Present Situation and Prospects of Energy Storage Technology in the Context of New Power System Construction

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Abstract—With the promotion of new power system construction, due to the *real-time-balance* characteristics of power system and the randomness and volatility of renewable energy, the power system needs more adjustable means, which boost the development of large-scale energy storage. This paper summarizes the problems faced by new power system operation with large-scale grid-connected renewable energy. Furthermore, the current mainstream energy storage technology and its development status are summarized. On this basis, the security, economy, system and mechanism problems faced by large-scale application of energy storage technology in power system are proposed. Finally, the key development directions and prospects of large-scale energy storage applications are prospected.

1. INTRODUCTION

In order to protect the earth's ecological environment, build a community with a shared future for mankind, and embody the responsibility of major countries. On April 22, 2021, General Secretary Xi Jinping solemnly announced at the general debate of the 75th session of the United Nations General Assembly: "Carbon dioxide emissions strive to peak by 2030, and strive to achieve carbon neutrality by 2060." "Carbon peaking and carbon neutrality" is a major strategic decision based on China's national conditions and the international environment, which will surely set off a top-down carbon emission reduction revolution [1]. The power sector is the single industry with the largest total carbon emissions in China. In 2019, the carbon emissions of the power industry reached 4 billion tons, accounting for 42% of the total carbon emissions of the country. Therefore, the construction of a new power system based on new energy is a major trend in the development of the power industry. However, new energy sources are random and volatile, while the power of the power system needs to be "balanced in real time". How to ensure that the power system with a high proportion of new energy power supply provides stable and reliable power supply services for users is the biggest challenge facing the development of new power systems. Based on this basic physical law of conservation of energy, the development of large-scale energy storage is the only way to solve the development of new power systems. On July 15, 2021, the National Development and Reform Commission and the National Energy Administration issued the Guiding Opinions[2], which states: "By 2025, new energy storage will be transformed from the initial stage of commercialization to large-scale development." By 2030, we will achieve the comprehensive market-oriented development of new energy storage." It can be seen that the development of large-scale energy storage has risen to the national strategic level, which is the general trend of the development of the power system.

2. ENERGY STORAGE REQUIREMENTS FOR NEW POWER SYSTEMS

From the perspective of the power system as a whole. Mainly the contradiction between new energy intermittent and real-time power balance requirements of power systems is becoming increasingly prominent. Look at it locally. Mainly the withdrawal of traditional thermal power units has led to the serious "hollowing" of the load center power supply. The local voltage support capacity of the power grid is insufficient. From the load side. The main reason is that the impact load has a great impact on the quality of power supply. All three types of problems can be effectively solved by configuring energy storage.

2.1 Conflict between the intermittent of new energy sources and the real-time power balancing requirements of the power system

When a power mismatch occurs, the frequency stability problem and even the major blackout accident will occur in the power system with a high proportion of new energy.

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Such risks do not come out of nowhere. Similar crises have emerged at home and abroad. A major power outage in the UK on 9 August 2019[3]. As well as the September 2021 Northeast Power Grid shutdown incident[4] indicate the existence of such risks.

Between 1996 and 2017, the change in the proportion of various types of power installed in the UK power grid is shown in Figure 1. In the past five years, the proportion of wind power and solar power in the UK's power structure has risen rapidly, while the proportion of coal-fired power generation has decreased year by year. It is a typical new energy power system with high proportion of new energy. The UK power grid has had multiple power deficit events in a short period of time. This results in a frequency change rate exceeding the protection threshold of 0.125 Hz/s in the distribution network regulations. 350MW of off-grid distributed generation. Exacerbate the frequency drop. Off-grid with distributed power generation forms a chain reaction event. It can be seen that the British blackout is a concentrated

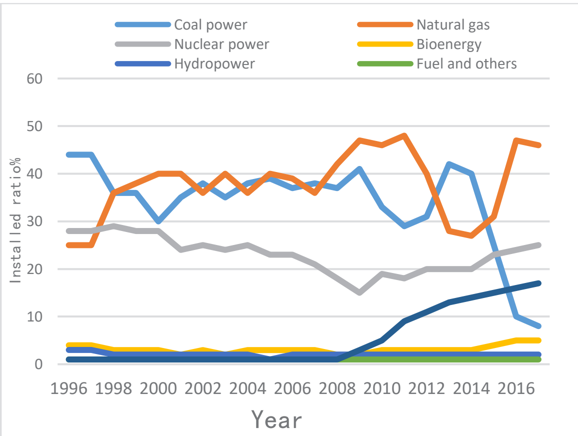

Fig. 1. The trend of the proportion of installed power supplies of various types from 1996 to 2017.

With the advancement of the construction of the new power system, the total installed capacity of wind power in the three northeastern provinces of China has reached about 35 million kilowatts。 But after the cold air passed on September 21. Wind power output has decreased significantly. During the recent power outage. Wind power output is far less than 10% of installed capacity. Liaoning Province launched 3 rounds of Class II (load gap 10-20%) orderly power consumption measures. In some periods, under the implementation of orderly power consumption measures with a maximum of 4.1692 million kilowatts, there is still a power supply gap in the power grid. According to the Regulations on the Administration of Power Grid Dispatching. The dispatching department of the northeast power grid shall follow the relevant plan. Directly issued an order to implement the "power grid accident brake power curtailment". A pre-notice of power curtailment of the Northeast Power Grid issued by the Northeast Power Dispatching Center of the State Grid on September 23 shows that the frequency adjustment means of the whole network have been exhausted. The Lugu DC to Shandong and Gaoling DC to North China lines do not have room for reduction. The system frequency is below 49.8 Hz. According to the relevant documents. To ensure the safe operation of the power grid. Take the accident to pull the brake and limit the power.

The addition of energy storage can give full play to its role in peak shaving and valley filling. Significantly improve the utilization rate of new energy. As shown in Figure 2, during periods of low electricity demand (blue), the maximum output of the wind turbine is greater than the output of the scheduled schedule. At this time, the energy storage device can be charged. During periods of high electricity demand (orange), the maximum output of the wind turbine is less than the dispatch plan arrangement. At this time, the energy storage can be discharged. Meet the power demand of the grid.

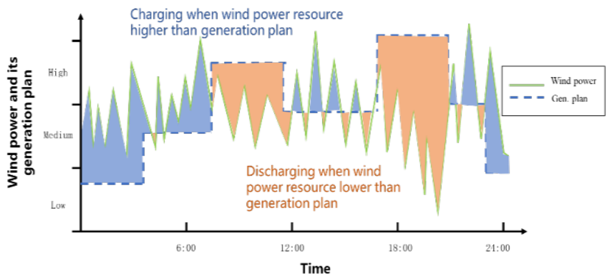

Fig. 2. Energy storage-new energy joint to improve the utilization rate of new energy

2.2The withdrawal of traditional thermal power units has led to serious "hollowing-out" of the load center power supply

With the construction of new power systems, conventional coal-fired units were decommissioned. The phenomenon of "hollowing" of the load center power supply is prominent. Take the Chengdu power grid as an example. Its maximum load has reached more than 20 million kilowatts. However, the installed capacity of Chengdu's power grid is only 3 million kilowatts. Long-distance generator sets can provide active support though. However, it cannot provide sufficient reactive power support for the Chengdu power grid. This makes it difficult to restore the grid voltage after a serious failure. Serious restrictions on the safety of electricity.

In view of this, the appropriate deployment of large-scale energy storage in the load center is an important way to solve the lack of hollowing voltage support capacity of power supplies. As shown in Figure 4, under the large mode of the abundant water period, the Kangding channel sends 6.3 million kilowatts (not exceeding the sending limit specified by the dispatch). After the N-2 fault of the Kangding hydropower transmission channel, the voltage of Chengdu's power grid cannot be restored to normal levels. It is necessary to limit the sending capacity of the Kangding channel to 600,000 kilowatts. If a 600,000 kilowatt pumped storage unit is added to Dayi(e) [5], the voltage of the Chengdu power grid will be effectively supported. In the case of Kangding sending 6.3 million kilowatts, the voltage recovery ability after failure can also be maintained.

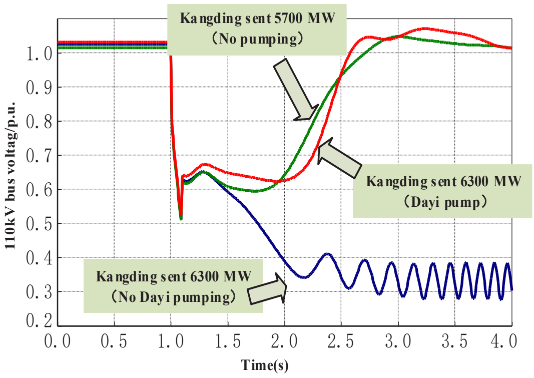

Fig. 3. Dayi pumping improves the voltage stability of Chengdu's load center

2.3Shock loads have a great impact on the quality of power supply

Power quality is important for sensitive equipment that needs to be protected. For example, in industries with high power quality requirements such as chip manufacturing and precision machine tool processing, energy storage to improve power quality is a good solution and good returns.

A typical scenario for this type of energy storage application is to deal with the impact load of electric iron. Energy storage can play an important role. The golden line of the Los Angeles subway in the United States is due to the frequency of train starts. It is far from the substation. Directly caused the net pressure to fall seriously here. Low power quality poses a safety hazard to train operation [6]. In order to improve the serious problem of voltage drops at the end of the traction power supply system, a flywheel energy storage system was installed in the substation with an installed capacity of 1 MW. Used to support traction net pressure. When the train starts, the flywheel stores energy to release power. Raise the bus voltage. When the train brakes, the flywheel energy storage absorbs power. Suppresses bus voltage rise. Ensure the stable operation of the train.

3. THE DEVELOPMENT STATUS OF ENERGY STORAGE TECHNOLOGY

At present, typical energy storage that is widely concerned at home and abroad can be divided into physical energy storage, electrochemical energy storage, electromagnetic energy storage and other categories according to the type of medium. Physical energy storage is a form of energy storage technology that generates storage and energy by physical means. According to the specific technology, it can be divided into three categories: pumped hydro storage, compressed air energy storage and flywheel energy storage. Electrochemical energy storage is a form of energy storage technology that generates storage and energy in the form of electrochemistry. According to the specific technology, it can be divided into lead-acid batteries, sodium-sulfur batteries, lithium-ion batteries and flow batteries. Electromagnetic energy storage is a form of energy storage technology that generates storage and energy through electrical conversion. It mainly includes two categories: supercapacitors and superconducting energy storage.

3.1Pumped storage[6]

Pumped storage is the most mature and widely used energy storage method in the current power grid. Pumped storage power stations use electricity from electricity at low troughs to pump water into the upper reservoir. During the peak period of power load, the water is then released to the lower reservoir to generate electricity, and the application of peak shaving and valley filling is realized. Pumped storage technology has the advantages of large adjustment capacity, fast load response, fast climbing rate, simple operation mode and long service life. The rated power and rated capacity of pumped storage power stations are large. It is generally a megawatt-level project. It has the ability to cooperate with large-scale nuclear power plants, large-scale wind power generation, and ultra-large-scale solar photovoltaic power generation. So as to provide effective support for the consumption of clean energy. However, pumped storage technology has high environmental requirements. The location of the power station depends on geographical conditions. There are certain difficulties and limitations. In addition, large project investment and long construction period are also constraints affecting its development.

3.2Compressed air energy storage

Compressed air energy storage is the use of electricity as a driving force to compress the air. When electricity is needed, the compressed air is released to generate a form of energy storage that drives the generator to generate electricity. Since 1949, the first compressed air energy storage patent has been present. Compressed air energy storage technology has been implemented in a variety of forms. It mainly includes non-adiabatic type, adiabatic type, and isothermal type. Compressed air energy storage projects have little environmental pollution and high safety factor. It is often used to adjust the peak-to-trough difference. The technical shortcoming of conventional compressed air energy storage is the low efficiency of the whole process. However, at the beginning of the 21st century, the severe challenges of the environmental climate and the demand for grid-connected consumption of new energy electricity. Awakening the research boom in advanced compressed air energy storage technology [7]. The gradual maturity of heat storage technology and its successful application in the field of centralized solar thermal technology have made many countries and regions focus on the research and engineering demonstration of a new generation of advanced insulation compressed air energy storage technology[8]. At present, the efficiency of advanced adiabatic compressed air energy storage systems can reach more than 60%.

At present, there are a number of compressed air energy storage demonstration projects at home and abroad. In October 2012, with the support of the State Grid, Tsinghua University, together with the Institute of Physics and Chemistry of the Chinese Academy of Sciences and the

China Electric Power Research Institute, carried out research on the key technologies of compressed air energy storage. In March 2014, the Institute of Engineering Thermophysics of the Chinese Academy of Sciences built an integrated experimental system for 1.5MW advanced compressed air energy storage in Langfang, Hebei Province, and completed 600 hours of test operation and performance test[9]. In December of the same year, Tsinghua University built the 500kW compressed air energy storage experimental system TICC-500 in Wuhu, Anhui Province. In December 2016, the Institute of Engineering Thermophysics of the Chinese Academy of Sciences, Huazhong University of Science and Technology, and China Southern Power Grid Corporation jointly carried out the joint commissioning of the integrated experiment and R&D platform of the 10MW compressed air energy storage system in Bijie, Guizhou[12]. In March 2018, the National Energy Administration's "2018 Energy Work Guidelines" pointed out that "actively promote the Jiangsu Jintan compressed air energy storage project." Research advances 100MW compressed air energy storage power plants"[13]. Looking at the world, Germany, the United States, Canada, Austria, Switzerland and other countries have announced, designed or built a number of compressed air energy storage power stations.A typical example is the Swiss company ALACAES dedicated to the development of thermal storage technologies for compressed air energy storage. A 1MW compressed air energy storage demonstration system was built in Biasca, Switzerland, in 2016[14].

3.3Electrochemical energy storage[6]

1) Lead-acid batteries are the earliest rechargeable batteries used in history. Today's lead-acid battery technology has been very mature. The manufacturing process is not complicated. Manufacturing costs are also relatively low. But the charging process of lead-acid batteries is slow. Can not be deeply charged and discharged, and the cycle life is short, the energy density is small, the volume is large. The lead and sulfuric acid used in raw materials are highly toxic, and leakage will endanger the environment.

2) Sodium-sulfur batteries are - batteries that can work in high-temperature environments. It can be used as a large-scale energy storage device in a variety of applications. Such as power quality, peak shaving and valley filling, as well as the control and integration of new energy power generation technology. Sodium-sulfur batteries have high energy and volume specific power. Energy efficiency of up to 80% or more, long cycle life, inexpensive manufacturing materials, sealed structure, insensitive to ambient temperature, and can work at a variety of different charge and discharge rates, discharge depths and discharge temperatures. Its limitations lie in the difficulty of maintaining energy efficiency and providing sufficient standby time, and the ceramic electrolyte used in the battery, which carries the risk of rupture under high thermal stress conditions.

3) Lithium-ion batteries are currently widely used in power systems. Its main advantages include fast charging response speed and high charging and discharging efficiency. In the prior art, the charging and discharging efficiency of lithium-ion batteries can reach more than 95%. However, the price of lithium-ion batteries is high and it is easy to overcharge and heat. There are certain security risks. The development of early lithium-ion batteries has played a great role in promoting the development of mobile electronic devices. However, the safety and cost constraints of traditional lithium-ion batteries make their applications often limited to small mobile electronic devices. To a large extent, it limits its large-scale application in grid energy storage. In recent years, the research and development of lithium-ion batteries has focused on the development of safe, efficient and inexpensive cathode materials. In the late 1990s, lithium iron phosphate (LiFePO4) was successfully synthesized. For the first time, the cost of lithium-ion batteries has been reduced materially. With the continuous expansion of production scale and the increase of application scenarios, the price of lithium-ion batteries has gradually declined. Therefore, the application in the power system is also increasing.

4) Flow battery is a new type of environmentally friendly battery. Rated capacity and power ratings can be designed and configured independently for high flexibility. Deep charge/discharge can be performed, and the energy storage capacity and output power are large. The liquid phase reaction of the flow battery makes it less electrochemical polarization effect than the solid phase change of ordinary batteries, and the dynamic response speed is faster (milliseconds). At the same time, its cycle life is long (design life up to 20 years), reliability and safety are high. The recycling of the electrolyte and the simple construction of the battery make it less expensive to material, renew and maintain, and environmentally friendly. In recent years, it has been favored at home and abroad, and the prospects are broad.

4.THE DILEMMA

4.1The technical safety of electrochemical energy storage

Electrochemical energy storage power stations have different degrees of safety risks in the battery body manufacturing, equipment selection, system integration, power station design, operation and maintenance. In recent years, there have been frequent fire or explosion accidents in electrochemical energy storage power stations. This is due to the fact that energy storage batteries are extremely prone to fire and explosion risk in the case of thermal runaway. The main causes of thermal runaway include: battery overcharge and overdischarge, electrical abuse caused by short circuit, and exothermic reactions between the positive and negative electrodes and the electrolyte inside the battery. In terms of battery intrinsic safety technology, it is necessary to develop flame-retardant and non-combustible electrolytes with good chemical properties and high safety and cathode materials with high safety. Key technologies such as battery intrinsic safety control, single battery status control, and battery thermal runaway barrier also need to be broken. From the perspective of process safety, the preliminary planning of the construction of electrochemical energy storage power plants is in a hurry. Individual projects have problems such as weak designers and inconsistent technical standards. As a result, there are functional safety design defects in energy storage power plants.

In addition, safety accidents in electrochemical energy storage power plants are often caused by lack or lag of early warning. The fault diagnosis and early warning of the energy storage system and the overall safety design technology need to be broken. Investment efforts also need to be strengthened. In terms of fire safety, the fire prevention and fire extinguishing control of energy storage power stations is insufficient. The existing firefighting measures in some energy storage power stations are not configured for battery fires. At this stage, it is necessary to develop clean and efficient fire extinguishing agents and adopt more accurate and efficient fire prevention and extinguishing strategies. When building energy storage power stations, when it comes to economy and cost, it is often the first to cut the cost of fire safety, thus sacrificing the safety of energy storage power plants. At present, the fire safety level of energy storage power stations needs to be improved urgently. Finally, in terms of safety standards and management systems, there are deficiencies in relevant domestic safety standards. Some standards require relatively loose indicators, and the safety management system of energy storage power stations has not yet been improved. Further specification and refinement is needed.

4.2The cost of energy storage is relatively high

During the *13th Five-Year Plan* period, the cost of energy storage is about 0.4 to 0.6 yuan. Among them, pumped storage power stations have the lowest cost of electricity, followed by compressed air energy storage. Electrochemical energy storage has the highest cost of electricity. At present, the cost of electrochemical energy storage is still far from the target cost of large-scale application. Not suitable for large power gaps that support large amounts. In addition, investment costs alone do not accurately reflect the cost of an energy storage system over the entire operating cycle. By quantifying the life-cycle cost of energy storage systems, the economy of energy storage systems can be more accurately measured. If you consider the whole life cycle cost of electrochemical energy storage power plants, you need to cover the initial investment costs, operation and maintenance costs, replacement costs, charging costs, recovery costs, etc. The cost of electricity will be higher. In the future, the cost of electrochemical energy storage can be reduced by optimizing operating parameters such as the number of cycles and charging prices.

4.3The business model of energy storage is not clear

Although energy storage technology has significant advantages, it has always been difficult in terms of real business development. There is no business path that can be developed for a long time. Relatively backward in terms of profit model. There is also not much room for profitability. The energy storage industry currently relies mainly on peak-to-valley electricity spreads to achieve profitability. However, there are still differences in electricity demand and supply patterns in different regions. The economic restructuring of some provinces has affected the operation of enterprises. Even if there is a reasonable electricity price difference, it cannot promote the work to be carried out, which further affects the stability of the profitability of the energy storage industry.

In addition, in the current business model, due to the small participation of energy storage stakeholders, the investment and operation of energy storage power stations are unattractive, and the energy storage profit model is relatively single. It is difficult to achieve multiple application scenarios to obtain benefits. In order to diversify the cost composition and enhance the revenue of energy storage. It is necessary to actively explore innovative business models such as shared energy storage, and improve supporting investment and operation incentive policies.

5. THE FUTURE DIRECTION OF LARGE-SCALE ENERGY STORAGE

In the future, the power grid needs to be deeply integrated with large-scale energy storage, so that the power system has a certain energy storage capacity to cope with the characteristics of intermittent and uncertain new energy and ensure the continuity of power supply for users. On the other hand, with the withdrawal of small-capacity coal-fired units and the access of new impact loads, the power grid is facing the problems of "hollowing-out" of power supply and insufficient quality of power supply on the load side. However, there are many problems in the safety, economy and institutional mechanism of the current large-scale energy storage technology, resulting in the inability of energy storage to achieve large-scale application. In view of this, the future development of energy storage has the following three important directions:

1) Continue to deepen the research and development of new technologies for energy storage bodies. Strengthen the research and development of new energy storage technologies such as full-power variable speed pumping, advanced adiabatic compressed air energy storage, sodium-ion batteries, and all-vanadium flow batteries, continuously improve the energy density of energy storage media, reduce energy storage costs, improve energy storage conversion efficiency, and improve the overall safety of energy storage systems.

2) Continue to strengthen energy storage to actively support power grid technology research. Strengthen the research of micro-meteorological forecasting, load forecasting, virtual synchronizers, virtual power plants and other technologies to promote the friendly interaction between source network load and storage, fully tap the potential of energy storage, and escort the safe and stable operation of large power grids.

3) Continue to carry out research on new application scenarios and business models for energy storage, and promote the establishment of market-oriented institutional mechanisms for energy storage. Establish and improve

mechanisms for energy storage to participate in the medium- and long-term electricity market, electricity spot market, power auxiliary service market, carbon trading market, etc., and explore diversified application scenarios and business models for energy storage.

6. Conclusion

In the context of new power system construction, energy storage will be further developed and play a key role in system supporting. Pumped storage and lithium battery technologies are basically mature and have been widely used. However, all kinds of energy storage have their own technical limitations, such as large geographical restrictions and long construction period on pumped storage; the fire hazards and low charge-discharge times on lithium batteries. So the development of energy storage needs to adapt to local conditions. In order to stimulate the development and application of energy storage technology, it is necessary to further improve energy storage related mechanisms, including spot electricity market and auxiliary service market.

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