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Advances in Battery Management Systems for Electric Vehicles: A Review of Circuitry, Smart Algorithms, and Next-Generation Technologies

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ABSTRACT

The rapid growth of the electric vehicle (EV) market has placed the lithium-ion battery pack at the center of automotive innovation. However, the inherent vulnerability of lithium-ion chemistry to overcharge, deep discharge, and thermal extremes necessitates a sophisticated Battery Management System (BMS). This paper provides a comprehensive review of the BMS, analyzing both its hardware circuitry configurations and the software algorithms that govern its operation. The study synthesizes recent literature to evaluate key BMS functions: parameter monitoring (voltage, current, temperature, strain), cell protection, passive and active balancing methods, state estimation (SoC, SoH, RUL, SoF, EIS), charging/discharging management, and communication protocols. A comparative analysis of the advantages, disadvantages, and implementation costs of various techniques is presented. Finally, the paper explores prospective research avenues, including the integration of artificial intelligence, big data analytics, wireless BMS architectures, fiber-optic sensing, and online impedance spectroscopy, concluding that the future of BMS lies in adaptive, intelligent, and wirelessly connected systems.

1. INTRODUCTION

Electrochemical energy storage technologies based on battery cells have been in use since the mid-19th century. Over the past century, accumulator battery technologies have undergone continuous advancements, leading to the development of new cell types and significant improvements in energy density, lifespan, and operational reliability. A key advantage of electrochemical batteries is their scalability, as multiple cells can be combined to form battery packs with desired capacity, voltage, and power characteristics. Today, battery manufacturing represents one of the fastest-growing sectors in the energy industry. Among various technologies, lithium-ion (Li-ion) batteries have emerged as the most widely used type due to their superior energy density and higher cell voltage, making them highly suitable for applications such as renewable energy systems, backup power supplies, and portable electronic devices Energy storage system technologies based on electrochemical battery cells have been used since the mid-19th century. Accumulator battery technologies have been consistently improved over the last 100 years; new types of cells have appeared, and energy density, service life, and working reliability have been enhanced. An important advantage of electrochemical accumulator batteries is the simplicity of scaling, i.e., the possibility to integrate a certain number of battery cells into a battery pack with the required parameters (capacity, power, voltage). Currently, battery manufacturing is one of the fastest-developing sectors of the energy industry. Lithium-ion (Li-ion) battery cells are the most common type of battery cell [1]. Compared to other battery cell types, Li-ion battery cells offer high energy density and cell voltage, which make them the most attractive choice for different technological systems [2], such as renewable energy source systems, standby power sources, and portable devices.

Li-ion battery technology is an important concept for the development of electric vehicles (EVs) [3]. Hybrid and EV battery packs are composed of series and parallel configurations of lithium-ion cells.

However, lithium technology is vulnerable and highly susceptible to catastrophic failures [4]. There are a variety of inherent and extrinsic problems with batteries that concern safe working conditions, temperature maintenance, and correct charging and discharging [5]. Thus, in order to efficiently and safely operate energy storage systems based on battery packs, it is necessary to carefully manage their charge and discharge processes. A battery management system (BMS) is a crucial component in battery management.

The BMS plays a pivotal role in regulating and controlling the charging and discharging of the battery pack to ensure safe and optimum operation [6]. The main components of the BMS are sensors, actuators, and controllers (Figure 1).

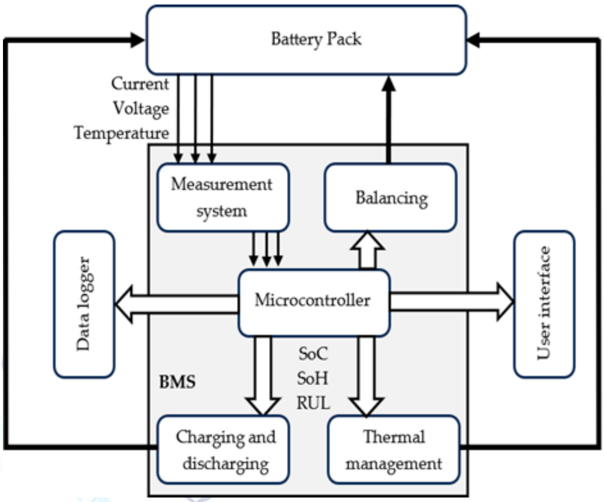

Figure 1. General flowchart of the BMS.

The BMS performs the following key functions [7,8]:

1. Battery cell parameter monitoring—the BMS mainly focuses on monitoring voltage, current, and temperature.
2. Battery cell protection—the BMS must ensure protection against battery system haz-ards (charge and discharge control; overcurrent).
3. Cell balancing—the BMS must use a passive or active equalization method, minimiz-ing the irregularity of cells.
4. State estimation (SoC, SoH) and fault diagnosis (insulation)— the BMS estimates and predicts the state of charge (SoC) and the state of health (SoH); the BMS is also responsible for detecting faults, such as fires, thermal runaways, and explosions, and for minimizing the consequences of fault effects.
5. Charging and discharging management—to ensure a long service life for the battery pack, the BMS must sustain the corresponding SoC and provide the most efficient method for charging and discharging procedures.
1. Communication and data logging—the BMS must govern and filer battery pack data, as well as accumulate crucial information.

Generally, direct measurements of battery cell voltage, current, and temperature are used in the BMS. The data obtained are necessary for the operation of all BMS functions (Figure 2).

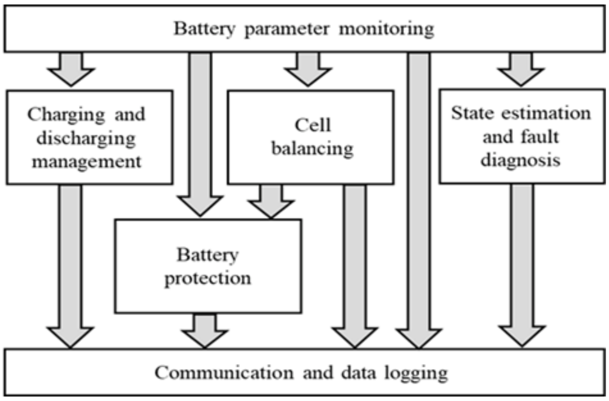

Figure 2. BMS key functions.

BMS techniques are being constantly improved. Their peculiarity is that, on the one hand, technology development for each BMS function can be considered a separate avenue. However, BMS functions are interconnected both on software and hardware levels. Thus, in order to obtain the required result and boost BMS operating efficiency, BMS techniques' improvement should be integrated and should combine achievements in different areas. With this in mind, a crucial task for BMS developers is the choice of proper algorithms and circuitry, BMS characteristics, and functional capabilities, considering the existing range of implementation variations for each BMS function and modern trends in development. Proper architecture, functional blocks, and advanced circuitry can extend battery life.

Many BMS review papers are available in the research literature, considering various construction techniques for management systems (Table 1).

Paper [8] provides a comprehensive overview of BMS technologies, such as monitoring, state estimation, charging and discharging control, temperature control, fault analysis, data acquisition and protection schemes, to improve the performance of batteries for EV applications. However, this review was performed in 2019. A description of diagnostic functions and charging algorithms is presented in paper [4]. A description of aspects of BMSs, covering testing, functionalities, topology, operation, architecture, and safety, is given in [9]. Paper [3] gives a review on strategies like battery modeling, state estimation and prediction. Paper [10] is devoted to the description of battery parameter monitoring, cell balancing and state estimation functions. Paper [6] provides an overview of cell balancing technologies, state-of-charge detection and the use of IoT for BMSs. Many of a BMS's functions are discussed in paper [11]. However, this review does not cover data logging methods and artificial intelligence technologies. In paper [12], the main focus is on state estimation and fault diagnosis technologies. Paper [13] discusses battery protection and diagnostic functions.

Table 1. Previous works related to BMS technologies.

Reference	Year	Description
Vaideeswaran et al. [8]	2019	Overview of the main BMS functions
Darwish et al. [4]	2021	Overview of diagnostic functions and charging algorithms
Gabbar et al. [9]	2021	Analysis of BMS structures used in EV and stationary energy storage
Mishra et al. [3]	2021	Overview of the BMS functions; lithium-ion battery modeling analysis
Spoorthi et al. [10]	2022	Overview of BMS balancing and diagnostic functions
Long et al. [6]	2023	Overview of BMS technological improvement directions
Devi et al. [11]	2023	Overview of BMS functions
Bhat et al. [12]	2024	BMS modeling
Vijaychandra et al. [13]	2024	Methods to improve battery safety

This paper provides a comprehensive review of the BMS literature in recent years. The purpose of the paper is to provide a comprehensive understanding of the development of both hardware and software components of BMSs. The main focus is on the BMS functions shown in Figure 2. The paper presents approaches to the implementation of BMS hardware, in particular for measurement, protection, and balancing systems. The already applied and promising algorithms that are used in the functions under consideration are analyzed. In addition, the paper provides a brief discussion of the limitations and problematic aspects, as well as promising research directions, related to artificial intelligence technologies. The reader is introduced to battery cell parameter monitoring and battery cell protection in Sections 2 and 3, respectively. communication and data logging (Section 4) are explained and analyzed. Finally, Section 5 discusses some aspects of future work on next-generation BMS technologies.

The paper can be a useful resource for researchers who are interested in the application of EV battery management systems and related topics.

2. BATTERY CELL PARAMETER MONITORING

Devices for measuring battery cell parameters can be divided into two groups: mea-surers of electrical and non-electrical parameters. Measuring only one parameter type is not enough to precisely estimate a battery cell's state.

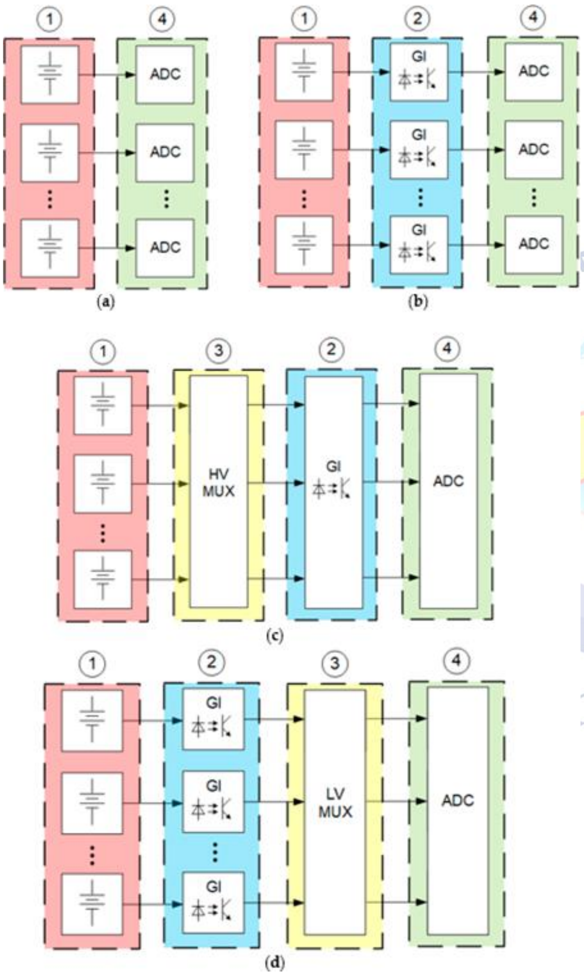

Figure 3. Measuring circuit architecture options to measure the battery cell voltage: (a) direct voltage measurement; (b) voltage measurement employing galvanic decoupling; (c) voltage measurement employing galvanic decoupling and a high-voltage multiplexor; (d) voltage measurement employ-ing galvanic decoupling and a low-voltage multiplexor; 1—battery pack; 2—galvanic decoupling; 3—multiplexer; 4—analog–digital converter

The basic minimal sensor set within a BMS to measure cell parameters comprises three sensor types: a temperature sensor, voltage sensor, and current sensor. This set of sensors is used in most series-produced BMSs. Here, only one current sensor is usually used for the battery pack. Individual voltage sensors are used for each battery cell, while the number of temperature sensors compared to voltage sensors is 4-6 times lower (1 temperature sensor per 4-6 battery cells).

Measuring non-electrical parameters (except temperature) is a prospective area for the development of monitoring battery cell state. However, the methods of measuring non-electrical parameters can be realized only within the framework of laboratory investigations.

2.1 Voltage Measurement

In order to ensure safe and efficient EV operation, it is necessary to monitor the voltage of each battery cell in the battery pack. Data of measured battery cell voltage values is necessary for most protection and diagnostics algorithms' operation.

Figure 3 shows the assessment method of circuit architecture options to measure the battery cell voltage. The simplest way to measure voltage is measuring with bias voltage circuits based on voltage dividers followed by digitalization (Figure 3a). Despite the low battery cell voltage (less than 5 V), this method is used exclusively for low-voltage battery packs due to the absence of galvanic decoupling. In addition, the measurement accuracy deteriorates when using bias voltage circuits [14].

When operating high-voltage battery pack, galvanic decoupling between the BMS and the battery cells is a necessary condition. In this case, optical or electromagnetic converters can be used, allowing one to eliminate galvanic coupling between the high- and low-voltage sides (Figure 3b) [15]. Employing an individual galvanic decoupling microcircuit and an individual analog–digital converter (ADC) allows one to obtain a high measurement rate. There are several drawbacks here, such as increased energy consumption for the measuring circuits, a large number of electronic components, and, consequently, greater sizes of printed circuit assemblies.

In order to reduce the energy consumption, number of components, and printed circuit assembly dimensions, multiplexers are used, allowing one to carry out consecutive measurements of battery cell voltage. The basic method of integrating a multiplexer into a voltage measurement system involves mounting it on the low-voltage side (Figure 3d). In this case, the number of ADC discrete microcircuits decreases. However, the number of galvanic-decoupling microcircuits remains the same.

Currently, a great number of ADCs with integrated multiplexers are produced in-series, allowing a decrease in the size of printed circuit assemblies. Examples of such microcircuits include the following:

- MCP3008, which enables one to measure the voltage of eight battery cells;
- LTC6802, which is a fully featured device for monitoring battery cell parame-ters [16,17].

Alongside that, despite the advantages of these devices, the necessity to connect digital isolators remains unsolved.

In order to eliminate the need for individual galvanic decoupling circuits, high-voltage multiplexers are used (Figure 3c) [18]. These measuring circuits' architecture allows one to minimize the number of microcircuits. The main issue of using high-voltage multiplexers is their reliability in long-term operation.

As far as voltage measurement is concerned, the considerable progress seen in battery cell construction is noteworthy. The employment of standard electrodes to allow for measuring voltage on cathode and anode circuits independently could be seen as an example of this [19].

2.2 Current Measurement

Current measurement is necessary to estimate battery pack service life, as well as to ensure protection from overcurrent's and overload. Real-time current value monitoring allows one to determine the accumulated energy volume for further SoC estimation. Data from current sensors gives an insight into the energy consumed by the battery pack, helping to determine the EV's remaining usable lifespan. In addition, real-time-measured current values can be used by safety systems for system malfunction notifications [20].

Currently, the following types of current sensors can be singled out as those typically used in battery packs: current shunt sensors; Hall effect sensors; magnetoresistive sensors (XMR); and fiber-optic sensors (fiber Bragg grating (FBG)).

According to structural design, the simplest method of current measurement is the shunt resistance one. The main advantages of current-measuring shunts are their low cost and wide range of operational temperatures. However, this type of sensor is characterized by high electric losses and poor measurement accuracy.

Hall effect sensors have the following advantages: galvanic decoupling, low energy consumption, and the wide range of the current measured [21,22]. Alongside this, this sensor type has a number of serious drawbacks: high cost, necessity for temperature compensation, and sensitivity to external magnetic fields.

Magneto resistive sensors, including anisotropic magnetoresistance (AMR), giant mag-netoresistance (GMR), and tunnel magnetoresistance (TMR), are characterized by high mea-suring accuracy [23]. Current meters based on XMR are a prospective area for development. However, their application is limited by the problem of nonlinearity in measurements [24]. Fiber-optic sensors are another prospective avenue for developing current sensors [25]. Such sensors are practically insensitive to temperature changes and environmental im-pacts [26]. However, the complexity of their construction is a serious drawback limiting their wide application.

2.3 Temperature Measurement

Measuring battery cells' temperature is an essential BMS function that is responsible for the battery pack's safe operation. One of the main considerations is the temperature detector location. Bearing in mind that the difference between the inner and outer parts of the battery cell can be considerable, the best option is to locate the detector inside the battery cell [27]. However, due to aggressive media and possible battery cell deformation, such a method of mounting temperature detectors can be difficult.

According to their operating principle, temperature detectors can be divided into resistive temperature detectors (RTDs), thermocouples, or fiber-optic detectors [27]. In-frared imaging devices can be used to study battery pack temperature modes. However, in BMSs, such devices are seldom applicable due to their high cost, large amount of data, and resulting complexity in data processing [28].

A set of sensors can be used to obtain a comprehensive picture of the battery cell's tem-perature distribution. Here, resistive temperature detectors are usually used [29]. Due to their simplicity of construction and sufficient accuracy to facilitate the functional ability of protection algorithms, resistive detectors are used in many temperature measurement sys-tems. However, their considerable nonlinearity narrows the range of effective temperature measurement [30].

Thermocouples are most often used for temperature measurement within wide ranges [31]. However, due to their low measurement accuracy in practice, a thermocouple (with temperature fixation over a wide range) combined with an RTD (with temperature fixation in nominal mode) is used in order to monitor battery cell temperature [32].

Fiber-optic Bragg gratings for precise temperature measurement (with an accuracy in the range of ±0,12 ◦C) are a prospective area for development [33]. Such systems are immune to electromagnetic interference [34]. However, the complexity of their construction is a limiting factor for the wide use of this type of temperature detector.

2.4 Strain Measurement

When battery cells operate in the area of maximum admissible limits, excessive thermal load causes considerable mechanical stress and expansion. Taking this into consideration, the detection of bubbling in a battery cell when performing the complex monitoring of its state appears to be a critical task. In addition, it is possible to circumstantially estimate the battery cell's state of charge on the basis of measuring its geometrical dimensions. Publications from various research teams present methods employing optical and fiber-optic sensors [35,36]; acoustic devices to, inter alia, estimate a battery cell's inner state [37]; and electromechanical sensors [38]. However, most methods are difficult to apply in an EV BMS structure due to their high cost and dependence on external conditions.

A prospective solution could be to use a strain sensor based on carbon nanotubes (CNTs) [39]. This sensor's operation is based on measuring the sensor resistance at its defor-mation. Experiments have shown positive results when measuring battery cell strain [40]. However, the linearity of resistance changes within narrow ranges and CNTs' temperature dependence limit the mass production of this sensor type. For EVs, the main indicators are measurement accuracy, linearity, and the cost of implementation. Table 1 does not contain data on strain sensors due to the complexity of integrating them into EVs.

3. BATTERY CELL PROTECTION

Battery cell protection involves the detection of and response to potentially dangerous operating conditions, such as overvoltage, undervoltage, overcurrent, and overtemperature. In addition, protective equipment can also be implemented at the site of battery cell deformation (for example, for EV accidents).

The differences between battery cell protection systems lie in the algorithms serving as their operating principles. Scientific research is mainly focused on developing and improving protection algorithms.

3.1 Protection from Overcurrent and Short Circuits

Current protection is a necessary component in energy storage systems. Apart from primary current protection, fuses can be additionally used to enhance system safety [7]. The following failure scenarios are possible for EVs: fault inception in the battery circuit; fault inception in the charger circuit; fault inception in the invertor circuit; or fault inception in the load circuit [41]. Detecting the place of failure is an important function of modern current protection systems. Such systems are more difficult to implement, but they are able to protect not only the battery pack but also the electric drive and charging infrastructure's key elements.

A comparator circuit is the simplest example and is used to determine overcurrent and battery pack disconnection [42]. The main disadvantage of such circuits is the high probability of false responses.

Special microcircuits are used in modern BMSs, providing the possibility of multi-level protection [41]. Thus, a microcircuit can have three levels with a fixed delay time for each (for example, two overcurrent levels and one short-circuit current level).

In order to realize time-current protection algorithms, relay protection methods are applied [43]. Battery pack protection systems based on such methods can be realized on the basis of microcontrollers, and alongside the current itself, this allows one to take into consideration other key operating parameters (for example, the temperature of the battery cells and ambient medium).

A promising research avenue is the adaptation of protection principles from the electrical energy system field to energy storage systems [44]. Thus, controlled reactors in protection systems not only allow one to switch off a faulty section but also preserve its operability at the nominal current. However, due to these reactors' large dimensions, such methods are not yet applicable for EVs.

3.2 Overvoltage and Undervoltage Protection

Overvoltage and undervoltage in battery cells have a negative impact on battery pack safety and service life. In most cases, battery cell protection algorithms are based on setting voltage threshold values [45]. Voltage threshold values are well known for common battery cell types. The main problem with such realizing this protection is connected with the error when determining the real voltage values of battery cells, which takes place due to voltage drops in their non-core elements. It is necessary to take into consideration charge/discharge current values in order to determine voltage values more precisely.

Undervoltage protection is aimed at preventing battery cell overdischarge, which can lead to a sharp drop in the battery pack's service life and a loss of its capacity. When the minimum admissible voltage is reached, at least one battery cell of the battery pack needs to be cut off from the load [46]. There are also algorithms that allow one to reconfigure the battery pack at a low voltage in its individual sections [47]. However, such systems are characterized by a large number of semiconductor switches and have not become widespread due to this fact.

Overvoltage protection prevents battery cell overcharge. Thermal runaway may occur at considerable overcharge, leading to hazardous situations (all the way up to battery cell explosion). Practically all battery cell protection means are based on setting voltage cut-off values; when these are exceeded, the charger switches off.

Currently, microcircuits are widely used to provide protection from both undervoltage and overvoltage [48]. Charger protection systems can also be used [49]. Such means of protection are additional to the main battery cell protection realized by a BMS. Protection duplication allows one to avoid emergency situations where one or several BMS protection elements fail.

Varistors can also be used in protection systems [50]. They make it possible to realize overvoltage protection at a comparatively low rate of voltage change (in standard charge mode). However, varistors are inefficient in short-circuit events.

3.3 Temperature Protection

The reasons for battery cell overtemperature can be the following: high ambient temperature, overcharge, thermal management system failure, or EV damage. Battery cells overheating can lead to increased consumption of electrolytes, cathode breakage, or an increase in resistance. These processes lower the battery pack's service life and capacity [51]. Battery cell temperature protection methods can be classified as passive or active. Passive ones comprise current interruption devices (CIDs) and temperature fuses [52]. Passive methods are not the most basic ones for EV battery packs because when they are actuated, maintenance work is necessary to bring the battery pack into operation once again. Active protection methods imply battery temperature regulation, including time peri-ods when the battery pack is not used or only prepared for operation. Battery temperature management systems (BTMSs) are responsible for temperature regulation in BMSs [53]. The methods of temperature regulation applied in a BTMS can be divided into passive (using natural air cooling, heat pipes, or phase transfer materials), active (using ventilators, liquid cooling, or thermoelectric coolers), and hybrid [54]. Passive battery pack cooling methods are cheaper compared to active ones, but they do not provide temperature control or eliminate thermal runaway When designing a cooling system, it is important to take into consideration heat carrier parameters, such as the material's melting temperature, thermal conductivity, mass, and distance between the cells [55]. Machine learning technologies and digital twins can be used to carry out the tasks of battery pack temperature forecasting and subsequent temperature regulation [56].

At low temperatures, battery capacity considerably decreases. Low-temperature pre-liminary heating is used to solve this problem. Preliminary heating methods are classified as external (air or liquid heating and using heat pipes), internal (discharge current heating, excitation current heating, and self-heating batteries), or hybrid [57]. External heating methods are simpler but require detailed designs and special materials to ensure safety. Internal heating methods provide higher efficiency and uniform temperature distribution. However, the implementation of these methods requires a more complex control system. In addition, internal heating methods' long-term impact on the battery pack's life and operational safety has not been researched.

3.4. Cell Balancing

Cell balancing methods are divided into two categories: passive cell balancing and active cell balancing. Each category comprises its own set of methods. Figure 4 shows a general breakdown of cell balancing methods. Both active and passive 3.4 Passive Balancing

The passive balancing principle implies leveling off all battery cells' state of charge via dissipating excessive charge using a passive element [58]. Here, fixed resistor balancing and switched resistor balancing can be singled out. The concept behind fixed resistor balancing is battery cell resistor shunting, where the battery cell is up to 100% charged but the charging of the whole battery pack is not yet completed. In this case, there are continuous currents passing through shunt resistors [59]. This method's advantages are its simplicity and the low cost of its realization [60]. However, it is characterized by energy wastage and a low rate of balancing. Switched resistor balancing involves an additional switch connected to each shunt resistor [59]. If one or several cells are fully charged earlier than others, the switches connected to them will be turned on. Compared to fixed resistor balancing, this method is characterized by a higher efficiency and rate of balancing, though the cost of its realization is also higher. Despite these disadvantages, EV manufacturers apply both passive balancing methods due to their reliability and simplicity to implement.

3.5 Active Balancing

The active balancing principle lies in the redistribution of energy from cells with a higher state of charge to ones with a lower charge state [61]. Active balancing methods can be applied during battery pack charging and discharging. Active balancing methods can be classified according to the active devices used to transfer the energy. Such devices include capacitors, inductors, transformers, and switching converters [62].

Capacitive cell balancing is also known as a charge-stabilizing method, in which capacitors store the charge and return it to the least charged cells [63,64]. The following basic capacitive cell balancing methods can be applied to EV battery packs: basic switched capacitors; single switched capacitors; and double-tiered switched capacitors.

Basic switched capacitors are the simplest method. According to their balancing principle, each cell contains a surge capacitor and the charge can be transferred only through adjacent cells [61]. Single switched capacitors are an enhanced variant of switched capacitors, requiring a single capacitor for balancing. In this method, the charge can be transferred directly from one cell to another through a surge capacitor within one module [65]. Double-tiered switched capacitors are based on double capacitor tiers for shuttling the charge between two cells. This requires n capacitors for a double-tiered capacitor for n cells, and 2n switches [61]. An intelligent control system is required to control the switches.

In inductor cell balancing, excess energy from overcharged cells is stored in the inductor, which is then used to charge the undercharged cells [66]. Three basic inductor balancing methods can be singled out: single-inductor balancing; multi-inductor balancing; and chain structure multi-inductor balancing.

For single-inductor balancing, a single inductor is used to balance the cells by control-ling different switches [67]. The advantage of this method is its relatively high efficiency. However, the method's disadvantage is its management complexity [68]. Multiple induc-tors are used to balance cells in multi-inductor balancing. Each pair of adjacent cells in the battery pack is balanced by an inductor. This allows for balancing multiple couples of cells simultaneously [66]. Compared to the single-inductor balancing method, this one allows one to reduce the balancing time and the number of switches needed. However, one notable drawback is the larger number of inductors required when more cells are connected in series [69]. In chain structure multi-inductor balancing, a capacitor is used in the multi-inductor balancing circuit. The capacitor provides an additional path for the current, which reduces the path distance between the first and last cells [66]. A chain structure cell balancing circuit with coupled-inductor-based modules is detailed in [70].

Transformer balancing methods provide energy transfer from one cell to another via various transformer types. The following transformer balancing types can be distin-guished: single-winding transformer balancing; multiple-winding transformer balancing; and multiple-transformer balancing.

Single-winding transformer (switched transformer) balancing is based on transferring energy from the battery pack to the switching transformer and transferring energy to the weakest cell by means of switches [71]. One transformer with one primary and several secondary windings is used in multiple-winding transformer balancing. The multiple-transformer balancing method utilizes several transformers, where all the primary windings are connected in parallel, and each of the secondary windings is connected to a separate cell via a diode. The primary winding is connected across the pack voltage via a switch, and power is transferred from the pack to the cells by switching to a 50% duty cycle [72]. Unlike the multiple-winding transformer topology, this method allows connecting additional cells without changing the controller.

In contrast to other methods, switching-converter cell balancing can control the flow of power in any way that the BMS commands, allowing more flexibility in managing the cells' SoC [72]. The following basic topologies can be singled out: Cuk converter balancing; buck-boost converter balancing; flyback converter balancing; and full-bridge converter balancing.

The Cuk converter balancing topology is detailed in [73]. A Cuk converter connects two adjacent cells. The cell voltage differences determine the control of the switches so as to control the energy flow between two adjacent cells. A bilateral buck-boost converter is used in buck-boost converter balancing as a bridge for the energy transfer between two adjacent cells [74]. There are several topologies of buck-boost converters which can be used for balancing circuits. One of the topology types is given in [62]. Flyback converter balancing is characterized by a high rate of balancing and is one of most common methods, including when a high-power battery cell is used [75]. Various topology types of this method can be found in the scientific literature: a conventional single-transistor converter [76], two-transistor converter [77], active clamp converter [78], bidirectional converter [79], flyback converter with multiple windings [80], and others. An example of the full-bridge converter balancing topology is given in [58]. Here, a sensing circuit senses the voltage across the battery cell, and a control signal is generated to operate the switch so that energy is transferred from one cell to another to maximize the charge capacity [81].

3.6 Development Trends of Cell Balancing Methods

The development trends of balancing methods imply the development of improved and upgraded modifications of the above methods, aimed at eliminating their deficiencies, as well as developing hybrid methods which combine several methods' advantages.

Modifications of active balancing methods are extensively presented in the scientific literature. For example, a modification of the single-switched capacitor-based balancing method, which uses 2n switches to shorten the balancing time, is detailed in [58]. An improved balancing strategy for an inductor-based balancing circuit, which increases the remaining charge of the battery pack after balancing, reduces losses, and shortens the balancing time compared to the original balancing strategy, is presented in [82].

A number of hybrid methods combining active and passive balancing principles have been suggested. An active- and passive-based hybrid balancing method is proposed in [83]. It combines a conventional switched capacitor circuit with a switched resistor passive balancing circuit. The circuit consists of two parts, namely, a switched capacitor circuit and switched resistor circuit. The research results show that the proposed circuit allows increasing the balancing speed significantly compared to the conventional switched capacitor circuit and passive balancing circuit. A similar hybrid balancing method is shown in [84]. The authors suggested a hybrid balancing technique for Li-ion batteries using capacitor- and converter-based balancing. Capacitor-based balancing is used between two consecutive cells when slow balancing is required, while converter-based balancing is employed for other situations to transfer charge to or from the cell in order to encounter the imbalance as fast as possible. A hybrid balancing method comprising inductor-based and resistor-based balancing techniques is shown in [85]. By leveraging the strengths of both techniques, the proposed method aims to achieve optimal cell balancing while minimizing energy loss and balancing time.

Thus, hybrid methods allow combining the advantages of active and passive balancing principles, thereafter improving the balancing process's efficiency.

4. PROSPECTIVE RESEARCH AVENUES

This section discusses some aspects of future work about next-generation BMSs. Advanced approaches are associated with the implementation of artificial intelligence and big data technologies, which can significantly improve the safety and efficiency of EV battery packs. The use of these technologies provides the following key capabilities: the comprehensive monitoring and analysis of battery parameters; the adjustment of battery charging strategies; high battery reliability under various operating conditions; the identification of potential battery performance issues; and the generation of predictive maintenance recommendations.

The use of artificial intelligence and big data technologies is not yet mandatory. How-ever, continuous technological advances and cost reductions should lead to the widespread use of intelligent BMSs in the future, including the use of digital twins. Some of the main limitations that slow down the implementation of artificial intelligence methods in BMSs are the high requirements for computing resources and large volumes of transmitted in-formation. A promising direction is to use external servers for storing and processing information. Ensuring high data transfer rates is a key task here.

An extensive review of the technologies for using artificial intelligence and big data in BMSs seems relevant for a more complete understanding of the limitations of these methods and ways to overcome them. For EVs, an important issue is ensuring safety in the event of the possible deformation of batteries. Even a small deformation of the battery due to a minor accident or damage to the EV can lead to serious consequences. A promising direction is fiber-optic sensors that record changes in the geometric dimensions of the battery pack. It is possible to perform a comprehensive assessment of the battery pack's condition based on linear dimensions (assessment of the SoC and remaining resources). Fiber-optic sensor systems could be used to obtain information about several battery pack parameters in the future. However, research into the use of fiber-optic sensors is limited to laboratory conditions. It is relevant to study the effectiveness of this method in real EV operating conditions. Another direction for the development of BMS functions that requires study is the use of online impedance spectroscopy technologies. Impedance spectroscopy methods allow us to determine important battery parameters such as internal resistance. In turn, information about the battery's internal resistance allows one to estimate the SoC and SoH with high accuracy. However, the implementation of online impedance spectroscopy methods in EVs is limited by the need for an additional source in the BMS.

5. CONCLUSIONS

The BMS is one of the key elements of an EV battery pack. The safety and durability of battery pack operation depend on the BMS's functional capabilities and efficiency. When choosing the circuitry configurations and algorithms for constructing a BMS with the required functional capabilities and characteristics, it is necessary to determine the optimum combinations of efficiency, degree of technical complexity, overall dimensions, computational resources, and cost.

In this article, we considered the circuitry configurations and algorithms of BMSs when applied to providing such functions as battery cell parameter monitoring, battery cell protection, cell balancing, state estimation and fault diagnosis, and charging and discharging management. A review and comparative analysis were carried out concerning already-applied and prospective solutions of each avenue. The paper forms an idea of both the implementation of BMS hardware and the software implementation of battery pack control algorithms. The results of the review will be interest to developers when solving problems of choosing how to implement the main BMS functions. Based on the key criteria, comparative tables were formed that can be useful when choosing BMS components.

The most promising technologies, the development of which will significantly increase the efficiency and reliability of EV battery packs, were identified. Such technologies primar-ily include artificial intelligence and big data. The implementation of these technologies will stimulate the transition to adaptive battery management and predictive maintenance. At the same time, the use of fiber-optic sensors and impedance spectroscopy technology can also be considered as promising areas for the development of BMSs.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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