Review on electrochemical energy storage technology in power system and relevant materials

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Abstract. The coordinated development of energy storage technology and renewable energy is key to promote the green development in power system. Due to the cost reduction and superior performances of electrochemical energy storage technologies, more and more related demonstration projects have been constructed in recent years. The paper focuses on several electrochemical energy storage technologies, introduces their technical characteristics, application occasions and research progress of relevant materials in details. Finally, development trends of energy storage technology in the future are discussed and prospected based on the actual situations in the west of Inner Mongolia.

1. Introduction
The importance of the coordinated development of energy storage technology and renewable energy has been further emphasized. Large-scale energy storage technology can be used to assist the safe grid connection of new energy, relieve the pressure of grid peak shaving, improve power quality, increase grid operation efficiency and as an emergency backup. According to incomplete statistics from China Energy Storage Alliance (CNESA), until the end of 2020, the cumulative installed capacity of energy storage in China has reached 35.6 GW, of which the cumulative installed capacity of electrochemical energy storage is 3.27 GW. Among them, the cumulative installed capacity of lithium batteries is the largest, at 2.90 GW[1]. Energy storage has entered a new stage of "scale development" from the stage of "early commercialization".

According to the energy form, energy storage technology can be classified into mechanical energy storage, electromagnetic energy storage, chemical energy storage and phase change energy storage. Different demands of energy storage determine the diversity of energy storage technology. As for electrochemical energy storage, safety and cost are key factors to evaluate the battery performance which directly influenced by battery materials.

In this review, several electrochemical energy storage technologies will be introduced in basic performance, application status, and the development of relevant energy storage materials. Finally, development trends of above technologies will be analyzed and discussed based on actual situations in the west of Inner Mongolia.

2. Electrochemical energy storage technology

2.1. Lithium battery
Benefit from the rapid development of electric vehicles in recent years, lithium batteries exhibit the superior performance in cost price, energy density, conversion efficiency, response time, cycle life and safety. Compared with ternary lithium batteries, LiFePO₄ batteries are safer, cheaper and longer-lived.
Coupled with a broad development market of the LiFePO$_4$ battery in China, it is more applicable to the power system energy storage. Several demonstration projects have been shown on Table 1.

Table 1. Some demonstration projects of common electrochemical energy storage technologies.

| Serial Number | Project Name                                                                 | Location                  | Energy Storage Type | Energy Storage Scale   | Finished Time |
|---------------|------------------------------------------------------------------------------|---------------------------|---------------------|------------------------|--------------|
| 1             | AGC Energy Storage Auxiliary Frequency Modulation Project                     | Shanwei, Guangdong, China | Lithium battery     | 30MW/14.93MWh         | 2018.5       |
| 2             | Power Grid Side Distributed Energy Storage Power Station Project              | Zhenjiang, Jiangsu, China | Lithium battery     | 101MW/202MWh          | 2018.7       |
| 3             | SDG & E Escondido Energy Storage Project                                      | The US                    | Lithium battery     | 30MW/120MWh           | 2017.2       |
| 4             | Sendai Substation Lithium Ion Battery Pilot Project                           | Sendai, Japan             | Lithium battery     | 40MW/20MWh            | 2015.2       |
| 5             | Wind and Solar Storage and Transportation Project (Phase I)                  | Zhangbei, Hebei, China    | Lithium battery     | 14 MW/63 MWh; 2 MW/8 MWh; 2 MW/12 MWh; 2 MW/1 MWh | 2011.12     |
| 6             | Flow Battery Energy Storage Peak-shaving Power Station National Demonstration Project | Dalian, Liaoning, China | Flow battery         | 200MW/800MWh          | 2020.12     |
| 7             | Duke Energy Business Services Notrees Wind Storage Demonstration Project     | Goldsmith, Texas, the US | Lead-carbon Battery | 36 MW/24MWh           | 2013.1       |

For the LiFePO$_4$ battery, improving safety performance is key to promote its large-scale application in power grid. Choosing appropriate materials of electrodes and electrolyte are hot spots in current electrochemical energy storage research which can not only effectively reduce the cost, but also improve safety performance of the battery.

At present, the commercial LiFePO$_4$ battery mainly consists of LiFePO$_4$ cathode material, graphite anode material and carbonate-based organic liquid electrolyte[2]. However, the olivine structure of LiFePO$_4$ and the thermal instability of the organic electrolyte have negative impacts on energy density, cost and safety. Choosing carbon nanotubes or graphene as a supplementary material, for example, combining with electrode materials, as a conductive agent, or using for membrane modification, have shown obvious advantages in improving batteries performance, not only can effectively increase rate characteristics and cycle performance, but also can improve the low-temperature performance defects of the LiFePO$_4$ battery[3]. Wei et al. added an appropriate amount of graphene as a conductive agent into the LiFePO$_4$ battery electrode, test results proved a better conductivity performance compared to the traditional LiFePO$_4$ battery[4]. It provides a new idea for the preparation method of a high-performance LiFePO$_4$ battery in the future. In addition, the solid-state lithium battery is one of main research and development directions in the future. It is prepared with polymers or inorganic electrolytes, which can not only helpfully overcome the dendrite problem, extend battery life, but also reduce costs[5].
2.2. Lead-acid battery

The traditional lead-acid battery, with mature technology, low cost, reliability and high recycling rate, has been widely used for peaking and frequency modulation, load shifting, power quality improvement and backup power supply in power system. However, the corrosion of the positive plate of lead-acid batteries and the irreversible sulfation of the negative plate in the high-rate partial state of charge (HRPSoC) seriously affect the battery performance and lead to a premature failure[6].

Lead-carbon batteries have attracted much attention because of their excellent performance in safety, economy and cycle life. Selecting a suitable carbon material, "internally" or "internally mixed" in the negative plate of the lead-acid battery, a lead-carbon battery is formed which can be seemed as a combination of lead-acid battery and supercapacitor. High specific surface area and high conductivity property of the carbon material contribute to the battery performance improved significantly[7]. Compared with traditional lead-acid batteries, lead-carbon batteries are obviously more outstanding in specific power, rapid charge and discharge, and cycle life [8]. Broad prospects in wind power grid access, peak shaving and valley filling, grid frequency modulation, and microgrid systems have been shown both in domestic and foreign. Part of application cases are listed in Table 1.

A FCP lead carbon battery developed by Shengyang Power and Japan's Furukawa Battery Co., Ltd. increased the battery cycle life to 4200 times through a series of optimization measures. It proves that the commercial application of lead-carbon battery energy storage is inseparable from a series of breakthroughs in active materials, electrolytes and additives aspects[9]. However, the complex diversity of carbon materials caused a series of problems, such as unclear mechanisms of carbon materials, uncertain type and amount of carbon materials added, uncertain approach to effectively suppress the hydrogen evolution reaction aggravated, in addition, the environmental pollution caused by the battery manufacturing process, all these problems are waiting to be further explored and improved.

2.3. Vanadium redox flow battery

The flow battery is a kind of redox battery which can achieve a mutual conversion and storage between electrical energy and chemical energy through changing the valence of positive and negative active materials. Among many kinds of flow battery systems such as zinc-bromide system, iron-chromium system, vanadium-bromide system, and all-vanadium system, all-vanadium battery is the most promising energy storage technology with the most demonstration projects [10]. The vanadium redox flow battery has outstanding advantages in response time, energy conversion efficiency, cycle life, power capacity adjustment, safety and environmental protection. However, the thermal instability of the active substance solubility and the complexity of the system device connection make it is lacking in energy density, initial investment cost and site selection[11-12]. Some applications of the vanadium redox flow battery in power system are shown in Table 1.

In order to promote the large-scale commercial development of vanadium redox flow batteries, it is necessary to improve and optimize the performance of energy storage materials such as electrodes, electrolytes and electrolyte membranes. The electrochemical activity, resistance, chemical stability and porosity of the electrode all have impacts on the performance of the vanadium redox flow battery. Some treatments for carbon electrode materials such as oxidation treatment, surface-supported electrocatalyst treatment or carbon nanomaterial modification methods can effectively improve the physical and chemical properties of the material surface, reduce polarization, and then improve the reversibility and power density of the battery[13-14]. Flox et al. developed a new type of graphene-supported Pt and PtCu3 nanocubic catalyst cathode material, test results showed a significantly increase in specific surface area, the electronic conductivity and battery energy efficiency are greatly improved[15].

The sulfuric acid electrolyte commonly used only has a good solubility and stability for multivalent vanadium ions in the temperature range of 10-40℃. This applicable temperature range can be expanded by optimizing the concentration of sulfuric acid, changing the type of electrolyte, or quantitatively introducing electrolyte additives, these methods also can further improve the energy
density and operational stability of the battery[16]. Currently, the most widely used membrane for flow batteries is the perfluorinated proton-conducting membrane by DuPont, which is expensive and account for 10-15% of the total cost of investment. Therefore, how to reduce the manufacturing cost of the membrane while improving the ion selectivity and ensuring its long-term stability has become a crucial issue that urgently need to be broken through[17].

3. Conclusion
At present, both the lithium battery and the lead-acid battery have a mature technology and a high degree of commercialization, they occupied most part of the electrochemical energy storage market in China. The flow battery and the lead-carbon battery, as emerging high-efficiency energy storage technologies, have shown a huge market competitiveness. It is an inevitable trend to use energy storage technology in the future for the development of a new generation of power system. The research and development directions are as follow: (1) Application of energy storage technology in power system has entered a large-scale investment stage, especially the LiFePO4 battery. The battery safety issues become increasingly important. Besides, relevant standards and policies from manufacturing to recycling of batteries need to be strengthened and improved; (2) The development of electrochemical energy storage technology is closely influenced by energy storage materials. Optimizing and innovating the performance of materials can directly improve the battery performance and reduce the investment cost of energy storage construction; (3) According to actual situations of energy distribution and climate in the west of Inner Mongolia, suitable integrated energy storage technologies can be applied to achieve more efficiently serve in power grid. The low-temperature climatic environment in winter requires a further research on the battery performance of safety and economy.

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