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TABLE OF CONTENTS

PREFACE

In recent years, under the goal of "carbon peaking and carbon neutralization", the efficient utilization and safety monitoring of energy has become the focus of global attention. With the continuous growth of renewable energy and the increasing complexity of power system, energy storage technology, as a key link to balance supply and demand and improve the stability of power grid, has become increasingly important. However, the safe operation and performance optimization of energy storage system put forward higher requirements for technology. It is in this context that deep learning technology, with its powerful data processing ability and pattern recognition ability, provides a new solution for the safety monitoring and intelligent management of power energy storage.

This book is divided into six chapters. The first chapter analyzes the development status of the energy storage industry from the perspective of international policies and standards, and provides the readers with the macro policy background and industry development trend; The second chapter goes deep into the different categories of electric energy storage technology, including chemical energy storage, mechanical energy storage and thermal energy storage technology; The third chapter focuses on the role of energy storage technology in power system and the application of grid peak shaving, frequency control and renewable energy technology; The fourth chapter discusses the application of deep learning technology in energy storage battery model construction and condition evaluation from the generation side; The fifth chapter describes the definition and function of grid side energy storage, and the application of deep learning in grid side energy storage;The sixth chapter describes the definition and function of user side energy storage, and the application of deep learning in user side energy storage.

The safety detection of electric energy storage system involves a wide range of aspects. Due to the author's level, it is ineviTab. that there are some mistakes in the organization and compilation of the manuscript. Please comment and correct. It is hoped that this book will serve as a platform for communication, establish contacts with readers, and promote the technical progress of in-depth intelligent learning in the field of intelligent power storage safety monitoring.

INTRODUCTION

This book comprehensively introduces the development history and technological classification of the power storage industry, the fundamentals, and applications of deep learning technology, testing and condition assessment of energy storage batteries, as well as the application of deep learning on both the grid side and user side. This book aims to explore the application of deep learning technology in the field of electric energy storage, as well as how to enhance the safety and efficiency of energy storage systems through intelligent means.

This book can be used as a reference for engineers, researchers, policy makers in the power industry, as well as scholars and students interested in deep learning and energy storage technology.

CHAPTER 1

INTERNATIONAL POWER ENERGY STORAGE STANDARDS

1.1 Standard of the International Electrotechnical Commission

The International Electrotechnical Commission (IEC) is a global standard-setting organization focusing on electrical, electronic, and related technical fields. IEC 62619 and IEC 62620 are safety and test standards for porTab. and stationary secondary batteries and battery packs, setting benchmarks to ensure safety during battery design, manufacture, use, and maintenance. In addition, IEC also involves the overall safety specifications of the battery management system (BMS) and energy storage systems, such as the IEC 62933 series, which guides the integration and deployment of energy storage systems.

The IEC TC 21/SC 21A is responsible for the development of safety standards for secondary batteries. The committee's work focuses on ensuring the safety performance of batteries under normal use and potential abuse conditions, covering all levels from single cells to battery packs. IEC 62619 is an important standard for SC 21A, which stipulates the safety requirements of porTab. and fixed secondary batteries and battery packs, including the design, manufacture, testing, use, maintenance, disposal, and recycling of batteries. It aims to reduce the risks of overheating, short circuits, explosion, and leakage that may occur during the use of batteries. The standards will also be revised regularly to incorporate new safety considerations and technical requirements. For example, the second edition of IEC 62619 released in 2022 has added additional requirements on moving parts, dangerous live parts, battery system design, and so on.

IEC TC 120 Committee is responsible for the development of standards for electrochemical energy storage systems (EES) in power grid applications. The focus of the committee is to ensure the compatibility and safety of large-scale energy storage systems with power networks and to promote the development and commercial application of energy storage technologies. The standard of TC 120 covers the design, installation, operation, maintenance, performance evaluation, and decommissioning of energy storage systems. These standards pay particular attention to system-level safety issues, including electrical safety, fire prevention, thermal runaway prevention, and stability when interacting with the grid. IEC 63056 is an important standard issued by TC 120, which stipulates the safety requirements of secondary lithium batteries and battery packs for power energy storage with a maximum DC voltage of 1500V. The work of the above two technical committees is crucial to the healthy development of the global energy storage industry. The standards they have developed will help establish a unified testing and verification process to ensure that energy storage devices and systems produced by different manufacturers can be safely deployed and operated worldwide.

IEC standards are adopted by many countries around the world as a basis for the development of local standards or directly as part of regulations. For example, Europe and Japan tend to formulate corresponding national standards concerning IEC standards. In China, GB/T series standards may be adjusted based on IEC standards to meet the specific needs of the Chinese market. In addition, the application of the IEC standard is very extensive, covering almost all aspects of electrical and electronic technology. The formulation and implementation of these standards help to improve the quality, safety, and reliability of products and also promote international trade and technical cooperation. Tab. 1-1-1 lists the application scope of IEC standards.

Tab. 1-1-1 The application range of IEC standard

application area	standard number	application
electronic product protection level (IP level)	IEC 60529 (Date 2004)	Defines the protection level and describes the degree of protection of the electrical enclosure against external solid foreign bodies and water intrusion.
secondary battery and energy storage system	IEC 62619、IEC 62933-5-1 (Lai et al. 2022)	IEC 62619: Safety requirements for porTab. and fixed secondary batteries and battery packs, covering design, manufacturing, testing, etc. IEC 62933-5-1: Installation and design requirements for electrochemical energy storage systems

substation automation	IEC 61850 (Mackiewicz 2006)	The information model, communication protocol, and service of the substation automation system are defined.
distribution management system	IEC 61968 (Yu et al. 2012)	The information model and interface of the distribution management system (DMS) are defined to support the monitoring and control of the distribution network.
electrostatic protection	IEC 61340-4-1 (Heinlein and Freimann 2022)	It provides test methods and basic requirements for electrostatic protection of electronic devices and helps to ensure that sensitive electronic devices are protected from electrostatic damage.

1.2 Standard of Underwriters Laboratories

Underwriters Laboratories (UL) (Wade 2023) is an independent, non-profit safety science company. Its standards include: (1) the safety standard for energy storage batteries UL 1973, which aims to ensure the safety of battery energy storage systems (BESS). This standard covers various types of batteries, including lithium-ion batteries, lead-acid batteries, nickel cadmium batteries, nickel hydrogen batteries, etc., and is applicable to a variety of application scenarios, such as solar energy, wind energy, standby power, communication base stations, etc; (2) The additional test procedure UL 9540a is used to evaluate whether the thermal runaway event in the battery energy storage system will spread to other battery units or modules, focusing on evaluating the risk and control measures of the battery energy storage system in the event of thermal runaway; (3) The safety standard UL 1642 for lithium-ion battery cells aims to evaluate the safety and reliability of lithium-ion battery cells under various extreme conditions, so as to avoid the risk of fire or explosion in actual use.

1.3 Standard of the United

UN standard is a series of rules and guidelines developed by the United Nations Transport of Dangerous Goods (TDG) (Lu, Whittal, and Shoib). These standards are designed to ensure the safety of dangerous goods during transport, reduce the risk of accidents, and protect the safety of people, property, and the environment. In the field of energy storage, especially in the transportation of lithium battery products, UN38.3 certification is particularly important. UN38.3 Certification is the testing and certification carried out by Part 38.3 of the UN Recommendations on the Transport of Dangerous Goods, Manual of Tests, and Criteria. The UN38.3 certification covers a series of safety performance tests for lithium batteries, including but not limited to :

(1). Height simulation test: simulate the pressure changes that lithium batteries may encounter in air transportation.

(2). Temperature test: including high-temperature test and low-temperature test, to evaluate the safety of lithium battery under different temperature conditions.

(3). Vibration test: simulate the vibration conditions during transportation to ensure that the lithium battery will not be damaged by vibration.

(4). Impact test: To simulate the possible impact of lithium battery during transportation and evaluate its impact resistance.

(5). External short circuit test: The thermal runaway and fire risk of lithium batteries are evaluated by the external short circuit.

(6). Overcharge test: simulate battery overcharge and evaluate its safety performance.

(7). Forced discharge test: evaluate the safety of lithium battery under forced discharge conditions.

1.4 Standard of the European Norm

EN standard, namely the European Norm, is a series of technical specifications and standards jointly developed by the European Standardization Organization (CEN) and its member institutions. The EN standard has a wide range of applications in many fields, aiming to promote the unification of the European market and the safety of products. In the field of energy storage, especially lithium battery products, the EN 62133 (Yang et al. 2021) standard is one of the most critical safety standards EN 62133 is a European safety standard for porTab. sealed secondary batteries and battery packs. It specifies the safety requirements that batteries and battery packs need to meet during design, manufacture, and use. The following is a detailed explanation of the EN 62133 standard: The EN 62133 standard contains some test contents to ensure the safety of batteries and battery packs. The following are some of the main test items (Yun, Jie, and Jun-Kai 2023):

(1). Continuous charging test: Evaluate the stability and safety of the battery under continuous charging conditions.

(2). Vibration test: simulate the vibration environment that the battery may encounter during transportation and use, and evaluate the vibration resistance of the battery.

(3). Temperature cycling test: evaluate the stability and safety of the battery under different temperature conditions.

(4). External short circuit test: simulate the behavior of the battery in the case of an external short circuit, and evaluate the safety performance of the battery.

(5). Drop test: Evaluate the impact resistance of the battery under drop conditions.

(6). Thermal abuse test: evaluate the stability and safety of the battery in a high-temperature environment.

(7). Squeeze test: Evaluate the stability and safety of the battery when it is squeezed.

(8). Overcharge and over-discharge tests: evaluate the stability and safety of the battery under overcharge and over-discharge conditions.

CHAPTER 2

ELECTRIC ENERGY STORAGE TECHNOLOGY

2.1 Chemical Energy Storage Technology

Energy storage refers to the technology of storing energy, such as electrical energy, in various forms and mediums, and releasing it for use when needed. Energy storage technology is one of the core technologies driving the global transition to cleaner, electrified, and more efficient energy systems, addressing resource and environmental constraints. Chemical energy storage technologies include lithium-ion battery storage, sodium-ion battery storage, all-vanadium redox flow battery storage, and lead-acid battery storage.

2.1.1 Lithium-ion Battery

Lithium-ion batteries refer to a type of battery that uses lithium-ion embedded compounds as positive electrode materials. They use carbon-based materials as the negative electrode and lithium-containing compounds as the positive electrode. The charging and discharging process of lithium-ion batteries involves the embedding and de-embedding of lithium ions. During this process, the embedding and de-embedding of equivalent electrons occur simultaneously. When charging the battery, lithium ions are generated at the positive electrode and move through the electrolyte to the negative electrode. The carbon used as the negative electrode has a layered structure with many micropores, allowing lithium ions to embed in these micropores. The more lithium ions that are embedded, the higher the charging capacity. Similarly, during discharging, lithium ions embedded in the carbon layers exit and move back to the positive electrode. The more lithium ions that return to the positive electrode, the higher the discharging capacity. The working principle of lithium-ion batteries is illustrated in Fig. 2-1-1.

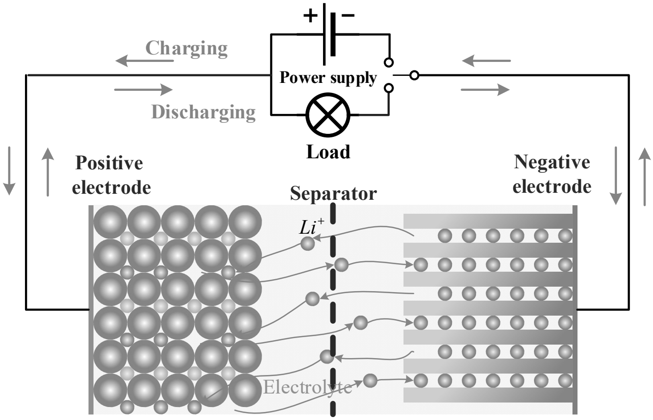

Fig. 2-1-1: Working principle of lithium-ion battery

The reactions during the charging and discharging of lithium-ion secondary batteries are represented by Eq. (2-1-1).

$$LiCoO_2 + C \leftrightarrow Li_{1-x}CoO_2 + Li_xC \quad (2\text{-}1\text{-}1)$$

The reason why it has become a leading innovative technology in the field of battery energy storage is mainly due to its high energy density, high energy efficiency, long life cycle, low cost, low self discharge rate and high safety. The characteristics of different types of batteries are shown in Tab. 2-1-1.

Types of Batteries	Energy Density (Wh/kg)	Efficiency (%)	Cycle Life
Lithium-Ion Battery	150-250	90-95	2000-5000
Lead-Acid Battery	30-50	70-80	200-300
Nickel-Cadmium Battery	50-80	70-85	500-1500

Tab. 2-1-1 Characteristics of different types of batteries

Lithium-ion batteries commonly use the following positive electrode materials: lithium manganese oxide, lithium cobalt oxide, lithium nickel oxide, ternary materials, and cobalt-free lithium iron phosphate. The negative electrode materials mainly consist of carbon-based materials, silicon-based, tin-based, and germanium-based lithium alloys. The electrolyte is typically a mixture of lithium salts, organic solvents, and a small amount of additives. The separator materials allow lithium ions to pass freely and prevent short circuits between the electrodes with a thin, corrosion-resistant film; the most widely used separator materials are polyethylene and polypropylene microporous membranes. Lithium-ion batteries are classified based on the materials used, with characteristics of each battery type summarized in Tab. 2-1-2.

Tab. 2-1-2 Types and characteristics of lithium-ion batteries

Types of Lithium-Ion Batteries	Voltage	Number of Discharge Cycles	Advantages and Disadvantages
Cobalt-Based Lithium-Ion Batteries	3.7V	500-1000	Widely adopted as the standard lithium-ion battery; expensive and not used in automotive applications.
Manganese-Based Lithium-Ion Batteries	3.7V	300-700	High security, fast charge, fast discharge
Lithium Iron Phosphate (LiFePO4) Batteries	3.2V	1000-2000	Cheap and long cycle life (aging due to charge and discharge), calendar life (aging due to use), lower voltage than other lithium-ion batteries
Ternary Lithium-Ion Batteries	3.6V	1000-2000	The voltage is high and the cycle life is long

2.1.2 Sodium-ion Battery

Sodium-ion battery is a kind of secondary battery that relies on the movement of sodium ions between positive and negative electrodes to complete charging and discharging. The sodium-ion battery is mainly composed of a cathode, an anode, a separator, an electrolyte, and current collectors. The separator prevents short circuits by isolating the cathode and anode, while the electrolyte saturates both electrodes to ensure ion conductivity. The current collector serves to collect and transport electrons. During charging, Na^+ ions are extracted from the cathode, pass through the electrolyte, and embedded into the anode, resulting in a sodium-poor state at the cathode and a sodium-rich state at the anode. The discharging process is the opposite, with Na^+ ions migrating from the anode through the electrolyte and into the cathode material, restoring the cathode to a sodium-rich state. To maintain charge balance, an equal number of electrons are transferred through the external circuit, migrating between the cathode and anode alongside Na^+ ions, leading to oxidation and reduction reactions at the electrodes. If Na_xMO_2 is used as the cathode material and hard carbon as the anode material, the reactions at the electrodes and the battery can be represented as follows:

Cathode reaction:

$$Na_xMO_2 \leftrightarrow Na_{x-y}MO_2 + yNa^+ + ye^- \qquad (2\text{-}1\text{-}2)$$

Anode reaction:

$$nC + yNa^+ + ye^- \leftrightarrow Na_yC_n \qquad (2\text{-}1\text{-}3)$$

Battery reaction:

$$Na_xMO_2 + nC \leftrightarrow Na_{x-y}MO_2 + Na_yC_n \qquad (2\text{-}1\text{-}4)$$

Similar to lithium-ion batteries, sodium-ion batteries can be classified based on cathode materials into layered oxides (Deyab 2015, Mariani et al. 2013), tunnel-type oxides, Prussian blue compounds, and poly-anionic compound systems. The characteristics of each system are shown in Tab. 2-1-3.

2.1.3 Vanadium Redox Flow Battery

The vanadium redox flow battery (VRFB) technology was proposed in 1985 by Skyllas-Kazacos from the University of New South Wales, Australia. It achieves energy storage and release through changes in the oxidation states of vanadium-ions (Zauner et al. 2017). VRFBs excel in various performance aspects such as safety, reliability, and cycle life, and they have promising applications in areas such as renewable energy generation and smart grid construction. The VRFB energy storage system mainly consists of components such as the electrolyte, cell stack, battery management system, and auxiliary systems.

Tab. 2-1-3 Characteristics of various systems in sodium-ion batteries

	Layered oxide system	Layer a Prussian blue compound system like an oxide system	Tunnel-type oxide system	Polyanionic compound system
Advantages	Reversible is higher than capacity High energy density High magnification performance Easy technology transfer	The operating voltage is adjusTab. Reversible is higher than capacity High energy density Low synthesis temperature	Good circulation Good multiple rate	High operating voltage Good thermal stability Good loop Good air stability
Deficiency	Easy to absorb moisture The loop performance is slightly worse	Poor electrical conductivity Coulomb efficiency is low	Low specific capacity Low operating voltage	The reversible specific capacity is lower Some contain toxic elements

The VRFB relies primarily on the redox reactions of vanadium ions in different valence states occurring at the electrode surface to store and release energy. During operation, the electrolyte is pumped from the storage tank into the cell stack by circulation pumps. After undergoing electrochemical reactions at the electrodes, the electrolyte is returned to the storage tank by the circulation pump, cycling repeatedly to achieve battery charge and discharge. During charging, the vanadium ions in the positive electrolyte VO^{2+} lose electrons to form VO^{2+}, while the vanadium ions in the negative electrolyte V^{3+} gain electrons to form V^{2+}. Electrons flow from the positive electrode to the negative electrode through an external circuit, generating a current and releasing the energy stored in the battery for user consumption. Meanwhile, H^{+} ions transfer through the ion exchange membrane from the positive electrode to the negative electrode, completing the circuit and ensuring the charge neutrality of the electrolyte. During discharging, the ion changes are exactly the opposite. The reactions occurring on the electrode surface during battery operation are shown in Eq.s (2-1-5), (2-1-6), and (2-1-7).

Positive Electrode Reaction:

$$VO^{2+} + H_2O - e^- \xrightarrow{\text{charging}} VO_2^+ + 2H^+$$
$$VO_2^+ + 2H^+ \xrightarrow{\text{discharging}} VO^2 + H_2O - e^- \quad (2\text{-}1\text{-}5)$$

Negative Electrode Reaction:

$$V^{3+} + e \xrightarrow{\text{ch arg ing}} V^{2+}$$
$$VO^{2+} \xrightarrow{\text{disch arg ing}} V^{3+} + e \quad (2\text{-}1\text{-}6)$$

Overall Reaction:

$$VO^{2+} + H_2O + V^{3+} \underset{\text{disch arg ing}}{\overset{\text{ch arg ing}}{\rightleftarrows}} VO_2^+ + V^{2+} + 2H^+ \quad (2\text{-}1\text{-}7)$$

VRFB not only boasts excellent safety and long service life, but it is also cost-effective. Moreover, as VRFB technology has developed over several decades, it has gradually matured. Some of the VRFB projects currently in operation worldwide are listed in Tab. 2-1-4.

Tab. 2-1-4 Selected Operational VRFB Projects Worldwide

Project Name	Project Scale	Supplier	Commissioning Year
Dalian Energy Storage and Peak Shaving Station Phase 1	100MW/400MWh	Rongke Power	2022
Hokkaido Renewable Energy Grid Integration	17MW/51MWh	Sumitomo Electric Industries	2022
Zaoyang 10MW Solar-Storage Phase 1	3MW/12MWh	Punu Energy	2019
Washington State Substation Energy Storage	1MW/3.2MWh	UniEnergy Technologies (UET)	2015

2.1.4 Lead-acid Battery

The electrodes of lead-acid batteries are primarily made of lead and its oxides, and the electrolyte is a sulfuric acid solution. Lead-acid batteries are categorized based on their structure and use into starter lead-acid batteries, motive power lead-acid batteries, stationary valve-regulated sealed lead-acid batteries, and others, including small valve-regulated sealed lead-acid batteries and miner's lamp lead-acid batteries.

Lead-acid batteries consist of a positive active material P_bO_2, a negative active material P_b, and an aqueous solution electrolyte H_2SO_4. The solidified paste on both the positive and negative electrodes contains various divalent lead compounds, including $3P_bO.\ P_bS0_4.\ H_2O$ *(3BS)*、$4P_bO.\ P_bS0_4$ *(4BS)*、P_bO_2 and P_b. When the lead-acid battery is charged, fine P_bS0_4 particles at the negative electrode are electrochemically converted into *Pb*, and at the positive electrode, they are converted into &. During charging, $S0_4^{2-}$ ions return to the electrolyte solution to form H_2S0_4 *(*. The charging process is shown in Eq 2-1-8, 2-1-9, and 2-1-10.

Positive Electrode Reaction:

$$PbSO_4 + H_2O - 2e^- = PbO_2 + 4H^+ + SO_4^{2-} \qquad (2\text{-}1\text{-}8)$$

Negative Electrode Reaction:

$$PbSO_4 + 2e^- = Pb + SO_4^{2-} \qquad (2\text{-}1\text{-}9)$$

Overall Reaction:

$$2PbSO_4 + 2H_2O = PbO_2 + 2H_2SO_4 + Pb \qquad (2\text{-}1\text{-}10)$$

During the discharge process of the lead-acid battery, the positive electrode receives electrons released from the negative electrode, forming P_bS0_4. The discharge process is described in Eq.s 2-1-11, 2-1-12, and 2-1-13.

Positive Electrode Reaction:

$$PbO_2 + 2e^- + 4H^+ + SO_4^{2-} = PbSO_4 + H_2O \qquad (2\text{-}1\text{-}11)$$

Negative Electrode Reaction:

$$Pb + SO_4^{2-} - 2e^- = PbSO_4 \qquad (2\text{-}1\text{-}12)$$

Overall Reaction:

$$PbO_2 + 2H_2SO_4 + Pb = 2PbSO_4 + 2H_2O \qquad (2\text{-}1\text{-}13)$$

During the charging process of lead-acid batteries, oxygen is formed at the positive electrode and moves towards the negative electrode through the separator. In addition to oxygen, the positive plate releases hydrogen ions that migrate in the acid, while electrons in the external circuit enter the negative electrode and recombine with the oxygen. As charging continues, the lead sulfate produced is rapidly converted back into lead, and water is generated as well. This oxygen cycle suppresses the hydrogen evolution reaction at the negative electrode, preventing water loss and thus establishing the oxygen cycle process.

In theory, the material exchange between discharge and charge in lead-acid batteries is reversible. However, in practice, P_bSO_4 cannot be fully reconverted into P_b and P_bO, and P_bO_2 may shed from the positive grid. These phenomena lead to significant capacity loss and may even result in battery failure. Therefore, understanding the failure modes of lead-acid batteries is essential to improving their lifespan (Wang, Wang, et al. 2023).

The main performance parameters of lead-acid batteries and lithium batteries are shown in Tab. 2-1-5. From the performance parameters of lead-acid batteries, it can be concluded that compared to lithium batteries, lead-acid batteries have lower specific energy and shorter cycle life. However, lead-acid batteries have good maintainability, a relatively simple structure, and are easy to maintain and troubleshoot, which reduces maintenance costs. In terms of recycling, the high recycling rate of lead ensures the effective reuse of old batteries, promoting resource circulation. Additionally, lead-acid batteries are sTab. in terms of safety, with a low risk of explosion or leakage.

Tab. 2-1-5 Comparison of Key Performance Parameters between Lead-Acid Batteries and Lithium Batteries

Performance Parameter	Lead-Acid Battery	Lithium Battery ($LiFePO_4$)
Specific Energy	30–50 Wh/kg	100–150 Wh/kg
Cycle Life	300–500 cycles	> 2000 cycles
Environmental Impact	Lead pollution	No pollution
Production Cost	Approximately 1.1 CNY/Ah	Approximately 2.2 CNY/Ah
Maintainability	Can be replaced on-site by dealers	Requires factory repair
Recycling Efficiency	Over 90%	Low recycling value
Safety Performance	High safety	Relatively challenging

Compared to other types of batteries, the advantages of lead-acid batteries mainly lie in the widespread availability of raw materials, which ensures the stability of the production chain and the controllability of costs. This prevents lead-acid batteries from being constrained by scarce resources during manufacturing, thereby maximizing cost efficiency in large-scale production. The low cost of the finished batteries meets the demand for affordability across various sectors, from basic communication infrastructure to everyday transportation. In terms of performance, lead-acid batteries are safe and reliable, with sTab. electrochemical properties that effectively reduce the risk of sudden failures during use, providing a dependable backup power source for various industries.

2.2 Mechanical Energy Storage Technology

2.2.1 Pumped Storage

Pumped storage energy uses water as the energy storage medium, and realizes the storage and management of electric energy through the mutual conversion of electric energy and potential energy (Rehman, Al-Hadhrami, and Alam 2015, Blakers et al. 2021). Electric energy is used at the low point of the power load to pump water to the upper reservoir, and then the water is released to the lower reservoir to generate electricity at the peak of the power load. It can convert the excess power when the grid load is low into high-value power during the peak period of the grid. It is suiTab. for frequency modulation and phase modulation, stabilizing the frequency and voltage of the power system, and improving the efficiency of the thermal power station and nuclear power station in the system. Fig. 2-2-1 shows the schematic diagram of the pumped storage system[Error! Reference source not found.]. Through a high-pressure diversion pipe, the lower reservoir is pumped to the upper reservoir to store energy and then generate electricity.

The advantages of pumped storage in energy storage are high efficiency, strong schedulability, and long service life. The installed capacity of pumped storage is large, which can provide efficient energy storage services. Compared with battery storage technology, pumped storage is cheaper; Pumped storage power also has good environmental friendliness.

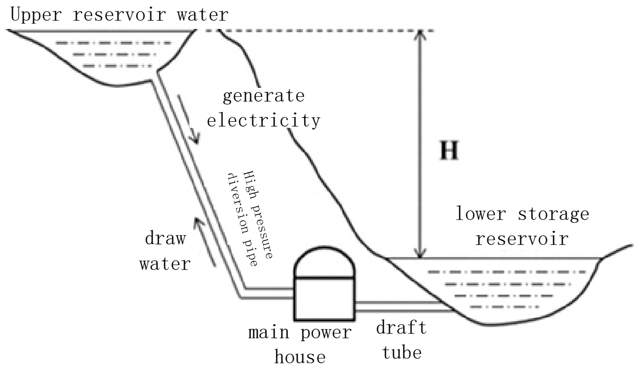

Fig. 2-2-1 Schematic diagram of pumped storage system

2.2.2 Compressed-air Energy Storage

Compressed air energy storage refers to the energy storage method that uses electric energy for compressed air during the low load period of the power grid, seals the air under high pressure in abandoned mines, settling submarine gas storage tanks, caves, expired oil and gas Wells or new gas storage Wells, and releases compressed air to drive turbine power generation during the peak load period of the power grid (Budt et al. 2016, Wang et al. 2017). Compressed air energy storage includes traditional compressed air energy storage, regenerative compressed air energy storage, supercritical compressed air energy storage, and liquid compressed air energy storage.

The principle of compressed air energy storage is to use the elasticity of compressed air to compress the air into high-pressure gas in the compressed air energy storage device, store it, and release it when needed to convert it into mechanical energy or electrical energy. Specifically, the compressed air energy storage system is composed of air compressors, gas storage tanks, pneumatic valves, coolers, control systems, etc. When the compressor is running, the air is compressed into the gas storage tank, and the volume of air is continuously reduced as the pressure in the gas storage tank rises, to achieve energy storage. When it is necessary to use compressed air to release energy, the high-pressure gas is released through the pneumatic valve, and it is converted into mechanical energy or electrical energy through the hydraulic cylinder, expansion machine, and other devices.

Compressed air energy storage is environmental protection and energy saving, the system will not produce any harmful gases, such as carbon dioxide, or sulfide; Can store excess energy, avoid energy waste, and release stored energy when needed to achieve energy recovery; The storage of electric energy avoids the waste of electric energy, reduces the peak-valley difference of the power system, and reduces the pressure of the grid. Renewable energy such as solar energy and wind energy can be used for charging to achieve renewable utilization of energy storage and energy.

Compressed air energy storage has high-efficiency performance, and the compressed air energy storage system has high energy density and can store a lot of energy. The ability to efficiently convert electrical energy into compressed air energy and convert compressed air energy into electricity when needed; Long life of the system, can maintain efficient operation for a long time; The system has fewer components, high reliability, and low maintenance cost.

2.2.3 Flywheel Energy Storage

Flywheel energy storage is a technology that uses rotating mechanical energy to store and release electrical energy (Faraji, Majazi, and Al-Haddad 2017, Olabi et al. 2021). Its working principle is based on the kinetic energy formula in physics, which states that the kinetic energy of an object is proportional to the square of its mass and rotational speed. The motor in the flywheel energy storage power system is both a motor and a generator.

The flywheel energy storage system mainly consists of the following parts: (1) Power conversion system: The flywheel is the core part of the energy storage system, usually made of high-strength materials, such as steel, carbon fiber, or glass fiber. The shape and design of the flywheel are designed to maximize its energy storage capacity and mechanical stability. (2) Motor: This device can be used as a motor to convert electrical energy into mechanical energy to accelerate the flywheel rotation; It can also be used as a generator to convert the mechanical energy of the flywheel back into electrical energy. Generally, the electric motor is the same device that stores and releases energy by working in both directions. (3) Bearing: the power conversion system includes motors and power electronic converters, of which the motor is the core component of the flywheel energy storage system to achieve energy conversion, the performance of the motor directly affects the performance and efficiency of the flywheel energy storage system. The motor is coaxially connected to the flywheel and acts as an electric motor during the charge and discharge of the flywheel, providing power. (4) Power electronic devices: is an important part of the power conversion system to achieve energy conversion, the most typical power converter topology is AC-DC-AC converter. (5) Shell: The flywheel will produce huge centrifugal force when rotating at high speed, so a strong shell is needed to protect the flywheel and ensure safety. In addition, the housing can also be operated in a vacuum environment, further reducing air resistance. The schematic diagram of the flywheel energy storage system is shown in Fig. 2-2-2.

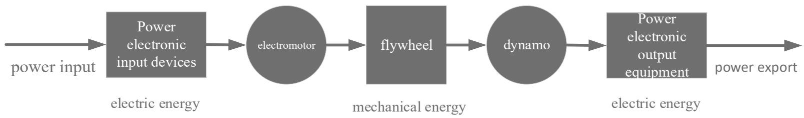

Fig. 2-2-2 Schematic diagram of flywheel energy storage system

In Fig. 2-2-2, when "charging", the flywheel is accelerated as an electric motor to convert electrical energy into mechanical energy; When "discharging", it is used as a generator to convert mechanical energy into electrical energy to supply external power; When supplying external power, the speed of the flywheel decreases continuously. When the flywheel is idle, the operating loss of the flywheel energy storage power system is very small.

When the flywheel rotates, its rotational kinetic energy is shown in formula 2-2-1:

$$E = \frac{J\omega^2}{2} \tag{2-2-1}$$

In formula 2-2-1, J is the moment of inertia of the flywheel; ω is the angular speed of the flywheel rotation. The kinetic energy E of the flywheel is proportional to the moment of inertia J of the flywheel.

2.2.4 Supercapacitor Energy Storage

A Supercapacitor, also known as an Electrochemical Double-Layer Capacitor (EDLC) or ultracapacitor, is a type of energy storage device between a conventional capacitor and a battery (Lemian and Bode 2022, Kouchachvili, Yaïci, and Entchev 2018). It has the characteristics of high power density, long cycle life, and fast charge and discharge, which shows unique advantages in many applications. Supercapacitors use the electrochemical double-layer principle to store energy, that is, a double electric layer is formed between the electrode and the electrolyte, and energy is stored and released through the adsorption and desorption of ions on the surface of the electrolyte and the electrode. Supercapacitors do not rely on chemical reactions to store charge, so they can be charged and discharged quickly and have a long service life. Fig. 2-2-3 shows the structure of a supercapacitor.

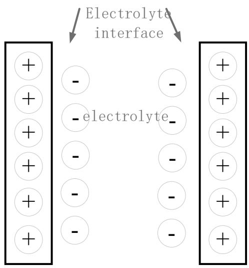

Fig. 2-2-3 Supercapacitor structure diagram

When charging, the positive and negative ions in the electrolyte move rapidly towards the poles under the action of an electric field, and store charge by forming a double electric layer at the interface between the electrode and the electrolyte.

RC model is the most representative supercapacitor model, where R_{ES} represents equivalent series resistance and C represents the ideal capacitor element, as shown in Fig. 2-2-4.

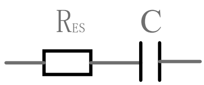

Fig. 2-2-4 RC model

According to the operation of R_{ES} equivalent resistance, the power regulation system can determine the heat loss characteristics of the supercapacitor. When the supercapacitor of the power storage system is charged and discharged, the voltage drop will be generated at both ends of the equivalent resistance in series. When the supercapacitor of the power storage system suddenly carries out constant discharge, the specific value of R_{ES} can be determined by dividing the voltage drop by the real-time current.

As can be seen from Fig. 2-2-4, the greater the value of equivalent series resistance applied by the RC unit, the less energy stored by the supercapacitor, and the smaller the real-time power of the power storage system.

Suppose the electrolyte ion of the power storage system is ψ, the charge with charge is C, the dielectric constant of R_{ES} resistance is x, the voltage drop is ξ, the charge and discharge vector is b, the Kelvin temperature is ω, and the energy storage power at the Kelvin temperature is $v\omega$. Combining the above physical quantities, the supercapacitor model expression can be defined as Eq. 2-2-2:

$$Z = \xi \sqrt{\frac{2\psi^2 v_\omega b}{xC}} \quad (2\text{-}2\text{-}2)$$

2.3 Thermal Energy Storage Technology

Energy storage is the process of storing energy in the form of heat in a storage medium and releasing it for heating, cooling, power generation, etc when needed. The thermal energy can be stored for short or long periods based on thermophysical and thermochemical reactions. There are three types of thermal energy storage technologies: Sensible Heat Storage (Seyitini, Belgasim, and Enweremadu 2023), Latent Heat Storage (Nomura, Okinaka, and Akiyama 2010), and Thermochemical Energy Storage (Chen, Zhang, et al. 2018).

Sensible heat storage (SHS) is based on the storage of heat through the change in temperature of some liquid or solid material which is called dielectric. A more common example in life is heating water or graphite to a high temperature and then storing it in a container to release the heat when needed. This is a very effective technique because of the high thermal conductivity and storage density of water and graphite. If there is no phase change in the process, the sensible heat stored or released by the medium can be calculated as shown in Eq. (2-3-1):

$$\boldsymbol{Q = M c_p \Delta T} \quad (2\text{-}3\text{-}1)$$

Where Q is the heat, J; M is the mass of the medium, kg; c_p is the specific heat capacity of the medium, kJ/ (kg-K); and ΔT is the temperature change, K. Normally, the solid medium can be rock, metal, sand, concrete, etc.

While water, molten salts, oil, etc. are generally used as liquid media. In general, solid media can store energy at both low and high temperatures because they have a wide temperature range and do not change phase. Most solid storage materials, such as concrete, rock, or sand, have a wider operating temperature at ambient pressure (ranging from 200-1500°C) than liquid storage media, making them suiTab. for large-scale industrial applications. Nevertheless, other aspects such as energy density, cost, stability, and environmental suitability will be considered in the selection process of the medium. Materials with high specific heat capacity, low cost, and good thermal stability under thermal cycles of energy storage and release are promising storage media. Typically, solid media have a high density but a low specific heat capacity, which results in a larger storage mass and volume than liquids when storing the same amount of energy.

Considering the large number of materials that can be used for sensible heat storage, several studies have developed methods to categorize them according to their thermophysical properties, which usually affect the sensible heat storage performance and its time scale (short-term or long-term storage), depending on the specific application. The classification of long-term sensible heat storage is obtained based on the energy stored per unit volume and the cost E^*, as shown by Eq. (2-3-2):

$$\boldsymbol{E}^* = \frac{\boldsymbol{c_p \Delta T}}{\boldsymbol{V C_m}} \quad (2\text{-}3\text{-}2)$$

Where V is the volume of the material; and C_m is the specific cost of the material.

Short-term sensible heat storage requires a high volumetric specific heat capacity, as well as a good thermal diffusivity, as in Eq. (2-3-3), which can also take into account the time factor to cope with dynamic and long-term problems：

$$\boldsymbol{\alpha} = \frac{\boldsymbol{\lambda}}{\boldsymbol{\rho c_p}} \quad (2\text{-}3\text{-}3)$$

where α is the thermal diffusivity, m^2/s; λ is the thermal conductivity, W/(m-K); ρ is the density, kg/m^3; and c_p is the specific heat capacity, J/ (kg-K).

Latent heat storage (LHS), where physical state changes occur during the release or absorption of thermal energy, therefore allows for higher energy storage densities compared to sensible heat storage. The isothermal nature