Research on the safety of electric vehicles charging on board

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Summary

Based on the statistical data of EVs fire accidents recently, the reasons of battery fire caused by charging are analyzed from the perspective of mechanism in this paper. The current regulations of the shipping industry for the on-board charging of EVs have been sorted out, as well as the main technical standards for EV charging, and the relevant advices for the installation of EVs AC charging piles on-board are considered. Then the risks of EVs on-board charging are analyzed, and the corresponding safety protection suggestions are put forward, which provides a reference for formulating rules of EVs on-board charging.

Keywords: EV charging, on-board, EVs fire accidents

1 Introduction

With the progress of the Paris Agreement, It has become the consensus of governments and the automobile industry widely that to vigorously develop clean, environmentally friendly, efficient and energy-saving EVs in the field of road traffic. The power of EVs is mainly provided by the electrical energy stored in the lithium-ion battery. At present, the most common charging method with the highest energy utilization rate is the energy replenishment through electrical conduction when the electrical energy is consumed.

When transported by water, cars can be boarded as commodities on car carriers. It can also be used as an operational vehicle on a ro-ro carrier with passengers. With the current rapid development of EVs, it has been urgently expressed by related industries to add charging devices to such ships that can transport cars.

The chemistry property of lithium-ion batteries is more active. Therefore, accidents may occur in the process of using lithium-ion batteries, resulting in environmental pollution and economic losses. Many EV accidents are related to thermal runaway of lithium-ion batteries. Smoke, fires, and even explosions occurred in these accidents[1].In particular, in February 2022, the car carrier "Felicity Ace" carrying more than 4,000 EVs suddenly caught fire while sailing near the Azores in the Atlantic Ocean (the fire lasted for nearly a week). It makes the public realize that there are huge safety risks and economic losses when ships carry lithium-ion battery-powered vehicles. It also brings new analysis and consideration to the marine industry in how to carry lithium-ion battery-powered vehicles. Considering that it is much more difficult for people to escape when a fire occurs on a ship than on land, the transportation and charging of EVs need to be carefully considered and strictly regulated.

Firstly, based on incomplete statistical data from EV fire accidents in China in the past two years, the reasons of battery fire caused by EV charging are analyzed from the perspective of mechanism in this paper. And then the current requirements of the International Maritime Organization (IMO) and the world's major classification societies for the on-board charging of EVs, as well as the main technical standards for EV charging have been sorted out. The current regulations of the International Maritime Organization (IMO) and the world's major classification societies for the on-board charging of EVs have been sorted out, as well as the main technical standards for EV charging. Then the relevant requirements for installation on the ship which are considered for the AC charging piles of EVs are put forward. Finally, the fire risk of EVs being charged on board is analyzed through the accident tree analysis method, and measures are proposed to provide a reference for the formulation of standards for EV charging on board.

2 The Statistics and the Analysis of EV Charging Fire Accidents

2.1 Statistics of EV fire accidents

According to incomplete statistics of online information, from January 2020 to December 2021, there have been 133 major EV fire accidents in China. Through the specific statistics of the cause of the accident, the time of the accident, the area where it occurred, etc., the details of the accident are shown in the figure below.

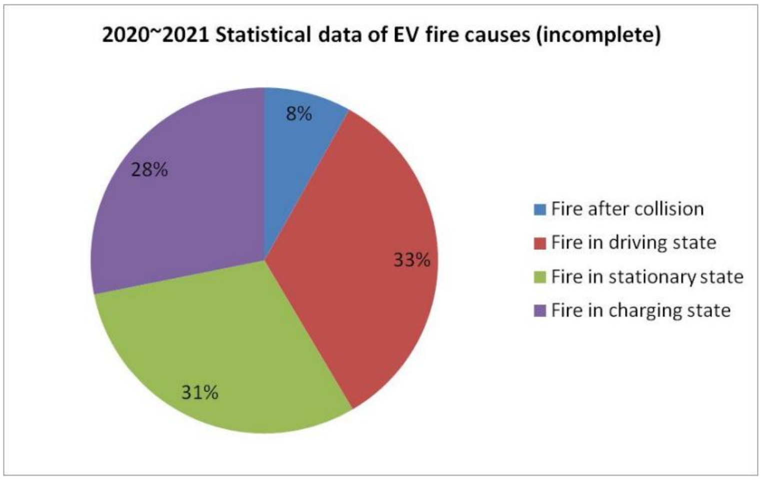

Figure1: 2020~2021 Statistical data of EV fire causes (incomplete)

As shown in Figure 1, it is obtained from the data that the proportion of fire caused by charging accounts for about 28% of the total fire accident tree. Considering that the accident exposure rate during road driving is high, the exposure rate of accidents that occur in the venues of vehicle operators and charging operators will be much lower due to timely disposal. Therefore, the statistical data in this paper still has a certain deviation, that is, the proportion of fire accidents during charging may be higher.

When the causes of these statistics accidents are deeply probed into, it is found that besides the fire accidents during charging, some EV fires at rest and during operation are also related to charging, as shown in Table 1.

Table1: The Cases of EV Fire Accidents Related to Charging

Label	Time	Location	Description of the accident
1	July, 2020	Taiyuan city, Shanxi Province, China	An EV of Lalamove was driven after being fully charged. It suddenly made an abnormal noise during operation, and then the car self-ignited and caught fire.
2	July, 2020	Anyang city, Henan Province, China	After an electric logistics vehicle was fully charged at the charging pile, the charging gun was not pulled out, and it suddenly self-ignited and caught fire.
3	February, 2021	Wenzhou city, Zhejiang Province, China	An EV produced a strange smell because of immediately running after charging. The car caught fire after the owner stopped the engine.

As shown in Figure 2, through statistics on the monthly distribution of EV charging accidents, it is found that with the change of seasons, in summer when the temperature is higher (May to September), the number of EV fire accidents increases significantly.When the temperature gradually drops, the monthly distribution of EV accidents is relatively flat (excluding the impact of the COVID-19 pandemic in early 2020).

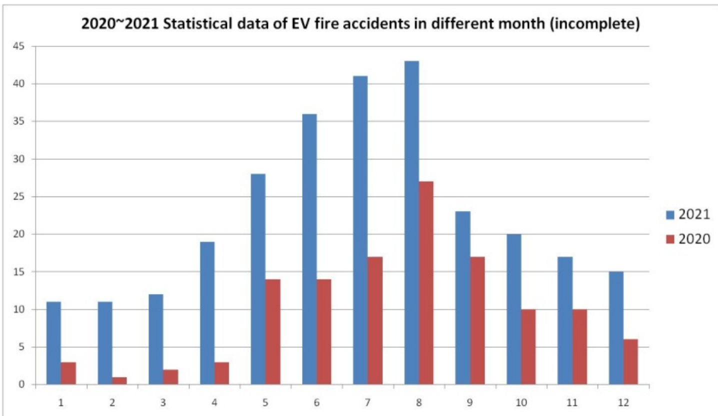

Figure2: 2020~2021 Statistical data of EV fire accidents in different month (incomplete)

As shown in Figure 3, through statistics of EV accidents in different regions of China in 2021, it is found that the overall number of accidents in the southern region is significantly higher than that in the northern region.There are two main reasons for this:

.1 The average temperature in southern regions is higher than that in northern regions. It has longer periods of high temperature. Therefore, it is more likely to cause vehicle self-ignition (especially represented by Guangdong);

.2 In winter, the temperature in southern regions is higher than that in northern regions. And winters in the south are shorter in duration. In this case, the impact of low temperature on the power battery is relatively small (the cruising range of the power battery is significantly reduced at low temperatures). Therefore, the penetration rate of EVs is relatively higher.

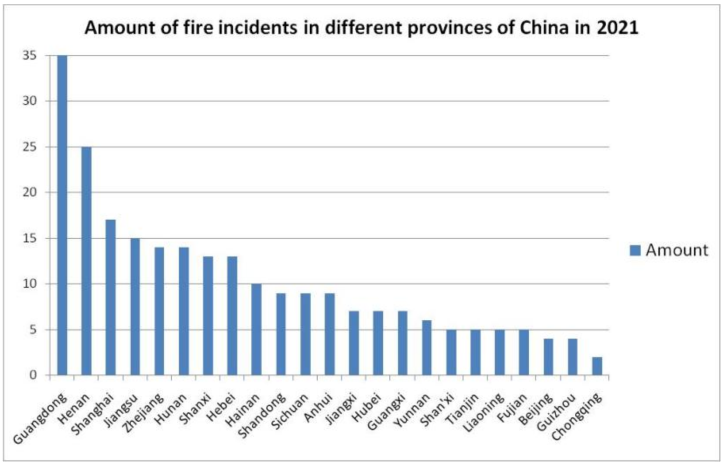

Figure3: Amount of fire incidents in different provinces of China in 2021

Combined with the public report of Chinese National Electric Vehicle Engineering Laboratory[2], it can be found that the charging process, stationary after being fully charged, and running after being fully charged are the main components of fire accidents, and most of the fire accidents of EVs occur in a high SOC state (as shown in Figure 4).

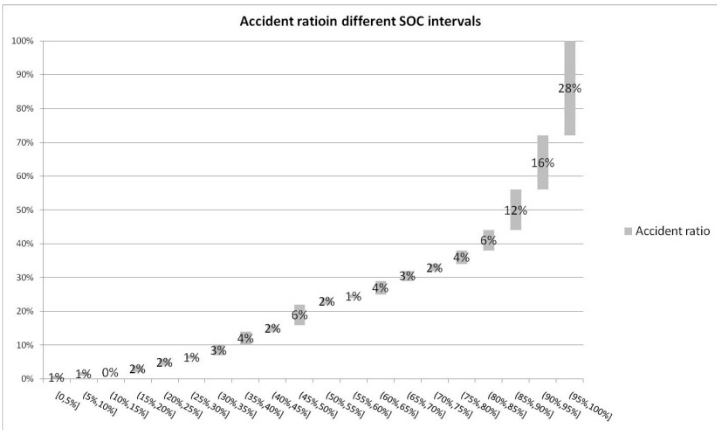

Figure4: Accident ratioin different SOC intervals

2.2 Analysis of the causes of EV charging fire

EV fires are mainly caused by lithium-ion battery fires, and thermal runaway is the most important cause of lithium-ion battery fires[3]. Thermal runaway of lithium-ion batteries is usually induced by mechanical abuse, electrical abuse, and thermal abuse. There is a certain internal relationship between these three abuse situations, as shown in Figure 5: Mechanical abuse leads to deformation of the battery, and the deformation of the battery leads to the occurrence of internal short circuits, which leads to the occurrence of electrical abuse. With the generation of Joule heat and heat of chemical reaction, electrical abuse causes thermal abuse of the battery. As the temperature increases due to thermal abuse, a thermal runaway chain reaction (a series of exothermic reactions) of Li-ion batteries is initiated. It raises the temperature, which eventually leads to thermal runaway. A large number of gas jets are produced or even ignited.

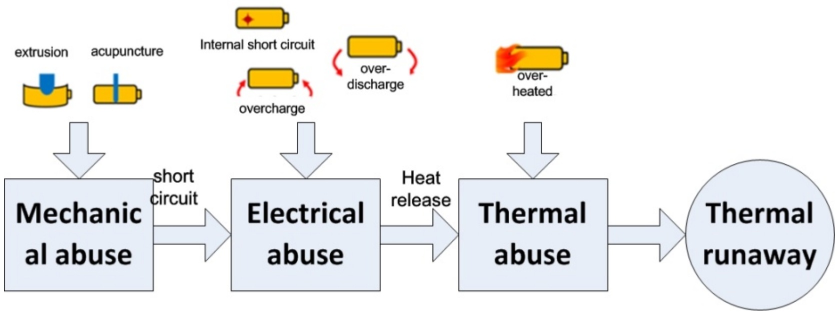

Figure5: Mechanism of thermal runaway of lithium-ion batteriess

A short circuit in the battery is the root cause of thermal runaway in the battery. Due to an internal short circuit in a lithium-ion battery for some reason, a large current will be generated inside the battery for a short period of time. It causes the temperature inside the battery to rise sharply, which in turn leads to a charging accident [4]. From the analysis of the trigger mechanism, there are mainly three types of short circuits in the battery. They are internal short circuit caused by overcharge/discharge, internal short circuit caused by mechanical damage, and self-induced internal short circuit :

.1 The latent potential of self-induced internal short circuit is strong and the action time is long, which is mainly caused by the internal reasons of the battery;

.2 During overcharge/discharge, many needle-like crystal dendrites will be formed on the electrode, and these needle-like crystal branches will pierce the battery separator, causing many tiny short-circuit loops, and continue to release heat;

.3 The internal short circuit caused by mechanical damage is caused by the battery being squeezed/punctured when the car collides, which is difficult to predict.

The main reason for a battery to catch fire while charging is overcharging[5]. During overcharging, the battery is continuously powered externally. This keeps the vehicle power battery in an unsafe charging state for a long time, which will eventually lead to safety accidents. Overcharging can be caused by:

.1 The battery cells are inconsistent between lithium battery packs: Since the lithium battery pack is composed of single cells, its capacity conforms to the "cask principle", that is, the capacity of the worst cell determines the capacity of the entire battery pack. Therefore, in order to ensure that all single cells are fully charged, some single cells may be overcharged, thereby affecting the life of the battery pack;

.2 Influence of ambient temperature: In certain cases, whether the chemical reaction of the battery can proceed smoothly is affected by the surrounding environment. In the case of charging, when the ambient temperature is low, too many lithium ions are deintercalated from the positive electrode and deposited on the negative electrode of the battery pack after a period of time, causing a short circuit in the battery. When the ambient temperature is high, the safety and stability of the positive electrode of the lithium battery will be reduced;

.3 Monitoring failures: During the daily charging process, BMS ensures the safety of battery charging by monitoring various parameters of the battery pack. Once the BMS fails, or the communication between the charging pile and the BMS fails, it may lead to the failure to monitor and control the charging of the battery and overcharge.

In addition, when the charging pile is aging, the charging power quality is unstable, and the charging pile is faulty or the charging area is flooded, it may lead to the abnormal connection of the battery to cause a local external short circuit, which will result in a charging accident.

3 Sorting out the current charging requirements for EVs on board

3.1 IMO circulars and requirements of each CLASS

At the 101st meeting of the IMO Maritime Safety Committee (from June 5 to 14, 2019), the guideline named "INTERIM GUIDELINES FOR MINIMIZING THE INCIDENCE AND CONSEQUENCES OF FIRES IN RO-RO SPACES AND SPECIAL CATEGORY SPACES OF NEW AND EXISTING RO-RO PASSENGER SHIP " (MSC.1 /Circ.1615)[6]was adopted as a circular. The Interim Guide consists of five sections. The first section of the guidelines is a precautionary requirement, which includes the following requirements related to the on-board charging of EVs:

(1) Develop a maintenance plan for ro-ro ships supplying power to vehicles or cargo assemblies and for the cables, sockets and ancillary equipment of special spaces;

(2) Cables used to supply power to vehicles or cargo components shall be adequately protected from corrosion and effectively grounded. When cables are not in use, they should be stored in such a way that they will not be damaged by handling operations;

(3) In addition to the electrical connection line meeting the existing regulations of SOLAS, the socket shall also provide a protection level of at least IP56 in accordance with the standard IEC 60529. And the socket shall be provided with measures to maintain the same degree of protection after the plug is removed.

(4) Only trained personnel or other personnel under the supervision of the crew shall carry out the electrical connection and disconnection of cargo components and EVs;

(5) Items to be checked during patrol include electrical connections and the condition of ship-to-vehicle power cables.

By consulting the relevant requirements of classification societies including DNV, NK, LR, BV, ABS, and CCS, it is found that, except for ABS classification society, other foreign classification societies have no relevant principle requirements or technical requirements for the carriage of EVs on board. ABS classification society puts forward relevant requirements[7] for the carriage of EVs in the form of hybrid EVs using lithium batteries as power, plug-in EVs and pure EVs . including the requirements for EVs to be charged on board. It also includes requirements for EVs to be charged onboard ships. The specific requirements are as follows:

(1) A dedicated ro-ro transportation area for EVs should be designated.

(2) Fire detection and early warning:

.1 A video surveillance system is installed to complement the fire detection system in the cargo area for carrying EVs;

.2 At least two portable thermal imaging devices are provided for crew patrolling the ro-ro cargo hold;

(3) Fire extinguishing device: a fixed pressure water spray system should be installed in designated areas in the ro-ro cargo compartment of EVs.

(4) Additional Fire Fighting Equipment: In addition to the fire fighter's equipment required by the code, two additional sets of fire fighter equipment shall be provided for ro-ro cargo holds intended

for EV transport.

(5) EV charging facilities: The electrical equipment, wiring and power sockets used to supply power toEVs shall be of a certified safety type and can be used in explosive atmospheres in accordance with the corresponding provisions of the code (if applicable). Cables related to EV charging should be properly protected even when armored.

From this, it can be seen that with the vigorous development of EVs in the international community, key research on the safety of EVs carried by ships and the charging of EVs on board is being carried out. At present, for the on-board charging of EVs, international organizations in the field of ships mainly consider the electrical protection level and explosion-proof requirements of charging devices. The equipment requirements for fire fighting and detection equipment have been increased. As well as developing a maintenance plan for personnel to achieve safe monitoring of EV charging is passed.

3.2 Requirements for charging equipment

In Dr. Wu's research[], it was found that in the constant current and constant voltage charging mode, the maximum heat generation rate of the battery presents a quadratic function change trend with the increase of the charging current. And its heat production shows a linear growth trend with the increase of current. It is considered that excessive charging current and uneven distribution of pole piece coating may also cause local overcharging. And in the charging pile market, the price of a single set of high-power DC EV charging piles (fast charging) is generally dozens of times the price of a single set of AC EV charging piles (slow charging). From the point of view of safety and economy, it is more suitable to choose AC charging equipment to charge EVs on board.

The general requirements for the AC charging of the conductive charging system and the interface requirements for the AC charging device in the current main technical standards for EVs are shown in the following table. Among them, the standards of the IEC 61851 series are formulated by the IEC organization. It is the earliest charging system standard in the world and has important reference significance for the formulation of charging system standards in other countries.

Table2: Standard of main conductive charging systems for EV

Main Standard Technology category	IECStandard	ENStandard	SAEStandard	GB/TStandard
General requirements forconduction charging systems	IEC 61851-1	EN 61851-1	/	GB/T 18487.1
AC charging device interfacerequirements	IEC 61296-2	EN 61296-2	SAE J1772	GB/T 20234.2

Considering the applicability of the charging device, it is recommended that each region select an appropriate reference standard according to the EV interface situation in each region. And under the premise of meeting the requirements of marine electrical equipment for use on board [8], the product inspection requirements to be considered for AC charging piles installed on board for EVs should be formulated from four aspects: functional requirements, interface requirements, environmental adaptability and electrical design:

(1) The functional requirements shall at least include the functions of continuous monitoring of the continuity of the protective grounding conductor, confirmation of the correct connection between the EVs and the power supply equipment, control of the power supply, control of the power

failure, and monitoring of the charging current.
(2) The interface requirements should at least include: rated voltage/current value of the charging interface, electrical parameters and function definitions of the contacts, layout of the contacts, size of the interface, service life, mechanical strength, etc.
(3) The electrical design requirements shall at least include requirements for protection against electric shock, requirements for grounding measures, requirements for electrical protection grade, requirements for insulation resistance and dielectric strength, requirements for creepage distance and electrical clearance, etc.;
(4) Environmental adaptability should include at least the requirements of corrosion resistance and rust resistance,requirements of heat resistance and flame resistance, and requirements ofaging resistance, etc.

4 Fire risk analysis of EV charging on board

Considering the potential fire risk of EV charging on board, based on the analysis of the causes of EV charging fire in Chapter 2 of this paper, the accident tree method is used to sort out and analyze the reasons that may lead to the risk of EV charging fire on boardfrom the perspective of the fire in the entire EV carrying space.

Table 3 Basic Events

Symbol	Basic Events
X1	The charging device is submerged in water
X2	Ship power grid fluctuates greatly
X3	Aging charging equipment
X4	Manufacturing problems with the battery itself
X5	Overdischarge
X6	Inconsistent battery
X7	Charge to full state
X8	Communication failure between the charging device and the BMS
X9	BMS system failure
X10	EV lashing failure
X11	Hit hard object
X12	Failure of Ambient Temperature Control
X13	Heat source in the premises
X14	EVs without thermal isolation
X15	Ineffective fire strategy
X16	Failed or untimely fire detection

A fire in the carriage compartment is considered an overhead event. Taking the top event as the main analysis object, the accident tree analysis is carried out layer by layer. The reasons why EVs charging on board could cause a fire and cause the fire to spread can be found. Considering that the whole cabin fire must meet the two key elements of single vehicle fire and fire spread, it can be analyzed from these two perspectives. Through macroscopic analysis of the root cause of the battery charging fire accident, the accident tree is constructed as shown in Figure 6, and the following basic events are finally obtained, which are listed in Table 3.
Simplifying the accident tree using Boolean algebra, it can be obtained:
T=A1*A2=(A3+A4+A5)*(X14*A11)=((X1+X2+X3)+

(X4+A6+A7)+X12*X13)*(X14*(X15+X16))
=((X1+X2+X3)+(X4+(X5+A8)+(X10*X11))+X12*X13)*(X14*(X15+X16))
=((X1+X2+X3)+(X4+(X5+(A9+A10))+(X10*X11))+X12*X13)*(X14*(X15+X16))
=((X1+X2+X3)+(X4+(X5+(X6*X7+(X8+X9)))+(X10*X11))+X12*X13)*(X14*(X15+X16))
=(X1+X2+X3+X4+X5+X6*X7+X8+X9+X10*X11+X12*X13) *X14*(X15+X16))
=((X1+X2+X3+X4+X5+X8+X9)+(X6*X7+X10*X11+X12*X13))*X14*(X15+X16))

If the overhead event is broken down into minimum cuts, there are 20 ways to cause a car cabin fire (minimum cuts). According to the symmetry of the paradigm, the structural importance coefficients of all basic events are calculated directly by the definition of the structural importance coefficients.

$$I_{\varnothing}(i)=\sum[\varnothing(1,x_i)-\varnothing(0,x_i)]/2^{n-1} \tag{1}$$

Among the 16 basic events, there are 2^{16} combinations of 2 states, Xi is the object of change, and there are 2^{15} control groups whose other events remain unchanged. $\sum[\varnothing(1,x_i)-\varnothing(0,x_i)]$ represents the number of times the top event changes due to changes in Xi in these 2^{15} states. Therefore:

$I_{X14}=(2^{13}-3*2^2+3)*(2^2-1)/2^{15}=0.749$

$I_{X15}=I_{X16}=(2^{13}-3*2^2+3)/2^{15}=0.250$

$I_{X1}=I_{X2}=I_{X3}=I_{X4}=I_{X5}=I_{X8}=I_{X9}=(2^2-1)*(2^2-1)*(2^2-1)*(2^2-1)/2^{15}=0.0024$

$I_{X6}=I_{X7}=I_{X10}=I_{X11}=I_{X12}=I_{X13}=(2^2-1)*(2^2-1)*(2^2-1)/2^{15}=0.0008$

According to the calculation results, it is compared: $I_{X14}>I_{X15}=I_{X16}>I_{X1}=I_{X2}=I_{X3}=I_{X4}=I_{X5}=I_{X8}=I_{X9}>I_{X6}=I_{X7}=I_{X10}=I_{X11}=I_{X12}=I_{X13}$, The importance of lithium-ion battery fire accidents corresponding to each basic event decreases accordingly.

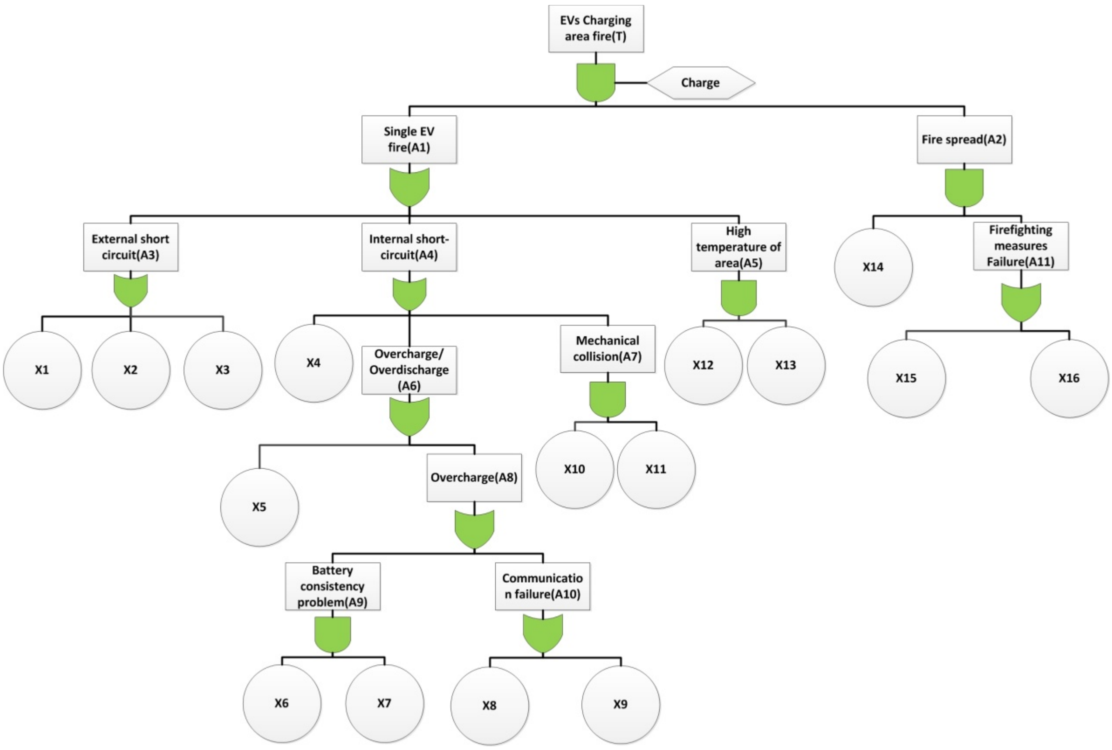

Figure6: Accident tree of EVs fire risk on board for charging

The structural importance of the basic events indicates that thermal isolation between vehicles is most important when a fire occurs. Research should be carried out on the distance between vehicles and the increase of measures to prevent heat radiation. At the same time, fire control strategies and timely fire detection are also very important. Only by formulating appropriate fire fighting strategies and realizing the judgment at the very early stage of battery thermal runaway can lithium battery fires be better extinguished and the spread of EV fires prevented. For EVs charged on board, the following methods can be considered to realize the extremely early judgment of battery thermal runaway and the linkage with fire protection:

.1 Lithium-ion battery thermal runaway electrical signal, temperature signal change threshold should be set. The electrical signal, temperature signal and other information transmitted by the BMS are collected in real time through the charging device.When they reach the threshold, alarm in the manned space of the ship to realize extremely early judgment of thermal runaway;

.2 After the thermal runaway of the lithium battery occurs, a large amount of gas will be produced and ejected through the pressure relief valve. By setting up a multi-gas detection device (including at least three gases of CO, H_2 and CO_2[]) at the vehicle premises, it is possible to detect the gas generated by the thermal runaway and issue an alarm before the thermal runaway of the lithium-ion battery catches fire, so as to realize the extremely early stage of thermal runaway judgement;

.3 When all of the above alarms appear, immediately stop all non-explosion-proof electrical equipment in the space, and issue a fire start prompt in the manned space. After confirmation, start the fire-fighting equipment directly.

In addition, based on the strategies already put forward in the existing IMO guidelines and the rules of IACS member classification societies, the following precautionary suggestions are put forward for the risks that may cause a single-volume EV to be charged and ignited on board:

Table 4 Precautionary suggestions

Symbol	Basic Events	Precautionary suggestions
X1	The charging device is submerged in water	Specifies the degree of protection of charging equipment
X2	Ship power grid fluctuates greatly	The ship power station itself has the ability to stabilize
X3	Aging charging equipment	Require ships to regularly check charging equipment
X4	Manufacturing problems with the battery itself	Check the inspection certificate of the EV on board
X5	Overdischarge	Vehicles with too low SOC are not allowed on board
X6	Inconsistent battery	It is not allowed to be charged to a fully charged state on board, and the maximum SOC is 80%.
X7	Charge to full state	
X8	Communication failure between the charging device and the BMS	The charging device is required to have the function of stopping charging immediately in the event of a communication failure
X9	BMS system failure	
X10	EV lashing failure	Refer to the ship's existing lashing requirements
X11	Hit hard object	Hard objects are not allowed in the premises
X12	Failure of Ambient Temperature Control	Set the temperature adjustment device to keep the temperature in the cabin stable at 25°C±5°C
X13	Heat source in the premises	No heat source is allowed within the vehicle premises

5 Summary and recommendations

This paper analyzes the causes of battery fires caused by EV charging, based on incomplete statistics of EV fire accidents in China in the past two years.By sorting out the current requirements of the International Maritime Organization (IMO) and the world's major classification societies for the on-board charging of EVs, the research progress of the current marine industry on the on-board charging of EVs is analyzed.And by sorting out the main technical standards for EV charging, the product inspection requirements that need to be considered for EV charging on board are proposed.On this basis, the accident tree analysis method is used to analyze the factors that may lead to the fire of EVs on board for charging, and the measures are proposed. It provides a reference for the formulation of EV on-board charging specifications.

The research in this paper is still shallow, and in-depth research can be considered in the future based on the following questions:

.1 The most appropriate distance between the EVs charged on board is what, and whether it is necessary to add measures to prevent heat radiation on the basis of the separation distance;

.2 How to set the alarm threshold of EV thermal runaway in the very early stage and the concentration parameter of gas detection alarm;

.3 What kind of fire fighting strategy is adopted for the fire of EV charging.

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