



Review

# Review of the Charging Safety and Charging Safety Protection of Electric Vehicles

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**Abstract:** With the continuous development of society and the economy and the popularization of the environmental protection concept, more and more people have begun to turn to electric vehicles. The application of electric vehicles can effectively avoid the damage caused by automobile fuel emissions to the surrounding environment and promote the development and utilization of new energy. However, the development of the electric vehicle industry has led to frequent accidents related to charging safety. In order to prevent accidents related to the charging safety of electric vehicles and ensure proper safety of passengers and people, the charging safety and charging safety protection methods of electric vehicles have become the research priorities for scholars. This paper reviewed the existing research results on the charging safety of electric vehicles, analyzed the influencing factors of the charging safety of electric vehicles, summarized the charging safety protection methods, and forecast the future research direction of charging safety, which has reference value and reference significance for the charging safety research of electric vehicles.



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**Keywords:** electric vehicle; charging pile; charging process; safety protection

## 1. Introduction

In recent years, as the energy crisis and the ecological crisis intensify, people have begun to explore new means of transportation to replace traditional fuel vehicles [1]. The advent of electric vehicles (EV) provides effective solutions for energy conservation and environmental protection, becoming a research hotspot for academics and industrial circles [2,3]. The electric vehicle industry continues to thrive. The simulation results of the “EV30@30 model” released by the International Energy Agency shows that the global number of electric vehicles will rise to 240 million by 2030 [4]. Electric vehicles, the mainstream travel tool in the future, have their inherent and unique charging safety problems, which have aroused many interests and disputes [5,6].

On-board power batteries, the main source of power for electric vehicles, are extremely important to battery life. Compared with other types of on-board power batteries, the lithium-ion battery has the advantages of a long lifecycle, large single-cell energy density, high efficiency and no pollution; therefore, it is used on a large scale [7–9]. The on-board lithium-ion battery can be charged by conduction. The process of the energy supply system supplying energy to electric vehicles through charging piles, cables, charging guns and other components is known as conductive charging, which is the most widely used and energy-efficient charging mode [10]. In the process of conductive charging of electric vehicles, incidents such as elevated charging line temperature, short circuits in batteries or use of electric vehicles before finishing charging often occur. Spontaneous combustion and even explosion during the charging of electric vehicles, reported by news media, websites and newspapers, seriously threaten the personal safety of electric vehicle owners [11]. Frequent electric vehicle charging accidents have affected the sales and promotion of

electric vehicles, and even restricted the development of the electric vehicle industry, and seriously deviated from the sustainable development strategy, a national key strategy [12]. Therefore, the safety of charging has gradually become a barrier to the promotion of the electric vehicle industry [13].

The standards [14,15] for charging safety protection of batteries and charging equipment of electric vehicles have been formulated globally, including insulation [16], leakage [14], superheat [15], communication [17–23], and further research has been carried out on this basis. However, charging accidents of electric vehicles still occur frequently. How to effectively analyze the mechanism of various failures between batteries and charging equipment, and further establish a complete charging safety protection system is still a hot issue for scholars. Ouyang Minggao, an academician at Tsinghua University, points out that battery thermal runaway is the main reason for frequent charging accidents of electric vehicles, which restricts the development of the electric vehicle industry. Reference [10] also indicates that thermal runaway causes fires and explosions of electric vehicles during charging. The German ZSW Research Center, through experimental data analysis, shows that the lithium dendrites formed inside the battery during charging are the primary cause of battery thermal runaway [24]. In order to solve the thermal runaway caused by lithium dendrites, experts and scholars have conducted a lot of experimental simulation verification and proposed to improve the charging safety performance from two aspects. First, use the battery management system (BMS) to supervise the real-time battery status during charging [25,26]; second, analyze and simulate the failure cases that induce battery thermal runaway, reveal the growth essence of lithium dendrites, and then establish effective diagnosis schemes and early warning models to improve the charging safety performance of batteries [27,28].

Charging piles, the most important supporting facility for charging, are attracting people's attention. In the charging process, the output voltage of a charging pile is up to several hundred volts. Any failure in the insulation or communication system of charging equipment may lead to charging accidents, even casualties. Reference [29], combined with relevant safety protection standards, summarizes the requirements and methods for insulation protection of charging piles and designs a three-layer safety protection system to improve the insulation protection level of charging equipment. Pile communication is another major feature of electric vehicles that is different from traditional fuel vehicles. The surge of electric vehicles will lead to increasingly frequent information interaction between electric vehicles and charging piles, which brings new challenges to the communication safety between electric vehicles and charging piles. Experts and scholars from various countries have conducted studies on the information safety in the charging process. Reference [30] expounds the importance of an embedded security system in the process of electric vehicle communication and analyzes the current challenges of charging pile communication safety and the future research direction. To ensure the privacy, controllability and completeness of data transmission between the charging pile and background service center, the authors of [31] designed a set of information safety protection schemes based on the background service center, which can effectively improve the safe operation environment of charging facilities and help to promote the development and application of supporting facilities for electric vehicles.

To sum up, experts and scholars have conducted many studies on charging safety and have achieved certain results. However, there are still gaps in the research on the influencing factors of charging safety and early warning and protection model, requiring in-depth discussion and improvement. This paper summarized the influencing factors of the charging safety of electric vehicles, summarized the technologies, methods and models of charging safety protection, presented the challenges and prospects of the future charging safety research in respect of improving the charging safety standard system, building a complete charging safety database, and improving the charging safety fault early warning mechanism, which has reference value and reference significance for further in-depth charging safety research of electric vehicles.

The structure of this paper is categorized as follows: Section 2 summarizes the influencing factors of the charging safety of electric vehicles. Section 3 introduces the safety protection methods of battery and charging facilities. Based on the current development status, Section 4 presents some prospects for future development. Finally, Section 5 concludes the paper.

## 2. Analysis of the Influencing Factors of the Charging Safety of Electric Vehicles

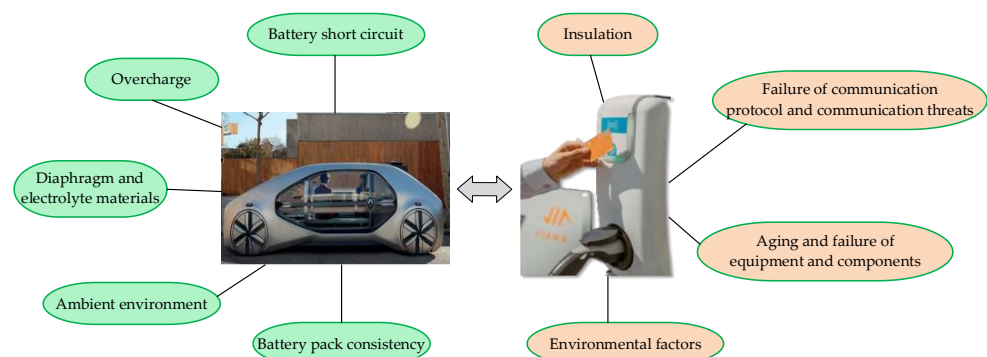
The charging accidents of electric vehicles involve a wide range and various complex factors, which include damage to people, cars and surrounding facilities [26]. Research and analysis of influencing factors is the theoretical basis for studying the charging safety of electric vehicles.

As shown in Table 1, some published articles have reviewed the research on charging safety of electric vehicles. However, in fact, the charging safety of electric vehicles is closely related not only to the characteristics of the battery itself but also to the operating characteristics of charging facilities. Based on the existing review results, this paper takes the whole electric vehicle charging process as the research object and analyzes not only the relevant charging safety factors of electric vehicles but also the impact of charging facilities on charging safety.

**Table 1.** Review articles on charging safety of electric vehicles.

Literature	Main Contributions
[32]	Introduces the composition of BMS and the research status of key problems such as voltage measurement and state estimation and puts forward the problems to be solved in future research.
[33]	Summarizes the model-based and non-model-based fault diagnosis methods and analyzes their advantages and disadvantages.
[34]	Reviews, classifies, and compares different adaptive mathematical models of deep learning algorithms for residual service life prediction and provides suggestions for improving the remaining battery life prediction algorithm.
[35]	Reviews SOC and SOH estimation technologies for electric vehicle batteries, and specifically reviews model-based and data-driven methods for SOC estimation.
[36]	Reviews some battery cell balancing technologies and evaluates their relationship with battery performance.

In order to effectively reduce the probability of charging accidents, this paper summarized the influencing factors of electric vehicle safety and charging pile safety, which are shown in Figure 1.



**Figure 1.** Influencing factors of electric vehicle safety and charging pile safety.

### 2.1. Influencing Factors of Electric Vehicle Safety

The state parameters of an on-board power battery can represent the advantages and disadvantages of electric vehicles and further reflect the safety performance of electric vehicles in the charging process [37,38]. An on-board power battery, the energy storage

device for electric vehicles, is the main source of power for electric vehicles [39]. The battery performance is not only related to the daily range of electric vehicles but also affects the economic performance, safety performance and power performance of electric vehicles [40]. However, in recent years, the rising number of electric vehicle fires reported by media news has made the safety of electric vehicles the focus of attention. Figure 2 shows the statistics of electric vehicle fires worldwide from 2015 to 2019. It suggests an increasing proportion of electric vehicle fires during the charging process. Multiple electric vehicle fires occur every year around the world, which sometimes cause casualties. Table 2 presents the statistics of worldwide charging accidents of electric vehicles in recent years. It shows that the charging accidents caused by battery failure account for the main proportion. Therefore, the charging safety protection has become the primary problem in on-board power batteries.

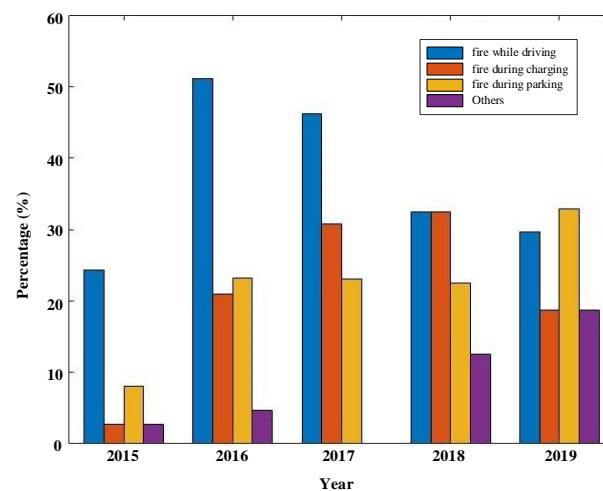
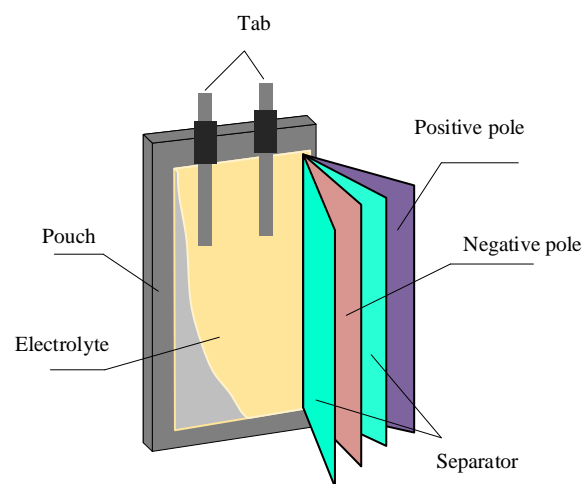


Figure 2. Statistics of worldwide electric vehicle fire status from 2015 to 2019.

Table 2. Statistics of worldwide charging accidents of electric vehicles in recent years (2015–2020).

No.	Time	Place	Accident Description	Cause Analysis
1	April 2015	Shenzhen, China	Smoke erupted from the battery of an electric car, then it caught fire	The electric car did not stop charging after full charging, which caused overcharging for 1.2 h, causing a short circuit inside the battery
2	January 2016	Gjerstad, Norway	A charging Tesla electric car in a charging station burst into fire	The battery was in low-temperature for a long time and was charged in a high-rate charging mode too long, resulting in thermal runaway of the battery
3	April 2019	Shanghai, China	A Tesla electric car suffered spontaneous combustion while charging	The single battery failed, causing a short circuit in the battery
4	June 2019	Antwerp, Northern Belgium	A charging Tesla electric car suddenly smoked, then caught fire and was burned completely	A short circuit occurred during charging
5	October 2019	Taegu, South Korea	A KONA electric car suddenly caught fire while charging	There were internal problems with the power battery components
6	May 2020	Shaowu, China	A VM electric car caught fire while charging, and was burned	The core supplier mixed impurities into cores, so the power battery produced abnormal lithium plating, causing a short circuit in the battery
7	May 2020	Dongguan, China	An electric car burst into fire while charging	A charging fault occurred to the battery pack
8	August 2020	Guangzhou, China	A short-circuit occurred to an electric car in a charging station of Wanjiang Bus Terminal	Overcharging caused a short circuit in the battery

The cut view of a battery is shown in Figure 3. A battery is mainly composed of positive and negative poles, the separator, tabs, the electrolyte and the pouch. With a complex working environment, the battery may experience mechanical damage, liquid immersion, overcharge, discharge, internal short circuit and other abuse scenarios during its whole life cycle [41], where its internal temperature may climb sharply. When the temperature rises to a certain range, decomposition of anode material, lithium insertion of cathode material, diaphragm melting, oxidation of electrolyte and then fierce burning inside the battery may happen, resulting in a sharp increase in battery temperature, i.e., thermal runaway [42–44]. By summarizing the journals, reports and standards of charging safety, this paper analyzed the influencing factors of the charging safety of electric vehicles, such as battery short circuit, overcharge, diaphragm and electrolyte materials, battery pack consistency, and ambient environment, and other influencing factors. Now, this paper will describe the features and action mechanisms of these influencing factors one by one.



**Figure 3.** The cut view of a battery.

#### 2.1.1. Battery Short Circuit

Battery short circuit, one of the electric abuse triggers, is also the most common cause of thermal runaway [45]. Lithium-ion batteries may be short circuited for multiple reasons, generating a large current in the battery in a short period of time, resulting in a sharp rise in battery temperature and then a charging accident [46]. There are three types of battery short circuits from the perspective of a trigger mechanism; namely, a battery short circuit caused by overcharge/discharge, a battery short circuit caused by mechanical damage, and a self-induced battery short circuit. Compared with the other two types of battery short circuits, the self-induced battery short circuit features strong latency and long action duration [47].

#### 2.1.2. Overcharge

Battery overcharge is one of the important causes of thermal runaway [48,49]. During overcharging, the battery is powered continuously, making it a prolonged unsafe charging state, and even safety accidents. In addition, incorrect charging methods, excessive ambient temperature and uneven distributed polar coating cause battery overcharge [48]. The authors of [50], through test analysis, found that the risk of battery overcharge is strongly associated with the ambient temperature of the battery and the number of charging cycles.

#### 2.1.3. Diaphragm and Electrolyte

The diaphragm, an important component of a battery, is aimed at separating the cathode from the anode to avoid battery short circuits. Battery safety is affected to some extent by the quality and performance of the diaphragm material. The uneven surface of the diaphragm material is likely to form lithium dendrites during the electrochemical

reaction, which destroy the diaphragm material, causing a short circuit in the battery. In addition, long service time will lead to aging of the diaphragm, which may cause the battery to short circuit. Therefore, it is necessary to pay attention to the inspection and maintenance of the diaphragm during use. Reference [51] indicates that anode material, type of solvent, and external temperature will affect the solid electrolyte interface (SEI). It also points out that the risk of a battery short circuit can be reduced by selecting suitable materials and reasonably adjusting the product parameters in the production process.

Electrolyte, an important component of battery material, has a great impact on the performance of the battery [52]. During the whole life cycle of the battery, the electrolyte is subject to a degradation effect as the number of charges and discharges increases. Electrolyte, a combustible, easily produces gas in heat abuse and other bad cases, leading to expansion and even fierce burning of the battery.

#### 2.1.4. Battery Pack Consistency

In the process of battery pack manufacturing, the different single battery manufacturing process directly affects the internal structure of battery, resulting in differences in parameters such as battery capacity, internal resistance and single battery voltage [53]. Even if the parameters of the battery pack are exactly the same when leaving the factory, the accumulative charging and discharging of electric vehicles will cause an internal attenuation effect in the battery pack, resulting in differences in a single battery [54,55]. For example, a single battery with large internal resistance is more difficult to fully charge than other single batteries, that is, the battery pack shows a “bucket effect” externally, making it difficult for the battery pack to reach the rated capacity [56]. In addition, the battery pack consistency also has some impact on its overcharging capacity. Some lithium-ion batteries, such as lithium iron phosphate batteries, are sensitive to overcharging. In order to ensure that all single batteries reach the full charge state, overcharge may occur in some single batteries, which may affect the life of a battery pack, and even threaten the safety of electric vehicles and supporting equipment [57].

#### 2.1.5. Ambient Environment

The essence of common electric vehicle batteries is to transform chemical energy into electric energy, which affects the energy efficiency and safety of batteries in use. This chemical reaction is affected by the ambient environment. Therefore, in the process of charging, the impact of environmental factors on the safety of a battery cannot be ignored [58,59]. Reference [60] points out that as the charging environment becomes more complex, the impact of ambient temperature on the safety of a battery is more prominent. For example, when the ambient temperature is too low, too much lithium ions are embedded from the cathode and, after a while, deposited in the anode of the battery pack, causing a short circuit in batteries; when the ambient temperature is too high, the safety and stability of lithium battery cathode will be reduced. Therefore, effectively monitoring the ambient environment when charging will be conducive to protecting the charging safety and reduce the probability of charging accidents.

#### 2.1.6. Other Influencing Factors

In addition to the factors mentioned above, battery type is another important factor affecting the safety of electric vehicles. There are many types of batteries used in electric vehicles, such as LiFePO<sub>4</sub>, NiMH, MnNiCo, et al. Due to the different performance of different batteries, their impact on the safety of electric vehicles is also different. For example, MnNiCo is easier to burn or even explode than LiFePO<sub>4</sub> under destructive actions such as impact or puncture. Therefore, MnNiCo has higher requirements for anti-collision protection of the shell than LiFePO<sub>4</sub>. At the same time, the low-temperature resistance of LiFePO<sub>4</sub> is not as good as that of MnNiCo. Therefore, LiFePO<sub>4</sub> needs low-temperature protection measures more than MnNiCo.

The charging safety performance of a battery is also affected by the battery charge and discharge ratios as well as the degree of self-discharge [61]. Furthermore, the safety of the battery pack is mainly guaranteed by accurate BMS control. In the daily charging process, the BMS ensures the charging safety of a battery by monitoring the parameters of a battery pack. Any mechanical failure of the BMS may threaten the charging safety of the battery [62].

## 2.2. Influencing Factors of Charging Pile Safety

Up to now, charging technology is no longer an important obstacle to the development of the electric vehicle industry. How to use effective methods to ensure the safe and stable operation of all kinds of equipment in the charging process has become increasingly important. In 2010 and 2013, the National Energy Administration officially released the NB/T33002-2010, NB/T33008.2-2013 and other standards, which give clear standards for the safety performance of charging piles during charging and regulate the test conditions, including insulation voltage resistance protection, environmental protection, lightning protection, and communication safety protection. Furthermore, the GB/T27930, a national standard, defines the equipment fault category during charging, which can be used to analyze the influencing factors of charging pile safety [63].

### 2.2.1. Insulation

To ensure personal safety during charging, good insulation protection is necessary for electrical equipment and lines [13]. The relevant sections in the GB/T18487.1-2015 clearly impose requirements on the structure and performance of charging piles [64]. In addition, the insulation design of charging piles can effectively provide a warning as to the failure of charging piles and other safety problems and then improve their safety. The insulation design of charging equipment includes insulation protection performance of the charging equipment shell, electrical clearance, creepage distance, dielectric strength, and insulation resistance. The following is the analysis of these elements.

First, the insulation protection performance of the charging equipment shell: The charging safety of charging piles is directly affected by the insulation protection performance of the charging equipment shell. The GB/T18487.1 clearly states that the insulation protection level of the charging equipment shell during charging can be represented as IPXXC [64], where C means whether there is a danger to the user while using the equipment. It also specifies the charging safety protection of connectors in different states [50,65]. Second, electrical clearance and creepage distance: Electrical clearance refers to the shortest distance between two conductor components or between the conductor and an adjacent protective interface measured in the air while ensuring electrical performance and safety. Creepage distance refers to the shortest distance between electric chassis and connecting terminal or between two conductive components measured along the surface of the insulation material [66]. Third, dielectric strength: The greater the dielectric strength of the insulation material, the better the electrical resistance performance. The GB/T18487.1 sets up provisions and requirements for the insulation material properties of the charging equipment. In particular, the dielectric strength of the insulation material must meet the relevant standard [65]. Finally, insulation resistance: The GB/T 18487.1-2015 specifies that the insulation resistance between the circuits connected to the power supply equipment shall be equal to or greater than 10 MΩ. In addition, to avoid electric shock accidents, protective measures shall be taken to overcome the air humidity change, aging, and moisture proofing of the insulation material of the charging equipment, so as to improve the insulation of the charging equipment [67].

### 2.2.2. Failure of Communication Protocol and Communication Threats

In the whole charging process, the reliability and safety of the communication system are of great significance to the safety of electric vehicles and supporting equipment such as charging piles [13,65,68]. When the communication protocol between the two is

mismatched or incompatible, the electric vehicle will not be charged. In addition, any wrong message received or sent by either party will cause an interruption of charging or even spontaneous combustion of electric vehicles and charging equipment. At the end of the charging process, once the actual output voltage of the battery reaches the set voltage threshold, the BMS will send a signal to stop the charging [11]. Any failure of the BMS may lead to battery overcharge, even equipment fire or battery explosion, and thus burning of the charging pile. Thus, the GB/T27930-2015 stipulates that in any stage of the charging process (except special circumstances), the failure of receiving a message or incorrect format of a message from either party within 5 s shall be immediately determined as a communication timeout, and action shall be taken to ensure the safety of charging equipment.

In terms of communication safety, charging piles face various information safety threats, including natural elements and human elements, which show a changing trend over time [69]. Natural elements include all kinds of natural disasters, bad communication places, and equipment performance degradation, etc. Human elements include destruction, deception, and theft, etc., which bring economic losses to equipment operators [70]. For example, malicious network technology attacks interrupt the charging, tamper with the charging data in the charging process, affect the operator's revenue, and steal and leak the user's vehicle models and charging messages, causing user panic. Therefore, it is urgent to design the information safety protection scheme for charging piles, so as to improve the safety of information interaction in the charging process.

### 2.2.3. Aging and Failure of Equipment and Components

The aging failure of the equipment and components inside charging piles also affects the safety of charging piles in use. The charging pile in its whole life cycle will face high temperature, water logging, exposure to the sun, which accelerate the aging failure speed of the charging module, rectifier module, terminal equipment, leading to charging pile performance failure and charging accidents. This raises more stringent requirements for the necessity and timeliness of the operation and maintenance of charging equipment. Prolonged operating of the internal components of the charging pile at a high temperature, especially in summer, will cause irreversible damage to the lifetime of components and the insulation performance of cables, as well as thermal failure and aging of rectifier module [71]. Reference [67] points out that prolonged overheating of the DC contactor connecting terminal may cause oxidation and blackening of it, increased contact resistance, and even insulation aging or scorching of the wires connected to it, which seriously threaten the safety of charging equipment. Outdoor charging piles need to prevent water from entering the interior and metal parts of key modules inside them from becoming rust and aging, otherwise the safety risk in use will be increased.

### 2.2.4. Environmental Factors

Environmental factors such as weather, temperature and humidity have no negligible effect on the insulation performance of charging equipment, even the safety of charging equipment [72]. The safety of outdoor charging piles, especially when the charging station is not under a roof, is affected by environmental factors. Their internal system may fail due to a thunderstorm, high temperatures, or a typhoon in summer. For example, charging equipment in a thunderstorm is prone to a charged reaction that can generate high voltage, which damages high precision integrated circuits and a large number of microprocessors, ranging from damage to the electronic system inside the charging pile to burning of the internal lines of electric vehicles directly connected to the charging pile, thus leading to major accidents [73].

### 2.2.5. Other Influencing Factors

During the charging and operation of a charging pile, electricity quality is also an important factor affecting the safety and stability of the charging pile. The voltage fluctuation,



electronic surge strike, or high harmonic in electric energy received by the charging station will affect the normal operation of the charging pile, causing the fault of the charging pile and even endangering the safety of the charging pile and electric vehicle equipment [67].

Moreover, the safety problems caused by safety function defects cannot be ignored. For example, interoperability function defects lead to a charging pile's failure to provide effective protection; an excessive output current of the charging pile can easily damage the structure of the electric vehicle battery system; insufficient IP protection levels of the system can easily cause a short circuit in the charging pile or even electric shock and other accidents to personnel [74]; in the case of emergency, the DC piles, due to no emergency stop device or their function failure, cannot cut off the interconnection between the piles in time and prevent the situation from deteriorating [75].

### 3. Analysis of the Charging Safety Protection of Electric Vehicles

Through the charging cycle, a charging accident will bring significant economic losses to the electric vehicle owners and system operators and will even cause casualties. Therefore, it is particularly important to timely and effectively provide early warnings of charging faults and take protective measures [13,76].

#### 3.1. Charging Safety Protection of the Batteries of Electric Vehicles

How to provide early warning, control the thermal runaway, and establish a comprehensive and effective battery safety protection system is an important technical difficulty to be solved urgently for the studying of charging safety of the batteries of electric vehicles [77,78]. Referring to the trigger and expansion mechanism of battery thermal runaway, in this paper, the charging safety protection technology of batteries were divided into the following parts: (1) internal short-circuit detection and protection technology; (2) battery overcharge mechanism analysis and diagnostic protection technology; (3) battery pack equalization technology; (4) development and application of highly stable battery materials; (5) battery status parameter monitoring and fault diagnosis method.

##### 3.1.1. Internal Short-Circuit Detection and Protection Technology

Internal short-circuit is one of the important causes of accidents related to charging batteries. To timely and effectively detect the short-circuit in the battery during charging, researchers put forward internal short-circuit detection methods based on direct characteristics and indirect characteristics, respectively, to effectively prevent serious battery faults [46]. The internal short-circuit detection method based on direct characteristics analyzes the BMS sensing signal, and then analyzes the values and changes the rules of the battery voltage, current and temperature, so as to realize internal short-circuit detection. This method works depending on the comparison of the individual battery parameter threshold and the comparison of the group parameter change law. The steps are as follows: (1) Judge whether the sensing signal exceeds the fault threshold set by the system. For example, by simultaneously detecting the battery terminal voltage rise/drop rate and the temperature rise/drop rate, compare it with the parameter threshold set by the system, and then determine whether the battery has an internal short-circuit fault [27]. (2) Compare the change law of the sensing signal of each single battery in the battery pack, and then identify the abnormal individual battery: when a single battery in the battery pack is subject to an internal short-circuit, the voltage change law is quite different from that of the other single batteries. Thus, Xia Bing et al. [25] detect the battery short circuit by calculating the voltage correlation coefficient between single batteries. When the voltage correlation coefficient between a single battery and another battery experiences a sudden drop, an internal short-circuit occurs in the battery. The internal short-circuit detection based on direct characteristics is easy to operate and can realize the online detection of internal short-circuit in the battery. However, it cannot accurately detect the early signs of the internal short-circuit, and it is difficult to quantify the severity of the internal short-circuit.

The internal short-circuit detection method based on indirect characteristics analyzes the relationship between the battery's internal short-circuit state and the equivalent resistance, self-discharge current and equivalent model parameters, makes the battery's internal short circuit detection equivalent to the parameter estimation, and then builds an equivalent model to realize internal short-circuit detection. Ouyang Minggao, an academician at Tsinghua University, and others carried out studies on the internal short-circuit in batteries [79–83]. The team proposed the fault diagnosis method based on the “average-difference” model to detect internal short circuits in lithium-ion batteries. Experimental analysis shows that the method could correctly detect internal short-circuits at least 30 min before thermal runaway. In addition, SEO M et al. [84] put forward an internal short circuit-detection method based on the switching model method (SMM), which updates the parameters of an equivalent circuit model of battery short circuit, so as to more accurately estimate the open circuit voltage and charge state in the model and warn the internal-short circuit in batteries in advance. Reference [26] proposes a short circuit identification method through background data comparison, and a method that synchronously calibrates the BMS data transmission and estimates the internal resistance of a single battery, so as to identify the potential fault single battery. The above analyses show that the method based on indirect characteristics can provide the internal short-circuit detection results more accurately and quantitatively than the method based on direct characteristics, but it requires a complex modeling and testing process for batteries.

### 3.1.2. Battery Overcharge Mechanism Analysis and Diagnostic Protection Technology

In recent years, domestic and foreign research on lithium-ion battery overcharge safety, from aspects of overcharge mechanisms, protective materials, overcharge diagnosis and modeling, has never stopped. There is mature research on the fault mechanism of battery overcharge. For example, the team of Persis, a professor at the University of Orleans, carry out studies on battery overcharge [85,86]. The team revealed the internal reaction mechanism of battery overcharge by analyzing the overcharge behavior under different experimental conditions. Qi Chuang et al. [87] reveal the influence mechanism between the overcharge flow of different rates and the battery stability using the multiphysical field coupling model. Lin Chengtao et al. [88] analyze the thermal phenomenon during the overcharge of such batteries from different angles using the electric-thermal coupling model of an LMO lithium-ion battery. The experimental results show that the side effects are the main hidden danger of lithium-ion battery overcharge. Therefore, measures should be taken to avoid the risk of thermal runaway caused by the overcharge side effects.

The development of new overcharge protection material is a simple and economical method that can simplify the production process and reduce the risk of overcharge from the root. The overcharge protection studies by Wang Qingsong's team, a team in the National Key Laboratory of Fire Science at the University of Science and Technology of China, show that PCM materials with low melting index have superior cooling performance, which helps to reduce the risk of thermal runaway probability [89,90]. Apart from this, the construction of an overcharge diagnosis model is the focus of studying overcharge protection. Reference [91] studies the possible overcharge fault in the charging process of lithium-ion batteries and verifies that the proposed method can accurately diagnose overcharge faults using the second-order resistance capacity model of lithium batteries. The above overcharge protection research is mature for lithium-ion batteries with general specifications and performance but not for the new lithium-ion batteries in the market, so it is urgent to further improve the overcharge protection research of lithium-ion batteries [92].

### 3.1.3. Battery Pack Equalization Technology

The on-board power battery consists of multiple single batteries in series to meet the daily driving needs of electric vehicle owners. Affected by the production process, battery aging and ambient temperature, the rated voltage, capacity, internal resistance inevitably differ, which accumulates and expands over time. Battery pack equalization technology, an

important method to solve the problem of battery pack consistency, plays a negligible role in the use of single batteries in groups. Different battery pack equalization methods have been proposed by scholars [93]. See Table 3 below for details.

**Table 3.** Comparison of various battery pack equalization methods.

Method	Literature	Advantages and Disadvantages	Equalization Circuit Diagram
Dissipative shunt equalization method	[94]	Advantages: low energy consumption, strong scalability, easy for modular design. Disadvantages: thermal management problems and only for small-power battery packs.	See Appendix A Figure A1
Complete shunt equalization method	[95]	Advantages: large equalization current and fast equalization speed. Disadvantages: high cost and strict variation range of charger output voltage.	See Appendix A Figure A2
Isomorphic CE equalization method	[96]	Advantages: can achieve the non-destructive balance between charge energy and discharge energy of battery pack. Disadvantages: strict requirements for battery voltage monitoring technology and complicated equalization circuit structure.	See Appendix A Figure A3
Multiswitching capacitance method	[97]	Advantages: low requirements for the intelligence of control system, and simple circuit structure. Disadvantages: low sensitivity to voltage and low equilibrium accuracy.	See Appendix A Figure A4
Single switching capacitance method	[98]	Advantages: only need a switching capacitance, good economy. Disadvantages: the equilibrium cycle is limited by the number of single batteries, slow equalization speed.	See Appendix A Figure A5
Multi-winding transformer method	[99]	Advantages: high efficiency and no closed-loop control and voltage monitoring equipment. Disadvantages: weak scalability, general tailor ability, difficult design of a multi-winding transformer.	See Appendix A Figure A6
Switching transformer method	[98]	Advantages: low cost, low circuit design difficulty. Disadvantages: large circuit loss, low equalization efficiency.	See Appendix A Figure A7

### 3.1.4. Development and Application of High Stable Battery Materials

Battery materials are closely related to battery safety, so the battery safety during charging can be improved by the development of highly stable battery materials [38]. Lithium-ion batteries are generally composed of a cathode, anode, electrolyte, and diaphragm, etc. The thermal runaway characteristics of lithium-ion batteries are improved by upgrading the cathode and anode [100–102], diaphragm [103] and electrolyte [104,105], which can fundamentally prevent the thermal runaway. The modification of electrode materials includes surface coating and doping modification [100,101], while the improvement [106] of the electrolyte includes the development of new lithium salt, solvent modification and addition of electrolyte flame retardant, so as to improve the safety of electrolyte. For example, Zeng Ziqi et al. [107] synthesize a new TFMP as a flame retardant, reducing the combustibility of the electrolyte and having less impact on the electrochemical properties of the battery.

The diaphragm is a key safety component of a lithium-ion battery. The development of high-strength inorganic diaphragm material can effectively improve the puncture resistance of a diaphragm and also enhance the thermal stability of a lithium-ion battery [108].

For example, the literature [109] compounds ceramic particles on the surface of the battery diaphragm to prepare a composite diaphragm. The simulation results show that the use of this composite can effectively reduce the high-temperature thermal contraction of the diaphragm and improve the charging safety of the battery. In addition, the development of hard-burning all-solid-state batteries will help to solve the thermal runaway problem of the lithium-ion battery from the root [110]. However, the simulation test data on the thermal runaway and thermal diffusion of all-solid-state lithium battery is scarce, and some parameters are not clear. Whether they can fundamentally solve the intrinsic safety problem of lithium-ion batteries still needs to be further studied [111].

### 3.1.5. Battery Status Parameter Monitoring and Fault Diagnosis Method

The BMS plays the most critical role in charging safety [12]. The monitoring device and signal collection device in the BMS can monitor and collect parameters of input current, input voltage, and charge state of the battery in real-time when charging, so as to keep the battery in a normal operating state [43]. Reference [32] introduces the composition of BMS and the research status of key problems such as voltage measurement and state estimation and puts forward the problems to be solved in future research. In addition to this, the battery fault diagnosis method needs to be upgraded and improved. Xiong Jing et al. [38] analyze the fault diagnosis and detection method of a lithium-ion battery based on coordinated probability and signal monitoring, pointing out that the method is too dependent on the thermal characteristics of a battery. Xiao Yao [28], a student at UESTC, provides BMS with a fault real-time online analysis system with functions of fault analysis, early warning, and processing, which can dynamically monitor the state of a lithium-ion battery in real-time, analyze the abnormal situation online, and immediately terminate charging for subsequent processing for any internal fault of the battery. The aging of lithium-ion batteries and the relationship between performance and failure are quantitatively analyzed in the literature [112]. This paper summarizes the model-based and non-model-based fault diagnosis methods and analyzes their advantages and disadvantages. It is suggested that the combination of methods can be used to improve the fault diagnosis process.

## 3.2. Charging Safety Protection of the Charging Equipment of Electric Vehicles

Charging equipment, an important supporting facility of electric vehicles, has complex structures and functions [113]. Any failure of key modules such as insulation detection and communication in the system will endanger the safety of personnel and equipment. Therefore, to effectively protect the safety of electric vehicle charging equipment, measures should be taken to ensure its health state in the charging process.

### 3.2.1. Insulation Protection Technology of Charging Equipment

During charging, the voltage between an electric vehicle and charging pile is up to several hundred volts. Once the equipment insulation fails, it will seriously endanger the safety of personnel [114]. With respect to insulation protection for electric vehicle charging equipment [115,116], basic safety protection assessment standards for charging equipment have been issued globally, and significant exploration and testing has been conducted with these standards as a benchmark. For example, the Electric Vehicle Association in Germany carried out a study on the DC leakage protection, charging cable self-inspection and other technologies of charging piles [112,117]. Reference [118] eliminates the insulation fault by using the charging pile added with a detection main control module to conduct insulation self-inspection on the charging pile before charging. Reference [29] takes protective measures for direct and indirect electric shock protection to improve the insulation protection level of charging piles. Direct electric shock protection is to insulate the parts of charging piles with which consumers may contact, so as to protect the personal safety of consumers. When the dangerous charged body is exposed, the charging pile has chaotic output current

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