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Safety Risks and Countermeasures of Lithium-ion Battery Energy Storage Power Station

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Abstract: With the continuous emergence of new energy storage technology innovation in the field of electrochemical energy storage in China, different megawatt-grade lithium-ion battery energy storage projects have been implemented, promoting the high-quality development of the energy storage industry. In the context of vigorously promoting the energy consumption revolution and enhancing the green transformation and development momentum, strengthening the safety construction of lithium-ion battery energy storage is of great importance to realize the transformation of energy structure and improve the utilization efficiency of renewable energy. However, in recent years, frequent safety accidents of lithium-ion battery energy storage power stations, such as fires, have aroused the public's high attention to the construction of lithium-ion battery energy storage power stations, affecting the large-scale development of energy storage power stations. Based on this, this paper analyzes the safety risks of lithium-ion battery energy storage power stations and focuses on how to improve their safety performance.

Keywords: Lithium-ion battery energy storage power station; Safety risk; Apply policy

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1. Information

The biggest challenge facing the world in the 21st century is the crisis of energy supply shortage and environmental pollution. To achieve the "two-carbon" strategic goal of "carbon peak" and "carbon neutrality," China urgently needs to promote the energy consumption revolution and provide strong momentum for green development by reducing the use of fossil energy and developing clean energy [1]. Under the influence of weather, season, and geographical environment, there are many problems in the process of using solar and wind energy to generate electricity, such as discontinuous and uncontrollable power supply. The large-scale electrochemical energy storage system shows strong advantages, which provides a new energy storage technology for the transformation of China's energy structure. Among them, lithium-ion batteries occupy an important position in the field of electrochemical energy storage. Therefore, strengthening the safe construction and management of lithium-ion battery energy storage power stations can effectively promote the high-quality development of China's energy strategy.

2. Lithium-ion battery energy storage power station safety risk analysis

2.1. Fire risk

A fire accident at the Aricell lithium battery factory in Republic of Korea in June 2024 killed more than 20 people. The incident was not unique, and the safety of lithium batteries has long been a global issue. For example, in the middle of May of the same year, the Gateway energy storage power station in the United States broke out in a fire. The fire fully exposed the shortcomings of lithium batteries, which are flammable and difficult to extinguish, reignited at least twice, and the burning time lasted for six days. The Gateway energy storage power station is one of the world's largest lithium-ion battery energy storage projects [2]. For example, back in August 2023. A fire broke out in a lithium-ion battery storage container in the Barban region of France, but the gas extinguishing agent in its internal device worked, and the fire did not cause serious casualties. These accidents caused a more serious public opinion, so that the public once again reviewed the safety standards and protective measures of lithium battery operations.

Lithium has a strong charge storage capacity and is a relatively ideal battery manufacturing metal. However, due to complex chemical reactions, lithium batteries are highly flammable. Heat, extrusion, and other conditions can induce a short circuit inside the lithium battery, which triggers a series of chain reactions. This is mainly because lithium batteries have a high energy density, which can store a lot of energy in a small volume. Once a lithium battery encounters an accident, its stored energy will burst out in a short period, resulting in a sharp increase in the combustion rate. The above fire accidents show that lithium-ion battery energy storage contains huge safety risks.

2.2. Gas production risk

In January 2025, the so-called world's largest lithium-ion battery energy storage power plant in California exploded. The explosion not only triggered a fire, but also released a large number of toxic gases, such as colorless but deadly hydrofluoride, fluoride, hydrocyanic acid, and so on. These toxic gases can corrode the eyes and skin, block the respiratory tract, seriously threaten the safety of public safety, and aggravate air pollution. In recent years, frequent lithium battery safety accidents and toxic gas leakage accidents as high as 70%, fully exposed the lithium-ion battery energy storage industry to high-speed expansion and safety management lag between the sharp contradiction. The cause of lithium-ion battery gas production lies in the trace water and positive and negative electrode materials in the electrolyte. These internal materials undergo exothermic chemical reactions when exposed to high temperatures, and produce flammable gases such as hydrogen and methane, as well as toxic gases such as carbon monoxide and dioxins. The pressure inside the lithium battery will continue to rise with the accumulation of these gases. Once the pressure limit is reached, the combustible gas and toxic gas will break through the safety valve of the battery and be released to form an explosion. If these gases react with an open flame to cause an explosion, it will further expand the scope of the accident, seriously threaten human life and health, and aggravate environmental pollution.

2.3. Waste battery recycling

The service life of energy storage batteries is mostly 3 to 5 years, which contains 10 to 100 times more energy metals than natural ores, and has a high recycling value. Waste batteries contain lithium, cobalt, nickel, fluorine, copper, aluminum, and other components; without proper disposal of waste batteries will not only cause the waste of metal resources but also destroy the social environment, and bring safety risks to human health.

However, the data show that by the end of 2023, the standardized recovery rate of power batteries in the field of new energy vehicles in China is less than 25%, and most of the used batteries flow to non-compliant "gray areas." Upstream unqualified black factories will violently break down the used power batteries after recycling them, and turn to reselling the used batteries to small workshops downstream. Downstream businesses will sell the assembled waste batteries to ordinary consumers. After decommissioning, energy storage batteries with a battery capacity of 50–80% can be used in echelon utilization scenarios, such as emergency power supply, energy storage equipment, etc. If the battery capacity is reduced to 40–50%, the metal can be recovered through hydrometallurgy and other methods. Illegal recycling of used batteries will exacerbate social chaos, transmit new governance problems to society, and affect public safety.

3. Coping strategies

At present, lithium-ion battery energy storage power stations have a high incidence of safety accidents, which has aroused great attention from all walks of life. Many universities and enterprises have been keenly aware of this problem and actively participate in the exploration of safety risks and coping strategies of lithium-ion battery energy storage power stations. Based on this, this paper carries out an in-depth analysis and system summary from four dimensions, namely accurate control of thermal runaway throughout the cycle, intelligent early warning of fire, fire suppression measures of energy storage power station, and comprehensive improvement of the fire protection system, as shown in **Figure 1**.

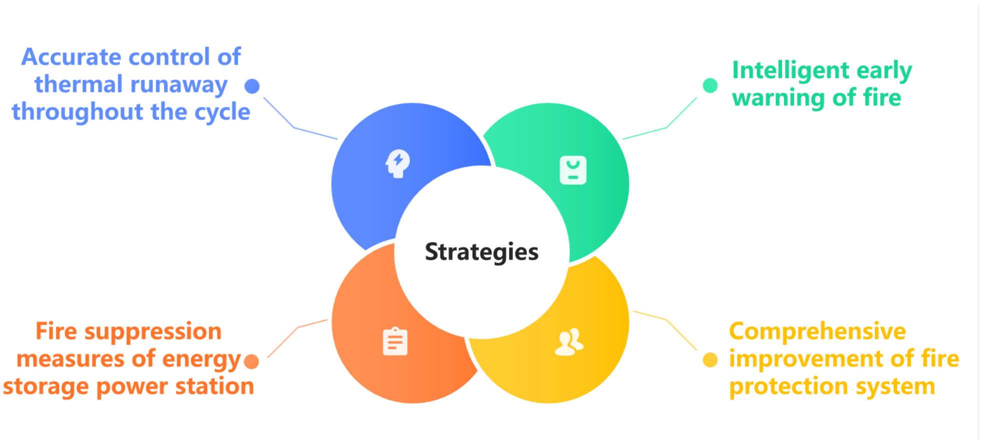

Figure 1. Safety response strategy of lithium-ion battery energy storage power station

3.1. Lithium-ion battery thermal runaway prevention measures

Fire is the main problem to be faced in the construction of lithium-ion battery energy storage power stations. Under normal circumstances, the thermal runaway of lithium-ion batteries is the key reason for inducing fire accidents in electrochemical energy storage projects. The lithium battery module in the electrochemical energy storage system is composed of single battery series, parallel, series-parallel, and other connection methods, so once a single battery thermal runaway occurs, the heat released will spread to the battery module, failing the entire energy storage system. At the same time, after the occurrence of thermal runaway, the lithium battery will release a large number of hydrogen, carbon monoxide, and other flammable gases, as well as olefin, alkane gas, etc., increasing the risk of fire and explosion accidents. Therefore, given the problem of lithium battery thermal runaway, this paper discusses the strengthening of the safety management of lithium-ion battery energy storage power stations from three aspects: the early stage of thermal runaway, the stage of thermal runaway, and the late stage of thermal runaway.

3.1.1. Initial stage of thermal runaway

The prevention and control work of lithium-ion battery energy storage stations is mainly focused on the early detection and warning of thermal runaway, that is, the early warning technology based on the battery management system and gas detection. Inserting thermal runaway early warning technology into the battery management system can realize real-time monitoring of battery voltage, current, battery surface temperature, and other signals, and promote their organic linkage with the fire protection system. In this way, once the fire protection system sends out the fire alarm signal, the battery management system can react quickly and cut off the circuit in time, to effectively implement the safety management principle of "power off first, fire extinguisher, and continuous suppression." Gas detection and early warning technology has an obvious advantage, even in the case of the battery management system failing to respond, it can provide 15 minutes in advance of the lithium battery being about to occur completely out of control early warning, leaving enough emergency disposal time.

3.1.2. Thermal runaway stage

In this stage, the key control strategies are to suppress thermal runaway, prevent the thermal spread of fire, and adopt effective extinguishing agents and fire-fighting strategies.

The common fire extinguishing agent to prevent fire thermal diffusion is perfluorhexanone, which is often used to install in the fire warning module and fire extinguishing system and can make the fire point release several capacities of fire extinguishing agent, to achieve long-term and effective control of the internal temperature of the battery module, to reduce the number of refires. The fire warning module and fire extinguishing system equipped with perfluorhexanone have been widely used in practice, such as the Three Gorges New Energy Wulanqab source network load storage demonstration project. In the early stage of a thermal runaway accident, a perfluorhexanone fire extinguishing agent can be used first, and then water mist can be used to continuously cool down the fire site. A large number of tests show that the intermittent release of perfluorhexanone by high-pressure water mist can effectively deal with lithium battery fires. When the thermal runaway of the lithium battery completely occurs, the fire probe can be softened and blasted according to the fireplace, and the perfluorhexanone can be released through its rupture, which can realize point-to-point accurate fire extinguishing.

In addition, liquid nitrogen can be used to extinguish the fire caused by the accumulation of combustible gas and the explosion of a lithium battery. The liquid nitrogen after gasification can block oxygen.

3.1.3. The later stage of thermal runaway

To prevent detonation and explosion caused by thermal diffusion, the prevention and control work in the later stage of thermal runaway focuses on the treatment of combustible gas accumulated in the emission space. In this regard, mechanical ventilation systems can be installed in lithium-ion battery energy storage power stations, explosion-proof fans can be arranged. The ventilation device not only needs to be equipped with an independent control system, but also needs to be designed in tandem with the automatic fire alarm system. When the concentration of combustible gas is higher than 25%, the automatic control system will start the ventilation function.

3.2. Lithium-ion battery fire early warning technology

The fire early warning technology can identify the abnormal situation by collecting, monitoring, and analyzing the status, temperature, gas concentration, and other parameters of the lithium battery, and issue a warning to the management personnel. With the comprehensive arrival of the era of artificial intelligence, deep learning, intelligent robots and other methods provide more exploration directions for the innovative development of lithium-ion battery fire early warning technology, promote the digital and intelligent development of safety management of lithium-ion battery energy storage power stations, and have important practical value for improving the reliability and accuracy of fire warning. Specifically, the intelligent technology can pass current, voltage, environmental humidity, and other information to the processor through wireless communication, and then estimate the status of the battery on this basis. For example, Zhu *et al*. used relaxation voltage as a capacity characteristic and estimated the remaining capacity of lithium-ion batteries through a variety of machine-learning methods [3]. Niu *et al*. proposed a battery capacity estimation method based on Lebesgue sampling and machine learning [4], replaced the battery model with deep belief networks (DBN) and particle filter (PF), and realized fault diagnosis and prognosis (FDP). The organic integration of artificial intelligence technology and lithium-ion battery fire early warning technology further improves the degree of digital intelligence of real-time monitoring and intelligent warning of lithium-ion battery energy storage power stations, and can effectively promote the integrated development of remote control (**Figure 2**).

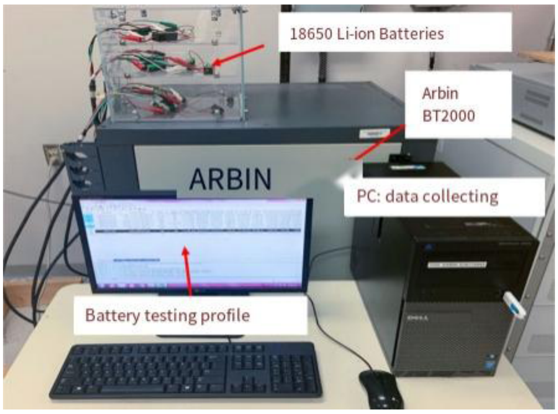

Figure 2. Lithium-ion battery test experiment through a deep belief network

3.3. The suppression methods of fires in lithium-ion battery energy storage power stations

3.3.1. Optimize battery materials

Improving the safety performance of lithium-ion batteries can fundamentally improve their safe operation coefficient and reduce the safety risks of energy storage power stations. The electrolyte has a significant correlation with the response characteristics. In the thermal runaway process, the electrolyte participates in the oxidation of the entire battery, resulting in the generation of considerable heat and even the runaway reaction. Therefore, it is necessary to obtain a safer electrolyte through modification. For example, Wu *et al.* studied the use of tri (2,2,2-trifluoroethyl) phosphite (TTFP), an important flame retardant (FR) additive, to inhibit fire and even explosion in lithium-ion batteries and maintain typical battery performance [5]. In terms of positive and negative electrode material modification, researchers usually adopt strategies such as surface coating and structural optimization. For example, according to Kim *et al.*, a composite insulating film consisting of stripped SnSe (tin selenide) and mesoporous silica bonded by Zn ion gelation makes it a promising candidate for improving the safety and reliability of LIBS [6]. The electrochemical stability of lithium-ion battery cycles can be effectively improved by incorporating boron gradients into $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ primary particles and applying *in situ* construction (**Figure 3**).

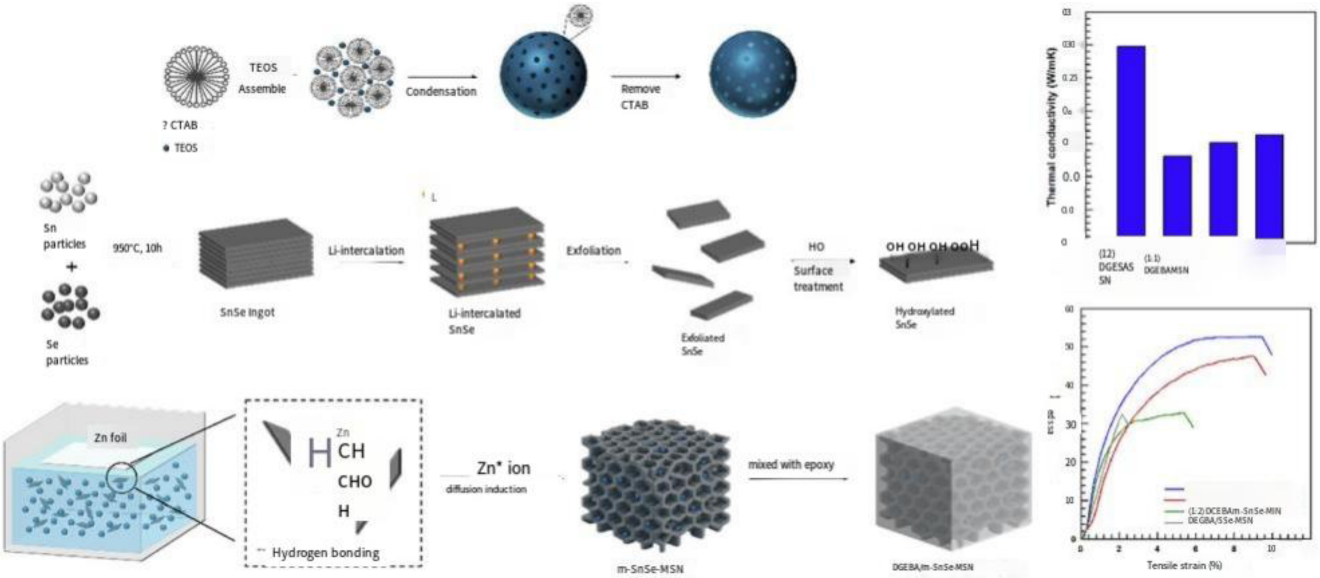

Figure 3. Schematic diagram of the synthesis of high-temperature resistant tin selenide/mesoporous silicon dioxide (SnSe/MSN) films for preventing thermal runaway of Li-ion batteries.

3.3.2. Optimize the thermal management system

The core component of the lithium-ion battery energy storage power station is the battery pack, and the key factor affecting the performance of the battery is the temperature difference between the monomer and its surface. Excessive temperature of the battery will not only reduce its performance, but also increase the risk of thermal runaway. The best working temperature of a lithium-ion battery should be maintained at 25–50°C, and the temperature difference of the single surface should be less than or equal to 5°C. In this regard, the introduction of battery thermal management technology can make the battery temperature and the temperature difference between batteries controlled within a reasonable range. With the continuous progress of battery thermal management technology, submerged coolant has achieved large-scale application in lithium-ion battery energy storage power stations, showing a superior cooling and temperature equalization effect, which can further reduce the temperature difference between batteries and control it within 3°C. In addition, through the development of an intelligent temperature control strategy, according to the real-time temperature of the battery, charging and discharging state, and other parameters, dynamically adjust the power of the heat dissipation equipment. Intelligent algorithms such as fuzzy control and neural networks are used to ensure that the battery module is in the best temperature range, improve temperature uniformity, reduce power consumption, and effectively inhibit the fire risk caused by thermal runaway.

3.4. Fire protection improvement strategy for lithium-ion battery energy storage power station

The use of big data analysis technology to intelligently analyze the safety accident report of lithium-ion battery energy storage power stations can provide targeted suggestions for fire rescue. For example, the toxic gas volume gathering causes the internal pressure of the power station to be greater than the external pressure, which leads to an explosion when the hatch door is opened [7]. Therefore, fire personnel can carry out real-time monitoring of the accident site through an intelligent monitoring system and be equipped with anti-gas suits in advance to detect the concentration of toxic gases in the confined space. At the same time, the lithium-ion battery energy storage power station can rely on the Internet of Things and smart fire technology to build a communication-linked environmental monitoring system, computer monitoring system, etc., to achieve remote control of fire prevention and control. It is very important to set up a micro-fire station in the lithium-ion battery energy storage power station, which can effectively inhibit the spread of fire before the arrival of the urban fire control force.

4. Conclusion

Ensuring the safe operation of lithium-ion battery energy storage power stations plays an important role in realizing the smooth transformation of energy structure and improving the safety level of electrochemical energy storage power stations. To this end, in addition to preventing lithium-ion battery thermal runaway, studying early fire warning technology, identifying fire suppression methods, strengthening fire safety construction and other measures, the country also needs to further improve the management system of lithium-ion battery energy storage power station from the strategic level, standardize its safety standards, and reserve high-quality professional skills for the energy storage industry. At the same time, relying on sensor technology and data analysis algorithms to develop new safety technologies for energy storage power stations and establish a sound safety early warning system and fire safety emergency mechanism can fundamentally improve the anti-risk level of lithium-ion battery energy storage power stations.

In this paper, various safety risks of lithium-ion battery energy storage power stations are analyzed, and various preventive measures to deal with fire and explosion accidents of lithium battery energy storage power stations are summarized. At this stage, for the fire characteristics of a single battery and its modules, a more scientific and comprehensive research system has been formed at home and abroad. In the future, in-depth research on lithium battery clusters and energy storage systems is needed to further improve the applicability, economy, and feasibility of safety prevention and control of lithium-ion battery energy storage power stations.

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Disclosure statement

The authors declare no conflict of interest.

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