BMS), which is an indispensable part of a battery that keeps track

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of, manages, and enhances battery performance.

This review of the literature pulls together the main ideas of researchers and experts in the field, and it is the first step toward understanding fundamental battery modeling, BMS hardware architectures, estimation algorithms, safety issues, EVs, smart grid applications, and evolutionary trends [5]. The review of works from the past to the present includes not only the landmark publications of the early 2000s, but also the most recent and advanced research of 2024. The BMS technology timeline, existing issues, and new opportunities can be seen in this paper.

FOUNDATIONS OF BATTERY MODELING AND EARLY BMS CONCEPTS

Battery modeling is the basis or platform upon which a successful BMS (Battery Management System) design is constructed. One of the first recognitions of this fact came from the outset of research in the field, which acknowledged the absolute necessity of an accurate battery behavior model for the estimation of SOC (state of charge), SOH (state of health), and SOP (state of power) parameters. In their comprehensive work, "*Battery Management Systems: Volume I - Battery Modeling*," Plett (2015) elaborates on various battery modeling methods considering different model levels from empirical to electrochemical, thus underlining the importance of this issue in his research [3, 4].

For example, simple battery models are easier and faster for a computer to solve; hence, they can be employed in real-time estimation, which is a common scenario in BMS operations, as shown in Figure 1. On the other hand, Plett strongly suggests that an electrochemical model, though capable of yielding more precise results, involves an intense computational process, making it impractical for use in a BMS that operates in real time. The phenomenon in which batteries exhibit nonlinear behavior is a favorite topic of Szumanowski and Chang (2008) [5]. Their modeling approach considers not only the temperature changes but also the aging effects as well as the non-linear charge/discharge dynamics.

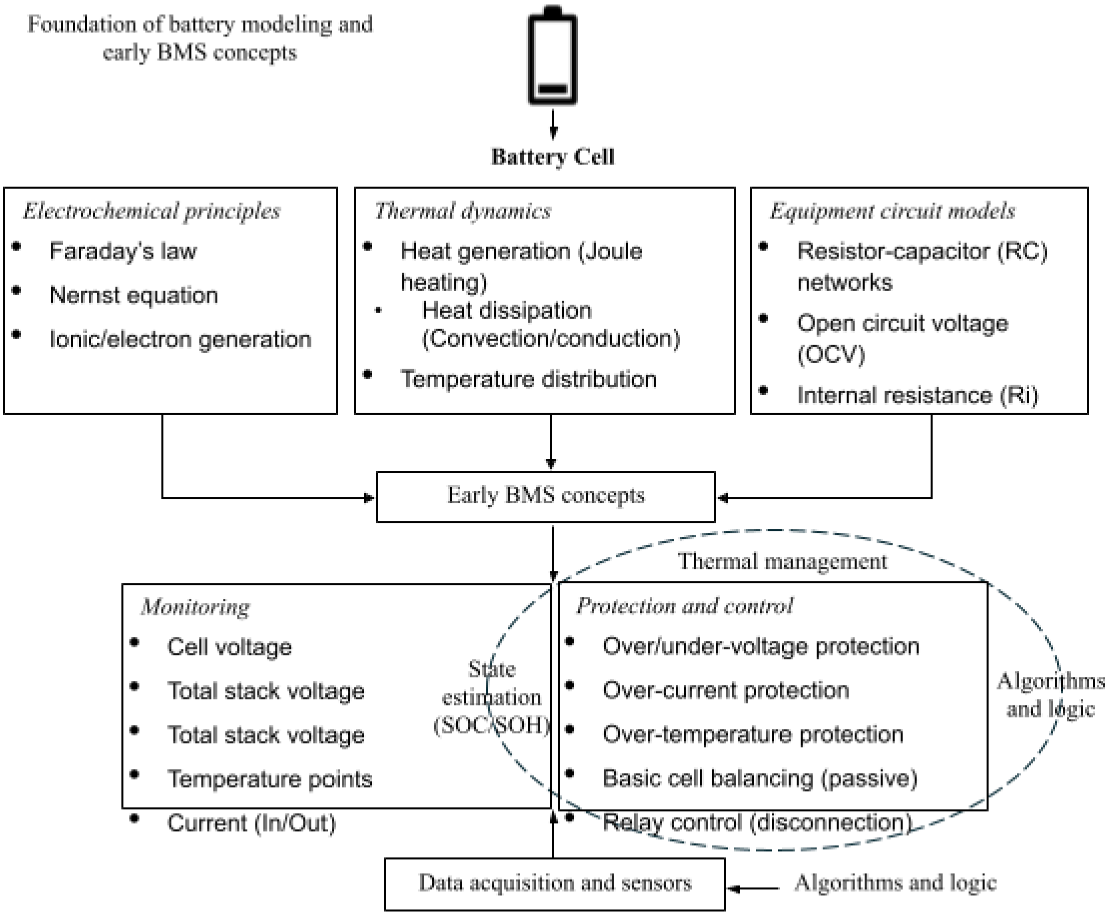


Figure 1. Foundations of battery modeling and early BMS concepts.

The authors pointed out that a dynamic model is the most appropriate one when it comes to dealing with variable load conditions under which SOC can be estimated; hence, the model can be applied to electric vehicles (EVs) as well as in hybrid systems.

As a next step, the methodological framework presented by Chatzakis et al. (2003) represents an important milestone in the evolution of a system that fully supports the integration, monitoring, and protection of BMS in a manager-controlled environment [6].

This can be seen from their work as a paradigm shift away from the conventional simple load controllers towards more sophisticated automated systems with the capability of diagnostics and control.

These seminal papers form a steppingstone that has advanced the field to present-day BMS technologies equipped with estimation algorithms and control strategies.

ADVANCES IN BMS HARDWARE AND SYSTEM ARCHITECTURES

To meet the requirements of an increasing number of battery applications, BMS hardware development has become more complicated and richer in functions. Lelie et al. (2018) provided an influential comprehensive survey of BMS hardware ideas, recognizing basic components, such as sensors, microcontrollers, power management circuits, signal processing units, cell balancing devices, and communication interfaces. The authors pointed out that modularity and scalability are two important design features, particularly in the case of EV battery packs with hundreds of cells.

Most hardware architectures can be categorized into the following types:

Centralized BMS

- One controller is responsible for both monitoring and control.
- Benefits include easy use and a minimal price.

Drawbacks

- Complicated installation and decreased dependability on big packets from Figure 2.
- *Distributed BMS:* Each component or device has its own tracking system. Good points: Work well and are easy to fix. Limitations: High cost and communication are difficult.

Modular/Master–Slave BMS

Combines central and spread characteristics. Has both types blended.

- Mostly, they are used in EVs and large-scale systems.

Distributed architectures will be the next generation because they have better fault tolerance and scalability [2].

The necessity of thermal management, charge control, safety features, and protection circuit integration in BMS hardware. They showed how hardware-related issues can influence reliability, particularly in tough industrial environments [6].

They argued that the complicated chemical-electrophysical nature of the battery is the major cause of significant challenges in monitoring and extending its lifetime. Their concern about the safety of operation is still influential in today's BMS standards [15–17].

Industrial standards include safety certifications, testing, and communication standards such as CAN, LIN, and IEC standards for battery systems. Their paper described the trend towards tighter regulations in safety, interoperability, and cybersecurity as aspects of BMS design [7, 8].

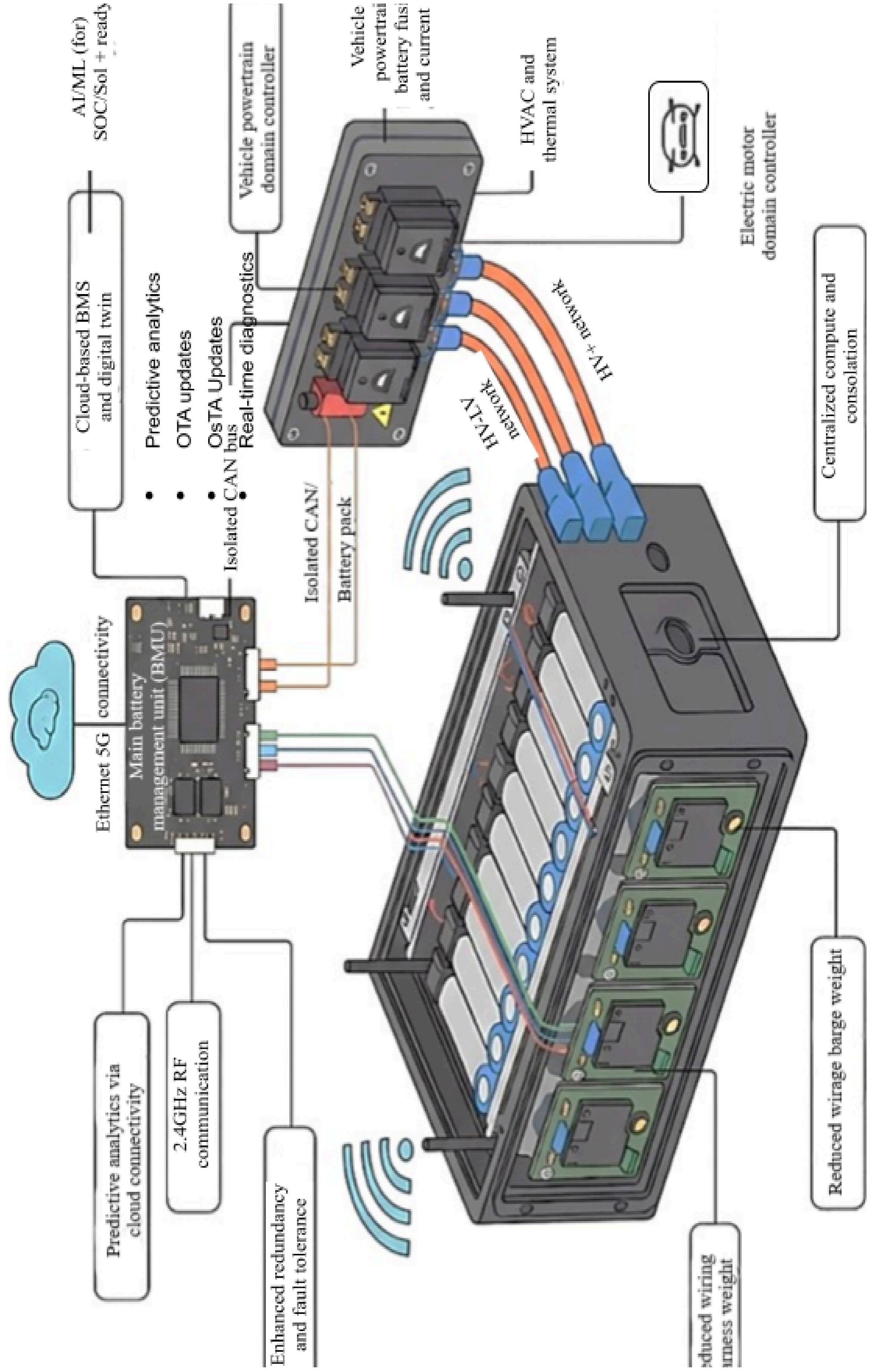


Figure 2. Advance BMS hardware and system architecture.

BMS Estimation Algorithms and Control Strategies

Accurate battery parameter estimation is the main feature of a BMS that facilitates optimal usage and keeps the system in safe conditions, as shown in Figure 3. In their work, they extensively surveyed a whole range of modern estimation algorithms, which mainly consist of the following:

- *Kalman filters (KF), Extended Kalman filters (EKF), and Unscented Kalman filters (UKF):* The main idea behind EKF and UKF, which are now the standard tools for SOC and SOH estimation, is that they can treat the nonlinearities inherent to battery systems in a proper manner [9].
- *Sliding mode observers (SMO)* methods mentioned are capacitated to sustain their correctness when there is a variation in load or the tested object is an old one.
- *Model predictive control (MPC)* helps plan in real time. It keeps charge right, keeps heat in check, and ensures that all are good.
- *Artificial intelligence (AI) and machine learning (ML)* are being gradually applied in the battery field for aging prediction and fault diagnosis.

BMS in the present day and suggested solutions, such as the use of advanced thermal models, the introduction of predictive fault management, and the improvement of estimation algorithms for real-time applications [4]. Their work also pointed out the following problems.

- Fast transient loads in EVs
- Nonlinear aging patterns
- The interrelationship between SOC, SOH, and temperature
- Difficulties in the prediction of rare failures

Through their studies, the authors pointed out that a single method of estimation cannot be ideal in every case; rather, they advocated the use of hybrid methods that combine physics-based models with data-driven techniques as a viable future prospect.

BMS frameworks that can have multiple applications. Their comprehensive review depicts the BMS algorithms employed in EVs, energy storage systems (ESS), drones, and consumer electronics [1]. They observed that grid-scale systems require long-term cycling stability and very accurate aging prediction, whereas EVs require fast-response algorithms and efficient fault detection in the case of rapidly changing loads.

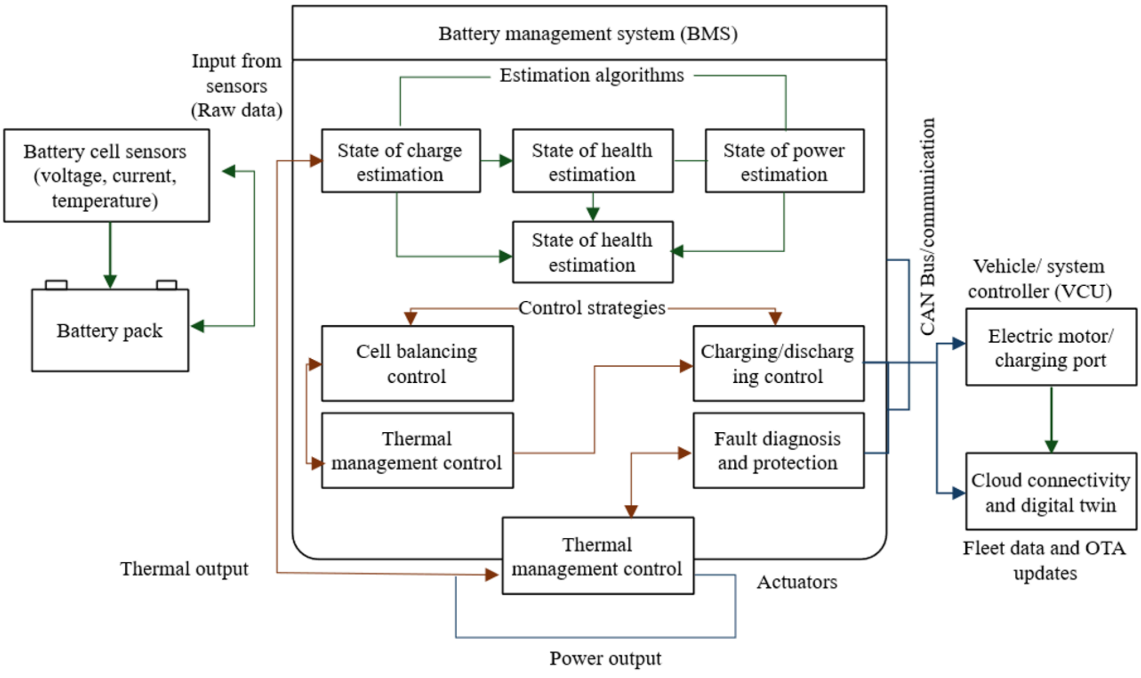


Figure 3. BMS estimation algorithms and control strategies.

BMS algorithms by referring to the use of BMS in vehicles; thus, they focused on timely execution and fault-tolerant architectures as a must [11]. Their research shows that the primary and most important objective in a large battery pack situation is the detection of faults occurring at an early stage to avoid the rapid succession of failures.

Among the works in this area, the publication of Chaturvedi et al. is still the most referenced because it goes beyond the mere connection between modeling and algorithms and covers the implementation as well as the real-time aspects, thus providing an essential framework for contemporary intelligent BMS systems [18].

Cell Balancing Methods and Safety Considerations

One of the major tasks of a BMS is cell balancing, which maintains the same level of charge in cells. Differences in cell capacity or resistance may cause

- Premature degradation
- Reduced usable capacity
- An increase in safety risks

The methods of balancing are of following two categories:

Passive Balancing

- The extra power comes out as heat.
- Easy and cheap.
- Usually found in lower-cost applications.

Active Balancing

- Energy is shared between the cells with the help of converters or capacitors.
- Higher by far in efficiency but complex and expensive.
- Indispensable in EVs and large battery packs.

In the future, there is a need for more efficient active balancing methods, mainly for high-capacity EV batteries [3]. It has been pointed out that situations such as thermal runaway, internal short circuits, and overcharging can lead to disasters [15, 16]. Therefore, the modern BMS from Figure 4 must combine the following:

- Thermal monitoring
- Cell voltage and current protection
- Fault detection algorithms
- Emergency disconnection switches

These capabilities allow compliance with the present safety standards, such as ISO 26262, for automotive functional safety.

BMS in Electric and Hybrid Vehicles

Electric vehicles (EVs) represent some of the most challenging scenarios for a BMS in terms of power demand and dynamic load profiles. In their paper, they illustrated the intricacies of BMS hardware and software in the battery systems of EVs and HEVs [10]. Such systems should be composed of the following:

- Very precise SOC and SOH determination
- Quick adaptation of the system to the changes in loading
- Energy-saving device for managing the heat
- Cell balancing that is resilient and stable

- Comprising help units in car communication

In addition, they outlined a standard EV module, which is composed of hundreds of cells that are connected both in series and in parallel, and thus demands extreme resilience and duplication.

The differences between the grid and EV BMS state that an electric vehicle battery management system is required [13].

- Be able to cope with very short and highly intensive battery charging and discharging operations.
- Handle energy usage under ever-changing drive conditions.
- Make sure the safety of device operation under vibration and variations in temperature.
- Improve charging speed with new technologies.

Moreover, when more people decide to buy an EV, the BMS will have to enable the V2G and V2H activities, which means that besides power control, communication will also be needed, which will be a way of two-way trading.

The BMS diagnostic system and its work presented methods for recognizing sensor failures, cell faults, and aging-related issues [11]. Their contributions are fundamental to the evolution of fault-tolerant EV BMS architectures.

Their main argument, which reached a consensus with other research, is that any BMS targeting electric vehicles should marry high-performance estimations, solid and dependable hardware, and forecasting techniques to be able to always function optimally and guarantee safety.

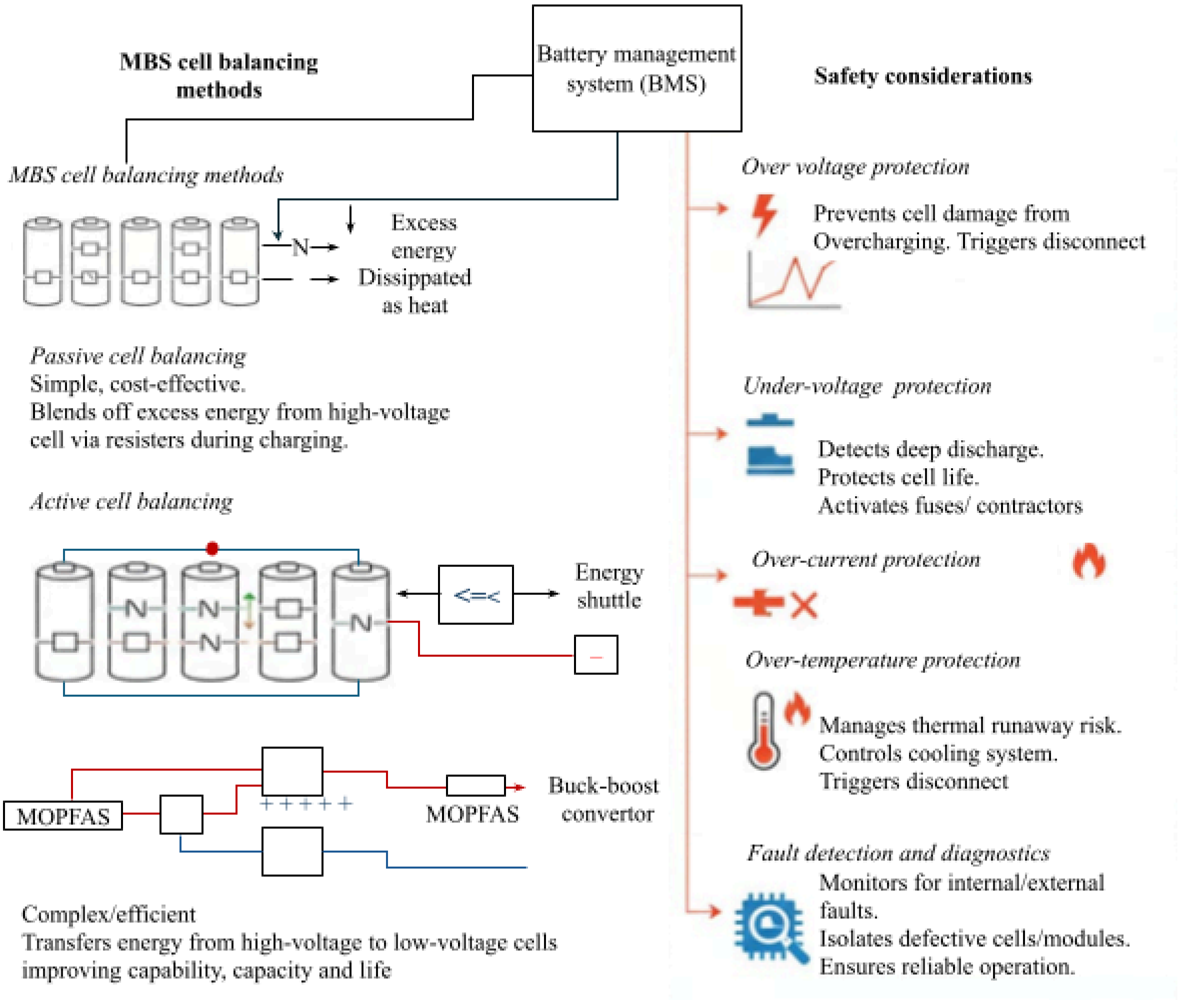


Figure 4. Balancing methods and safety considerations.

BMS IN SMART GRIDS AND GRID-SCALE ENERGY STORAGE

A BMS is a key enabler not only in electrically powered vehicles but also in the development of smart grids and decentralized energy systems based on renewable sources. Evidence of the increasing penetration of solar and wind power is the continued growth of grid-scale energy storage systems (BESS) from Figure 5, which has the main objective of ensuring stability, providing compensation for fluctuations, and managing peak demand [17, 19].

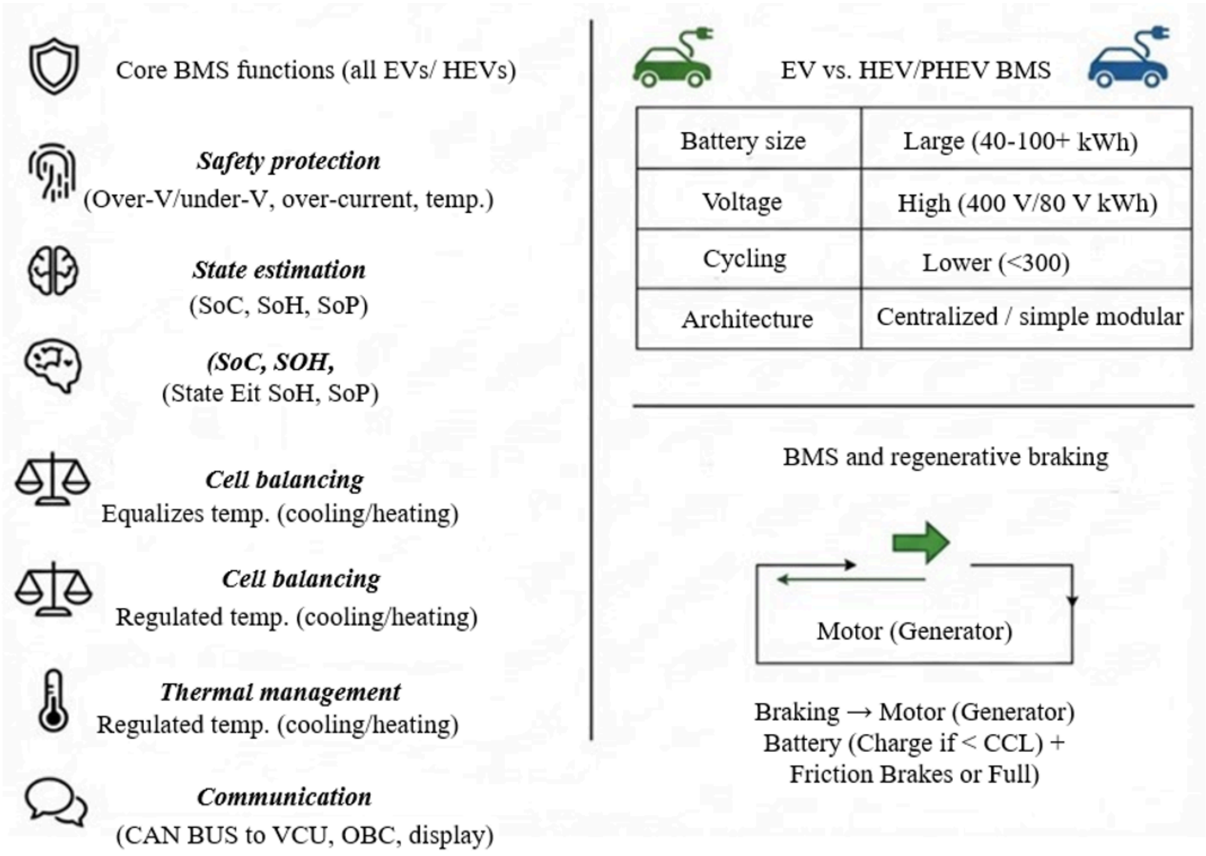
The role of battery management systems (BMS) in large-scale energy storage (BESS) and their outlined essential features [14].

Long-term Cycling Stability

Accurate SOH and capacity fading predictions. Thermal management of large battery arrays. Control strategies for peak shaving and load shifting. Integration with grid communication protocols. The significance of incorporating a local management system (LMS) into the ICT-based energy supply network framework (smart grid) [13]. To provide distributed energy storage, they underlined the necessity of high-level interoperability and remote monitoring.

A recent review of advanced BMS for energy storage systems identified emerging trends, such as [12] *AI-driven predictive diagnostics,* cyber security for BMS communication networks, cloud-based monitoring and remote diagnostics, and set rules to help large and green powers work well.

One big issue for big BMS is to guess how slow it will get worse. These run all the time. Air and heat were not the same on each day. Therefore, it is difficult to determine how long it will last. Knowledge of the health of a cell is crucial. We must study it a lot.



Battery size	Large (40-100+ kWh)
Voltage	High (400 V/80 V kWh)
Cycling	Lower (<300)
Architecture	Centralized / simple modular

Figure 5. BMS in electric and hybrid vehicles.

Industry Standards and Regulatory Requirements

Rules for Work and Law Needs

The new BMS must do well and maintain safety. These rules have grown annually. Currently, there are more rules. They observe how the BMS acts and stays safe, as shown in Figure 6. Identify the main industrial standards that regulate BMS design, which include:

- UL 1973 for stationary battery systems
- UL 2580 for EV batteries
- ISO 26262 for safe work
- IEC 62619 for big Li-ion cells
- IEC 61508 for electrical and electronic safety
- SAE J2464/J2929 for EV battery safety testing

These standards cover situations like:

- Overcharge/over-discharge protection
- Thermal runaway resistance
- Short-circuit protection
- Crash safety for EV batteries

The rising intricacy of the standards is indicative of the worldwide concern that is manifesting regarding the safety of batteries and, consequently, of the need for harmonized regulations to be put in place for different sectors [7].

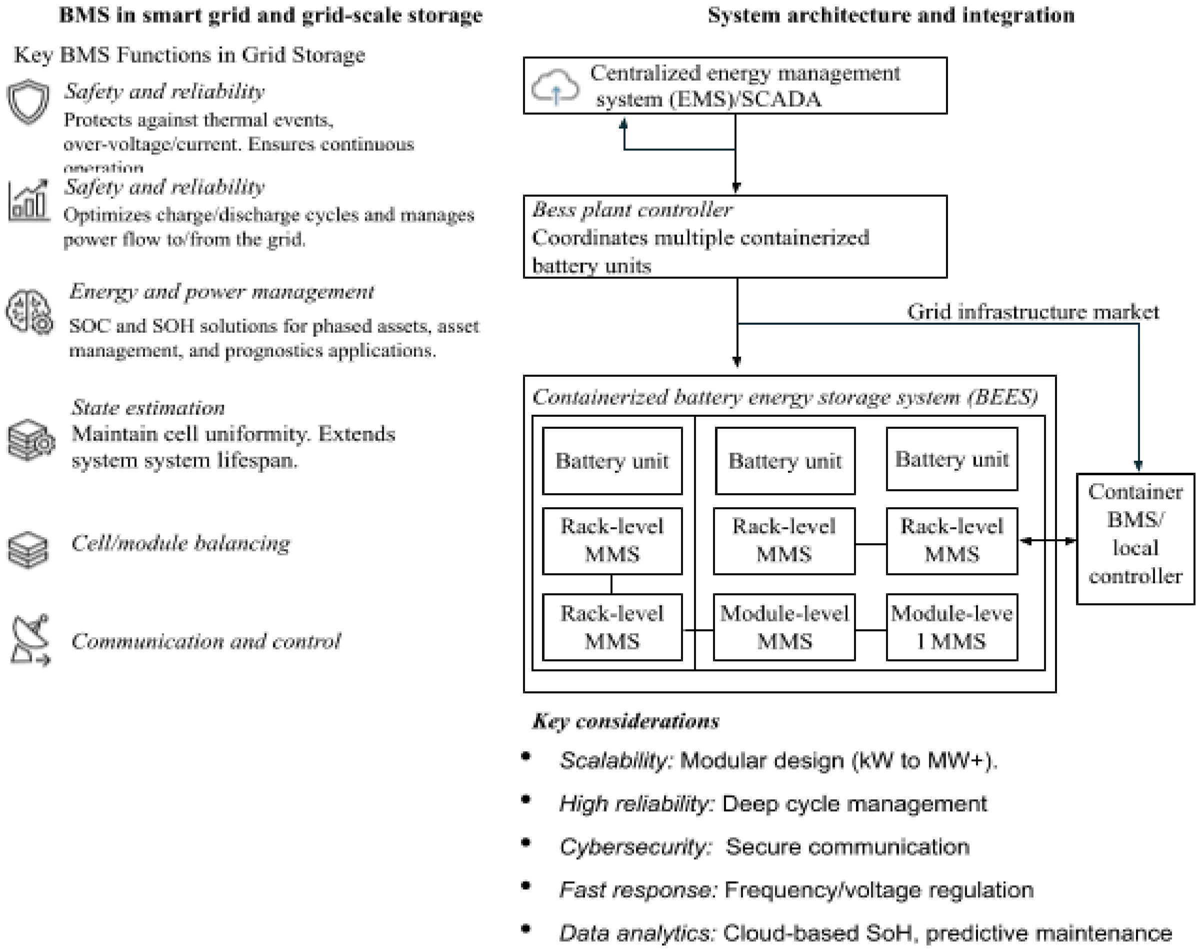


Figure 6. BMS in smart grids and grid-scale energy storage.

EMERGING TRENDS IN BMS RESEARCH

Battery management research is continuously evolving and improving. Recent publications have shown several different things [20].

AI and Machine Learning Integration

AI is increasingly being used for predicting SOH and aging, fault classification, and Remaining Useful Life (RUL) estimation [21].

Nyamathulla and Dhanamjayulu (2024) declared that AI-integrated BMS will be the trend of the Energy Storage Systems (ESS) and Electric Vehicle (EV) markets in the future [12].

Cloud-Connected and IoT-Based BMS

Innovative BMS systems include over-the-air updates, remote diagnostics, big data analytics, and cloud-based digital twins. These functionalities enable the implementation of prime maintenance and more accurate lifespan forecasting [22–31].

Solid-State Batteries and New Chemistries

Innovations in battery chemistry (solid-state, lithium–sulfur, lithium–air) call for new BMS strategies that can handle different properties.

Cyber-Physical Security

As BMS integrates more features, they become potential entry points for hackers. To address these issues, new frameworks revolve around strategies for encryption, secure communication, and intrusion detection.

High-Efficiency Active Balancing

Studies are gradually moving towards high-efficiency converter-based balancing for large EV packs with negligible thermal loss.

Ultra-Fast Charging

Fast EV charging (≤10 min per cycle) requires predictive thermal and SOC estimators to prevent damage. These emerging areas demonstrate that the BMS is transitioning from a monitoring system to an intelligent, predictive, and interconnected control platform.

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