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Electrochemical Energy Storage Power Station Safety Risk Analysis and Prevention Strategies

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Abstract

Under the guidance of the two carbon emission reduction goals of carbon peak and carbon neutralization, the installed capacity of China 's electrochemical energy storage power stations is constantly expanding, but its associated safety problems are posing severe challenges. In recent years, the fire and explosion accidents of electrochemical energy storage power stations have continued, and the safety problems of energy storage power stations have attracted much attention. In order to strengthen the safety protection of the whole life cycle of electrochemical energy storage power station, this paper reviews the development status of electrochemical energy storage from the perspective of industry and policy, and systematically summarizes the four main risk factors faced by energy storage system: thermal runaway of energy storage battery, electric shock caused by electrical equipment, natural environment under extreme conditions and misoperation caused by staff. Then, the main reasons for these risk factors are analyzed comprehensively: electrochemical energy storage has shortcomings in safety policy, enterprise management, safety technology and industrial ecology. Finally, based on the analysis of the development status, risk factors and causes, this paper proposes a four-layer protection route to strengthen the risk prevention and control of the whole life cycle of the electrochemical energy storage power station. The first layer is the intrinsic safety protection layer, the second layer is the system emergency protection layer, the third layer is the intelligent control protection layer, and the fourth layer is the safety toughness protection layer. These four-layer safety protection routes have certain reference significance for improving the safety of the electrochemical energy storage power station.

Keywords

Energy Storage Power Station; Full Life Cycle; Risk Factors; Safety Protection.

1. Introduction

Under the background of the double carbon strategic goal, new energy storage is playing an increasingly critical role as an important supporting technology for building a new power system[1]. Compared with pumped storage,new energy storage has the advantages of fast response speed, high regulation accuracy and short construction period. It is of great strategic significance to promote the large-scale development of renewable energy and achieve the goal of carbon peak and carbon neutrality[2]. The main energy storage technologies in new energy storage include electrochemical energy storage, mechanical energy storage, and electromagnetic energy storage. Among them, electrochemical energy storage is one of the most widely used energy storage technologies. According to the China Energy Storage Alliance, by the end of 2024, the cumulative installed capacity of new energy storage in China exceeded that of pumped storage for the first time, reaching 78.3 GW. Among them,lithium-ion batteries dominate the new energy storage with 97.1% installed capacity.

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Electrochemical energy storage is to convert the chemical energy generated by chemical reactions into electrical energy for storage,including lithium-ion batteries, lead-acid batteries,and flow batteries,among which lithium batteries are widely used[3,4]. With the rapid development of electrochemical energy storage power stations, there are also some problems,among which the thermal runaway of lithium batteries cannot be ignored. Thermal runaway is a phenomenon of chain reaction inside the battery caused by various incentives. The reaction will heat up and cause temperature to rise and produce various harmful gases. Further increase in temperature may lead to more failures or explosions[5]. With the frequent accidents of energy storage power stations,the safety of energy storage power stations has become a core challenge restricting the development of the industry. Fang Laihua[6] analyzed the safety situation of energy storage,and put forward safety risk prevention and control suggestions for energy storage system from intrinsic safety,active and passive safety. Yang[7] proposed the active safety system architecture of electrochemical energy storage power station,and set up three safety defense lines to realize the active protection of energy storage system. Ma[8] proposed emergency countermeasures for fire fighting and rescue in view of the fire risk of electrochemical energy storage power station. Li[9] analyzed the risk points of electrochemical energy storage power station,and put forward countermeasures in fire protection, policy and technology of energy storage power station. Although the above literature expounds the risk problems and prevention and control measures of energy storage power stations, it does not form a safety prevention and control strategy for the whole life cycle of electrochemical energy storage power stations from the aspects of power station manufacturing materials,operation management and ecological coordination.This paper will deeply analyze the development status, risk factors and causes of electrochemical energy storage. Finally, a four-layer risk prevention and control system is proposed from the aspects of manufacturing process,protection technology, power station management, enterprise side and government side, and the coping strategies and suggestions of energy storage power station are given to ensure the safe development of electrochemical energy storage power station.

2. Analysis of the Causes of Risks Faced by Electrochemical Energy Storage Power Station

As an important part of the new energy field, the safe operation of electrochemical energy storage power station is very important to ensure the stability and reliability of energy supply. The risk factors and main reasons are shown in Fig.1.

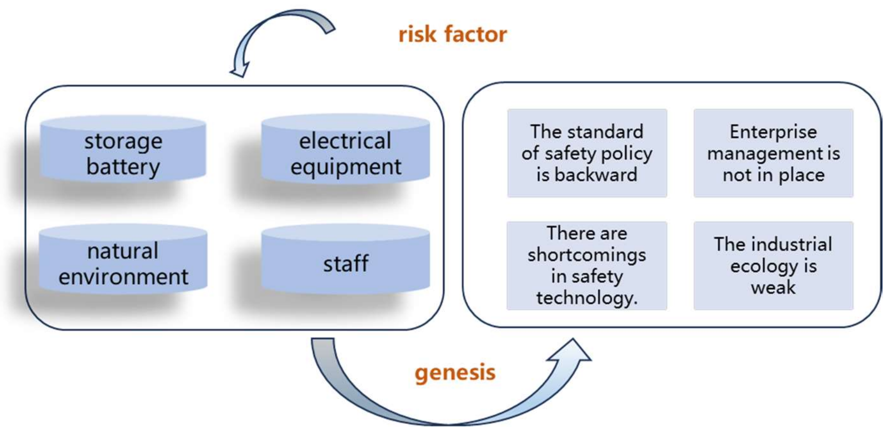

Fig. 1 The main risks and causes of energy storage power station

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2.1. Backward Security Policy Standards

At present, there are some problems in the relevant standards and specifications of electrochemical energy storage, such as lagging technical standards and insufficient supervision. The rapid development of electrochemical energy storage technology makes most of the current standards and specifications not suitable for new energy storage products, which requires new policy standards to support. There is a lack of clear technical requirements and testing standards for safety measures such as thermal management, fire and explosion prevention for different types of energy storage batteries [10].Although the five departments jointly issued the notice on strengthening the safety management of electrochemical energy storage, in the actual implementation, the information sharing and work linkage between departments are not smooth enough, and there are problems of blind spots in supervision and poor coordination. The whole industry chain of electrochemical energy storage involves a wide range and complex process, and the safety prevention and control management standard system of its whole life cycle is still in its infancy. This makes some energy storage projects have potential safety hazards. Once an accident occurs, it may cause serious consequences.

2.2. Weak Enterprise Management

The energy storage power station accidents caused by human factors are manifested as insufficient personnel skills and operational errors.In the final analysis, the energy storage safety management system of some energy storage power station management enterprises is relatively backward, and the internal operation system or procedure is not perfect. Most enterprises pay more attention to efficiency and despise safety in the management of energy storage power stations,resulting in insufficient safety awareness of operators,resulting in fluke psychology,no isolation measures during operation, no protection,and easy to cause accidents in the long run.At the same time,the operation training for employees is only a formality,and does not focus on improving the actual operation level of employees.Due to the lack of personnel skills,it is not found in time when safety hazards occur,and it cannot respond in time when an accident occurs. Failure to clearly divide individual responsibilities and establish a sound assessment system is also one of the causes of man-made accidents. Fuzzy responsibilities, less reward and punishment measures,and only punishing personnel without correcting wrong operations may lead to repeated accidents.

2.3. Backward Security Technology

The low maturity of the intrinsic safety technology of the battery, the lack of early warning accuracy, and the lack of effective measures to control fire accidents are the problems faced by the electrochemical energy storage power station in safety technology. At present,there are many problems in battery materials, such as interface reaction, lithium dendrite growth, flammable separator and poor thermal stability during operation. The system process and temperature control system design technology of the battery also need to be broken through[11]. For the early warning of energy storage power station,it is difficult to meet the complex practical requirements by using a single signal monitoring,and it is also difficult to achieve early detection and early warning before battery fire. The hierarchical early warning mechanism adopted is in the development stage and is not yet mature. The fire type of lithium battery is complex and the combustion is violent.After extinguishing the open fire,chemical reaction still occurs inside the battery, which is very easy to re-ignite and cause secondary fire[12]. For lithium battery fire extinguishing, there is no targeted fire extinguishing material to prevent reburning,which is basically realized in two ways:suffocation and heat absorption.Water mist fire extinguishing is now recognized as the best measure for cooling effect,but the watered-out battery cannot be used again [13].

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2.4. Weak Industrial Ecology

Electrochemical energy storage technology is diversified,the maturity of various industries is different, and China 's key materials rely more on imports,lack of coordination in some regions, vicious competition,and lack of innovative talents in the industry. Electrochemical energy storageIn addition to lithium-ion batteries,sodium-ion batteries,all-vanadium redox flow batteries and other technologies are facing various problems such as energy density,cycle life and high cost. Technological changes have led to increased investment risks, and power-side investment costs are difficult to recover[2]. Although there are many key materials in the upstream of China 's industrial chain,such as domestic lithium reserves,there are few high-quality lithium resources available for mining.The supply of upstream raw materials is insufficient, and it relies on foreign resources. There is vicious competition and blind investment among mining enterprises.Inferior batteries flow into the market through low prices, increasing safety risks. China 's existing energy storage talents have a pyramid structure, lack of top-level high-end talents, shortage of innovative talents with interdisciplinary background,and insufficient collaborative innovation kinetic energy in the upstream and downstream of the industrial chain.Talents have become the biggest weakness restricting industrial development and upgrading.At the same time, electrochemical energy storage involves many disciplines such as chemistry,electricity, and machinery, and requires multidisciplinary practical and compound talents. If the operation and maintenance personnel lack understanding of energy storage technology, it will also increase the safety risk of the power station.

3. Four-layer System and Countermeasures for Safety Prevention and Control of Energy Storage Power Station

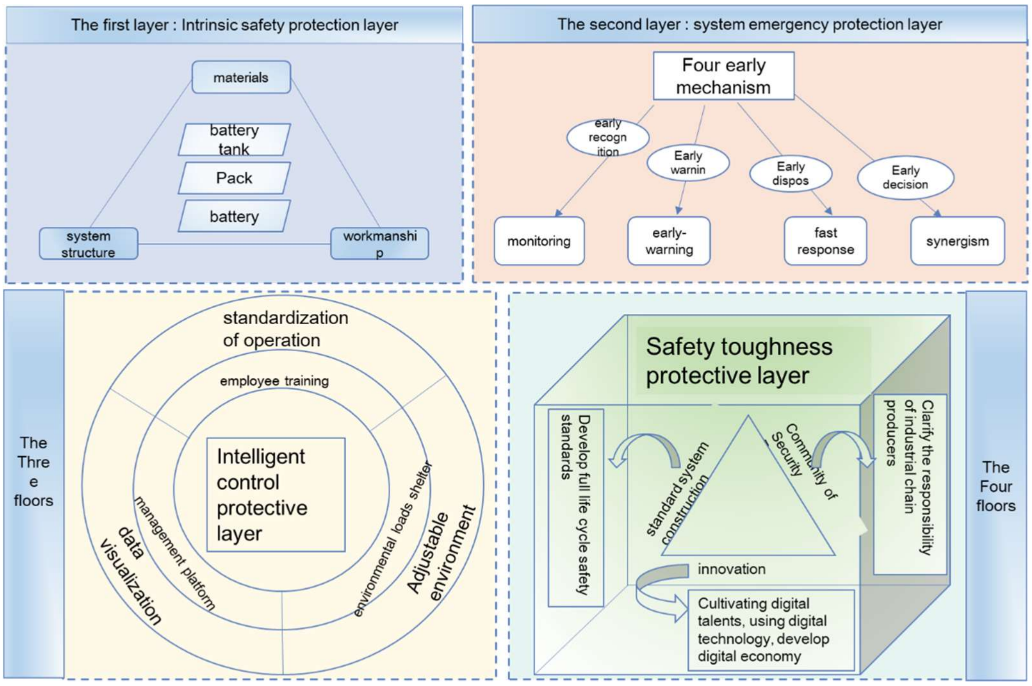

Fig. 2 Safety prevention and control system of energy storage power station

In the whole life cycle of energy storage power station from planning and construction to operation and retirement,there are many units, such as battery manufacturers,system integrators, construction units,operation and maintenance management units,inspection and supervision departments and personnel. No matter which subject or operation stage has security risks, it may lead to accidents in the next link.In the whole life cycle of electrochemical energy storage power station,the policy management system is not perfect, the core technical ability is short, and the industrial ecology is weak. In order to ensure the safe and stable operation of electrochemical energy storage power station,it is necessary to improve the safety level of electrochemical energy storage power station,accurately identify potential risk sources and prevent accidents.Combined with the analysis of the previous chapters, the key problems currently facing can be obtained.In order to ensure the safe and sustainable development of electrochemical energy storage power stations, it is urgent to build a risk prevention and control system covering the whole cycle. Therefore, this paper proposes a four-layer progressive full-cycle safety prevention and control system for electrochemical energy storage power stations. As shown in Fig. 2, the full-cycle safety prevention and control system of electrochemical energy storage power station is divided into four layers. The first layer is the intrinsic safety protection layer, the second layer is the system emergency protection layer, the third layer is the intelligent control protection layer,and the fourth layer is the safety toughness protection layer.

3.1. Intrinsic Safety Protection Layer

The first layer of defense is the intrinsic safety protection layer,which prevents accidents from energy storage materials,system structure and manufacturing process. Intrinsic safety refers to the safety of the body,reducing the probability of accidents from the source.The energy storage power station is divided into three levels:battery, module and battery cabin.The battery body includes positive and negative electrodes,separators, electrolytes and other materials.The module needs to connect the batteries in series and parallel to form a standardized unit. The energy storage cabin places various battery modules and other equipment.

(1) Energy storage materials

From the perspective of safety and innovation,batteries, modules and battery compartment materials need to adopt thermal stability, explosion-proof and other characteristic materials to construct the intrinsic safety protection of energy storage power stations and avoid fire accidents in electrochemical energy storage power stations. For the battery body material, the development of new battery materials such as nano-functional composite materials,the exploration of non-traditional materials to improve the electrical and mechanical properties of the separator,the improvement of the thermal stability of the electrode material, the use of non-combustible ionic liquids and electrolytes or the use of additives to improve the stability of the electrolyte, Zeng[14] pointed out that the thermal stability and low cost of germanium oxide-based,is expected to be used as an industrial anode material in the future;for the module level,high-performance materials are developed to improve the pressure resistance and insulation performance of the module materials,and thermal management system materials with high heat storage density and double heat absorption mechanism are used. For the energy storage cabin,a new type of fire-proof and explosion-proof material is used to make the energy storage cabin,so as to improve the fire resistance and explosion resistance of the cabin level,so that it will not break and spread to the surrounding cabin during long-term combustion. By improving energy storage materials to achieve intrinsic safety, it provides a material basis for building a multi-level security protection system.

(2) System structure

In the currently published accidents of electrochemical energy storage power stations, the fault of line contact point is one of the causes of fire accidents.In order to prevent accidents, it is necessary to strengthen the operation safety of energy storage power stations from the reasonable arrangement of power station wiring lines, battery structure and module cell placement.There are many equipment in energy storage power stations, most of which are connected by wire, so the line layout and crossing strategy are very important. A reasonable wiring form is designed to reduce the overlap between lines to meet the needs of convenient

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and reliable operation and maintenance. The module needs to integrate many batteries,install management systems and other components, and change the shape of the battery,the module and the internal placement of the module through structural innovation to improve the stability and safety of the system.For example, BYD 's blade battery improves the service life and energy density of the battery by changing the cell structure[15].In the design stage, the energy storage power station should fully consider the surrounding environment and the fire protection distance in the standard. Do not pile up a large number of combustible items during operation to avoid accidents.

(3) Manufacturing process

The battery is prone to defects such as pole burrs and separator micropores during the manufacturing process. These defects can easily cause internal short circuits in the battery and cause various chemical reactions, resulting in a gradual increase in the battery temperature, which ultimately triggers the thermal runaway of the battery. In the battery manufacturing process, safety agents or flame retardants are added to curb the occurrence of thermal runaway, and reliable manufacturing processes are used to reduce the defect rates such as battery pole burrs and diaphragm micropores. Before the battery leaves the factory, the control equipment is strictly tested, and the intelligent diagnosis method is used to detect the equipment body to reduce the risk of the battery during operation. At present, the preparation processes of separators include dry method, wet method and electrophoretic deposition method, and the physical and chemical properties of separators are closely related to their manufacturing processes[16,17]. In order to improve the physical and chemical properties of the separator, it is necessary to improve the existing production process or develop innovative processes to make the separator have ultra-high thermal stability and mechanical properties, so as to achieve high safety of the battery.

3.2. System Emergency Protection Layer

The second layer is the emergency protection layer of the system, which is the key link in the safety protection system of the electrochemical energy storage power station. It prevents the collapse of the electrochemical energy storage power station from the aspects of multi-monitoring of system status, early warning of key signals, rapid intervention in advance and rapid response after the event. On this protective layer, the ' four early ' mechanism of risk prevention and control of electrochemical energy storage power station is constructed, early identification, early warning, early disposal and early decision. Managers dynamically adjust and optimize the previous three mechanisms based on the historical database. After the first three mechanisms are adjusted, the fourth mechanism is improved according to the operation of the power station. The four early mechanisms are interrelated and mutually promoted to jointly ensure the safe operation of the electrochemical energy storage power station.

Electrochemical energy storage faults are mainly manifested as changes in voltage, current, temperature and gas release. Monitoring state variables such as surface temperature, voltage and current can realize system state detection and fault identification[18]. Therefore, real-time monitoring of the state of each component of the energy storage power station is very important to ensure the safety of the energy storage system. The high-sensitivity and high-precision monitoring system is studied, and the data evolution curves of various parameters of the energy storage system are simulated and analyzed by using big data, Internet of things and other technologies, so as to provide data support for the subsequent early warning and disposal methods. For example, Xia[19] selected voltage and temperature data to establish a feature data set to evaluate and predict the health status of the battery in the short term. Through BMS and various sensors, the key data such as voltage, current and temperature of each part of the energy storage system are monitored in real time, and multi-source data information is collected. Using mathematical model, equivalent circuit (ECM) model and other methods,

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combined with battery failure mechanism, specific failure causes such as internal short circuit of battery are taken as detection targets, so as to identify potential safety hazards and trigger early warning in the early stage, and improve the active safety protection ability of the system. The management platform will receive daily real-time monitoring data. According to the evolution mechanism of battery thermal runaway, based on the monitored multi-source data information, the energy storage power station early warning and fire multi-level response strategy are set. When the sensor signal reaches the set threshold, a specific action will be performed and an early warning signal will be issued in time. At this time, corresponding measures are quickly taken to deal with hazard sources for different early warning signals. For example, the system automatically starts the accident ventilation and hazard isolation program, disconnects the power supply, isolates the hazard source, and releases efficient fire extinguishing media to block the heat spread path and avoid casualties and property losses. The management platform maps the accident scene in real time, provides ' three-dimensional visualization ' disaster portraits for decision makers, assists decision makers in selecting the optimal path, and realizes human-machine collaborative decision-making.

3.3. Intelligent Control Protective Layer

The third layer of defense is the intelligent control protection layer, which manages the safe operation of the electrochemical energy storage power station from the aspects of operation constraints and personnel training, digital twin management platform, system construction and environmental protection. Personnel-equipment-environment is the three elements of safety management of electrochemical energy storage power station. The third layer of protection mainly revolves around these three elements, that is, it is necessary to standardize the unsafe behavior of people, eliminate the unsafe state of equipment and have the environmental factors of compliance. Under the intelligent control of the third layer, by reducing human risk, controlling the risk of equipment and creating a good environmental atmosphere, the operation standardization, data visualization and environment adjustment of energy storage power station are realized, and finally the " three modernizations " collaborative upgrading is realized.

(1) Operational constraints and personnel training

At present, in the energy storage power station, personnel is an indispensable factor, and a mistake by the operator may bring irreparable losses. Therefore, in view of the problems of staff operation and safety awareness in some enterprises, it is necessary to strengthen effective staff training, improve the professional quality of personnel, and standardize people 's unsafe behavior. In the staff training, the importance of operating in accordance with the rules and regulations is emphasized, and the corporate culture can be integrated into the skill training process, so as to enhance the sense of corporate culture identity of employees and improve the enthusiasm of employees for training. Regularly evaluate and check the effect of training, formulate reasonable improvement measures, improve the safety awareness of staff, and standardize the operation behavior of staff.

(2) Digital Twin Management Platform

Digital twin technology relies on the Internet of Things, big data and three-dimensional visualization to construct holographic digital mapping of the physical world. By constructing a multi-layer coupled digital twin management platform in the energy storage power station, the real-time synchronization of virtual space and physical space is realized by data-driven. Relying on reliable model support, it provides decision support for operators in different scenarios. The platform integrates the data information of battery cell, battery module and energy storage power station, monitors the state of each device, realizes the prediction of battery decay trend and the calculation of thermal runaway risk probability, and ensures the safety level of energy storage power station.

(3) System construction and environmental protection

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Environmental protection is divided into institutional environment and physical environment. Good power plant management rules and regulations can create a safe and stable institutional environment for employees, establish standardized operating procedures and rules and regulations, and ensure that employees work safely and efficiently in an orderly institutional environment through the implementation of responsibility system and reward and punishment system. The management system should meet the requirements of safety production standardization, and the content should be simple, popular and practical. For special physical environments such as high temperature, heavy rain, and lightning strikes, it is necessary to rely on both human and machine to eliminate the adverse effects of the physical environment. The adverse effects of the environment can be eliminated by selecting protective grade equipment, installing air conditioning, setting warning signs, installing lightning rods, lightning belts, lightning nets, etc., and the integrity of daily inspection equipment and various safety measures.

3.4. Safety Toughness Protective Layer

The fourth layer of defense line is the safety and resilience protection layer, which improves the safety level of electrochemical energy storage power station from the construction of energy storage standard system, the safety responsibility community of industrial chain and the innovation of digital-real integration.

(1) Construction of energy storage standard system

Based on the problems existing in China 's policies in the field of electrochemical energy storage, it is very important to strengthen the international standard coordination mechanism and formulate the whole life cycle safety standards from the cell level to the system level. Considering the pertinence and operability, the safety level evaluation standards of lithium-ion batteries and systems are formulated to reduce the applicable threshold of some technical indicators that are too strict to improve the safety of lithium-ion batteries for energy storage[20]. To formulate clear safety standards related to electrochemical energy storage technical requirements and testing, promote international mutual recognition, and promote equipment renewal and technological transformation with standard improvement. Establish safety standards for different aspects of battery body manufacturing to recycling and the monitoring and operation of the entire power station, strengthen the supervision of the whole chain supervision of energy storage power stations, and improve the safety of energy storage power stations.

(2) Industrial chain security responsibility community

Under the dual background of accelerating energy transformation and increasing risk of industrial chain, a multi-link responsibility community for the whole life cycle of electrochemical energy storage power station should be established, the thinking mode of " sweeping the snow before each door " should be broken, the main body of government and enterprise safety responsibility should be divided, and the responsibility of each manufacturer in the industrial chain should be clarified. Multi-departments on the government side jointly strengthen supervision and law enforcement;all manufacturers to strengthen cooperation, jointly upgrade security technology, to achieve data sharing ; the operation and maintenance unit of energy storage power station implements safety regulations, strengthens its own hidden danger investigation, feeds back the problems encountered in production to the manufacturer, and finally realizes the cross-link connection of design, production, operation and maintenance data. With the goal of controlling the risk of the whole chain, multi-party coordinated development is achieved to achieve common prevention before the accident and accountability after the accident.

(3) Innovation of digital-real integration

The deep integration of digital economy and energy storage real economy is becoming a key force to promote the innovation of safety protection of electrochemical energy storage power station. Therefore, building an internationally competitive digital industrial cluster, vigorously cultivating digital talents and using digital technology to develop the real economy are very important for strengthening the safety of electrochemical energy storage power stations to cope with increasingly complex risks. The government should provide policy guidance, vigorously support the cooperation of industry, university and research, and encourage diversified and in-depth cooperation between enterprises and schools. Enterprises and schools jointly cultivate talents in the field of electrochemical energy storage with independent innovation ability, and jointly develop safety protection technologies suitable for energy storage power stations, such as the development of fire extinguishing media that can effectively inhibit the chain reaction of battery thermal runaway, so as to realize fire extinguishing and prevent secondary re-ignition of fire. Actively carry out the transformation of scientific and technological achievements, accelerate the industrialization of technological breakthroughs, and provide strong support for the safety of electrochemical energy storage power stations.

4. Summary

In this paper, four protective layers for the whole life cycle of energy storage power station are established. In view of the development status, main risk factors and causes of the electrochemical energy storage industry, a four-layer prevention and control strategy of intrinsic safety-system emergency-intelligent control-ecological coordination has been formed. The safety level of electrochemical energy storage power station is improved from the aspects of battery body safety protection, passive protection of safety measures, strengthening safety management, government supervision and cooperation between enterprises and schools. In the future, it is necessary to further develop the safety protection technology of energy storage power station and strengthen the management of safety hazards to ensure the safe development of electrochemical energy storage power station. The main conclusions are as follows :

(1) In terms of industry, China 's electrochemical energy storage has gradually expanded its installed capacity in recent years, developed rapidly, and formed a relatively complete industrial system. In terms of policy, the five departments will jointly take safety as the premise of energy storage development in 2025, and clarify the responsibilities of all parties. In the future, policies related to the safety of electrochemical energy storage will be intensively released.

(2) The risk of energy storage power station mainly comes from energy storage battery, electrical equipment, external environment and staff. In view of these risk factors, the reasons for the formation of risks are summarized and analyzed : backward safety policy standards, inadequate enterprise management, shortcomings in safety technology, and weak industrial ecology. On the basis of risks and causes, a four-layer prevention and control system of ' intrinsic safety-system emergency-intelligent control-ecological coordination ' is established. From the material and process innovation of the power station to the whole life cycle management during the operation of the energy storage power station, a digital twin platform is established through big data, artificial intelligence and other technologies to carry out multi-monitoring, hierarchical early warning and emergency response of the energy storage power station, and at the same time improve the safety awareness and risk response ability of the staff. Finally, the government, enterprises and schools work together to formulate regional technical specifications, refine the main responsibilities, cultivate high-quality talents, and improve the safety protection ability of electrochemical energy storage power stations.

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