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Application research on large-scale battery energy storage system under Global Energy Interconnection framework

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Abstract: In the context of constructing Global Energy Interconnection (GEI), energy storage technology, as one of the important basic supporting technologies in power system, will play an important role in the energy configuration and optimization. Based on the most promising battery energy storage technology, this paper introduces the current status of the grid technology, the application of large-scale energy storage technology and the supporting role of battery energy storage for GEI. Based on several key technologies of large-scale battery energy storage system, preliminary analysis of the standard system construction of energy storage system is made, and the future prospect is put forward.

Keywords: Global Energy Interconnection, Large-scale energy storage, Key technology, Standard system.

1 Introduction

Under the overarching trend of GEI, energy storage technology is the key to improve the large-scale development of clean energy and safe, and guarantee the power grid safe and economical. By installing electricity storage units at key nodes of power system, a 'rigid' power system of real-time balance could be turned into a 'flexible' system to ensure the safe and steady operation of local grid [1,2].

This paper takes a look at widely applied battery energy storage technology, analyzes the current status of power system, and then proposes the supportive role played by battery energy storage under the GEI framework for power system. In addition, the paper introduces the current application of large-scale battery energy storage technology and several key technologies in battery energy storage systems, carries out preliminary analysis on the development of energy storage standard systems, and analyzes the future outlook for the development of battery energy storage technology.

2 Importance of large-scale battery energy storage under GEI framework

2.1 Improving the penetration rate of large-scale renewable energy

Areas that are rich in renewable energy are often sparsely populated and far away from load centers. They are often at the end of power grid with weak grid facilities. As power grid construction fails to keep up with the increasing proportion of large-scale renewable energy power generation, wind power and photovoltaic power are often discarded, and equipment utilization rate is low. Besides, due to the randomness and fluctuation of renewable energy, renewable energy can only generate

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electricity and cannot provide steady voltage frequency support. As a result, the inertia of power grid is diminished, and the operation stability of large power grid is affected. If we set up a battery energy storage station on the side of renewable energy power generation to supplement power and inhibit fluctuation, we can improve the adjustability of renewable energy such as wind and photovoltaic power, and strengthen the adaptability of power grid to renewable energy power generation [3,4]. Besides, the energy storage station could serve as allocable resources for power grid to provide auxiliary services to large power grid in combination with renewable energy, in order to cope with transient stability and the demand of short-time power balance of power grid, or issues such as blockage in transmission and distribution lines. Moreover, it can expand the application space and scope of renewable energy power generation, improve the utilization rate of renewable energy equipment, and increase power generation hours.

2.2 Supporting UHV grid construction

As the proportion of sensitive loads and summer cooling loads in the overall load of power system keeps increasing, along with the increase of the proportion of integrated renewable energy, the safety and stability of UHV lines are affected, and UHV transmission is under pressure. Battery energy storage station, by virtue of their swift response, can quickly absorb or release electricity to achieve complete power balance in emergent situations. When power failure occurs due to system breakdown, battery energy storage station can transmit power to the key load of the local grid, to prevent losses due to power outage. Battery energy storage station could improve the utilization rate of UHV lines and ensure the safe and stable operation of UHV grids because it could be deployed flexibly.

2.3 Coordinating distributed power sources across regions

Due to the fluctuation and unpredictability of renewable energy, with the penetration of renewable energy generation increasing, power grid will be susceptible to excessive fluctuation when the weather changes. Even if the local grid is equipped with certain regulating units, due to the limitation of the regulation, the grid may not satisfy the short-term demand of its load, and consequently, the quality of its electricity is affected, and the power system may even lose its balance, resulting in irrecoverable economic losses. As a solution, when the frequency or voltage fluctuation in local grid exceeds a certain threshold, we can adopt power grid dispatching or node control measures to find utilizable distributed energy storage capacities in interconnected grid, to achieve real-time electricity distribution across regions, or coordinate multiple distributed energy storage stations for joint supply. In this way, we can meet the demand for adjusting and controlling the local grid, improve the controllability of distributed power sources, and improve the quality of electricity supply for local grid. It is of great significance for ensuring safety and reliability.

2.4 Increasing the freedom of electric power trading

With the promotion of Chinese power system reform and increasing openness of electricity market, the market trading subject is changing, and electric power trading becomes more and more flexible. In order to reduce the impact on the safe operation of power grid, battery energy storage can be used as key technology to stabilize power output and provide backup power. This can also help adjust electricity prices and optimize the allocation of electricity resources on the market. As the electric power trading market expands, cross-region electric power trading and direct trading with big customers can be realized, to reduce risks of electricity supply by electricity-selling companies and provide better quality electricity sources to power grid. It can also enhance the bargaining power of electricity-selling and power generation enterprises, and realize free competition and free trading of electricity.

3 Current status of large-scale battery energy storage

As battery energy storage draws much attention around the world, its installed capacity is increasing greatly every year (as shown in Fig. 1). Major demonstration projects of large-scale battery energy storage include storage of lithium-ion batteries, sodium-sulfur batteries, flow batteries, lead-carbon batteries, etc. According to incomplete statistics from the US DOE Global Energy Storage Database, of all the existing battery energy storage stations in the world,

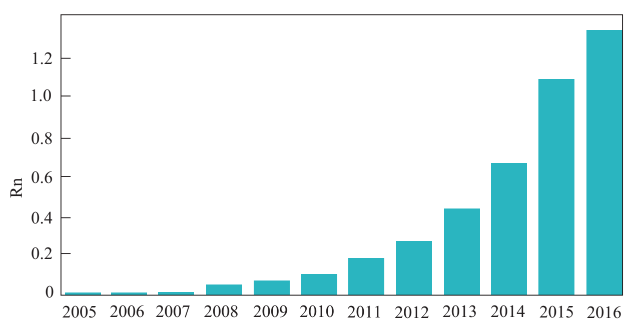

Fig. 1 Growth tendency of the installed capacity of battery energy storage stations in the world
(Data source: http://www.energystorageexchange.org/projects/data_visualization)

more than 400 are projects above the MW scale, and their total installed capacity is 3.3 GW. Among them, there are 96 projects above the 10 MW scale, with the total installed capacity of 2.5 GW [4]. Japan, USA, and China rank in the top 3 on the ranking of the installed capacity of electrochemistry energy storage. In Japan, sodium-sulfur battery energy storage is the main electrochemical energy storage technology, and its technological level is world-leading, but it is seldom used in other countries (only applied in the USA, UK, and Germany in small-scale). In the USA and China, lithium-ion batteries, flow batteries, and improved lead-acid batteries (lead-carbon batteries) are the main batteries used for battery energy storage, and multiple MW-scale demonstration stations of energy storage have been constructed in these countries. These battery storage technologies are also widely used in European countries [5]. Fig. 1 shows the growth tendency of the installed capacity of battery energy storage stations in the world.

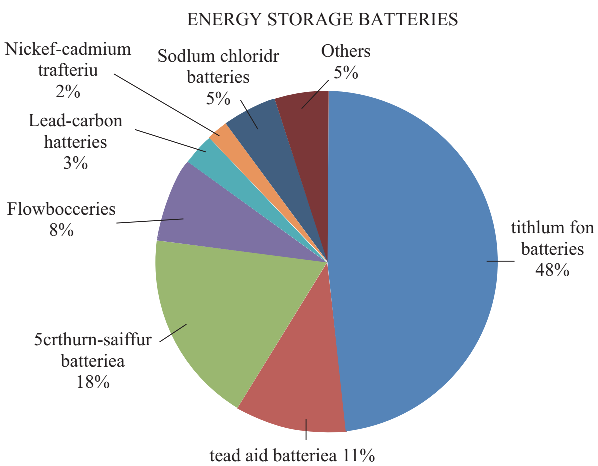

Fig. 2 Proportions of different energy storage batteries in MW-scale battery energy storage projects in China and in the world

Fig. 2 shows the proportions of different types of battery energy storage projects. As shown in the figure, lithium-ion batteries account for the highest proportion, about 48%; sodium-sulfur batteries account for 18%, and lead-acid batteries and flow batteries are also applied on a relatively large scale [6]. Lead-carbon battery, as an improved version of lead-acid battery, has drawn increasing attention in recent years because of its low pollution and low cost, and their demonstration project scale is increasing steadily.

3.1 Lithium-ion batteries

Lithium-ion battery is the most widely used energy storage battery, and the application types mainly include $LiFeO_4$ battery, ternary Li-ion battery, and lithium titanate battery. In 2013, a 40MW/20 MWh lithium battery frequency regulation power station was constructed in Sendai Substation in Miyagi Prefecture, Japan for the purpose of regulating power grid frequency to prevent instability. In 2017, a 30 MW/120 MWh lithium battery energy storage project was constructed in Escondido, near San Diego by San Diego Gas & Electric (SDG&E). This project was proposed as an energy storage solution to the electricity capacity shortage caused by the Aliso Canyon gas leak accident. It took just six months to complete the construction and put into operation, and it’s the largest lithium-ion battery energy storage project in the world. Meanwhile, with the development and popularization of electric vehicles, automakers such as Tesla and BMW have constructed demonstration power stations for their power battery teams to recycle waste batteries. In October 2017, BMW announced that it would use 500 battery packs replaced in the i3 model to construct an energy storage station, which is expected to provide 3/4 of the power of the BMW Leipzig factory. In China, lithium battery energy storage is developing rapidly and has so far been applied to pilot projects in multiple scenarios, such as renewable energy grid integration and improvement of electricity quality. The most typical application is the Wind and Photovoltaic Energy Storage Demonstration Project in Zhangbei, China, where 14 MW/63 MWh $LiFeO_4$ batteries and 1 MW/500 kWh lithium titanate batteries are configured along with wind power and photovoltaic power generation units to provide 6 operating modes. The project is used to test the contribution of energy storage batteries in tracking planned output, balancing renewable energy power generation, frequency regulation, voltage regulation, etc. In 2011, China’s first MW-scale battery energy storage station – Shenzhen Baoqing Energy Storage Station was constructed by China Southern Grid with the total capacity of 6 MW/18 MWh, and this station provides multiple functions such as load leveling, emergency system frequency regulation, emergency system voltage regulation, and backup power supply. In August 2016, China’s largest-scale PV energy storage station was constructed in Golmud, Qinghai Province, configured with 15 MW/18 MWh $LiFeO_4$ batteries to resolve the local issue of restricted electricity supply and unused PV power to improve the overall utilization of photovoltaic power. A number of distributed energy storage stations has been constructed by Jiangsu Grid and some are under construction, with a view to utilize the peak-valley difference of industrial and commercial electricity prices and implement the policy of “energy storage in low-load hours and release in peak hours” to achieve economic benefits. Table 1 shows some recent energy storage

Table 1 Recent projects of energy storage stations of Vanadium flow battery batteries

Project Name	Location	Rated Output Power/MW	Function	Time
Energy storage project of lithium ion batteries at Sendai Substation	Miyagi Prefecture, Japan	40	Frequency regulation and elimination of grid instability	2013
Mount Laurel energy storage station	West Virginia	32	Peak clipping & valley filling and smoothing wind power output	2014
Anjiamo lithium ion battery energy storage system	Meijilones, Chile	20	Power smoothing and voltage regulation	2013
Los Andes lithium ion battery energy storage system	Copiapo, Chile Table 1 Recent projects of energy storage stations of Vanadium flow battery batteries	12	Peak clipping & valley filling and backup power supply	2014
US SDG&E Escondido energy storage project	San Diego	30 MW/ 120 MWh	Participating in CAISO current and real-time electricity markets, and automatically responding to market signals	2017
Zhangbei Wind and Photovoltaic Energy Storage Demonstration Project	Zhangbei, Hebei	14 MW/ 63 MWh 1 MW/500 kWh	Smoothing wind power and peak clipping & valley filling	2012
Shenzhen Baoqing Station	Shenzhen, Guangdong	6 MW/18 MWh	Regulation of peaks, frequency, and voltage, and emergency backup	2011
Golmud photovoltaic energy storage station	Golmud city	15 MW/18 kWh	Improving the penetration rate of photovoltaic power	2016
Singapore industrial park energy storage system	Wuxi, Jiangsu	9 MW/72 MWh	Implementing the policy of "energy storage in low-load hours and energy release in peak hours" for economic benefits	2017

stations of lithium-ion batteries.

3.2 Flow batteries

There are many flow battery research systems, and among them, vanadium flow batteries are the most widely applied, with major suppliers including Japan Sumitomo, Dalian Rongke Power, and Beijing Puneng, etc. In May 2016, Japan Sumitomo reached an agreement with a large US power company named San Diego Gas & Electric to use vanadium flow battery technology to provide auxiliary services (such as frequency and voltagecontrol, emergency backup power supply, etc.) and to help California achieve the objective of increasing the penetration rate of renewable energy to 33% by 2020. In 2013, China's largest vanadium flow battery energy storage station was constructed by Dalian Rongke Power in Woniushi wind farm in Liaoning Province, China, with the capacity of 5 MW/10 MWh. This station is used for tracking planned power generation and smoothing the output of renewable energy. In 2016, Dalian RongkePower joined hands with Dalian City Thermoelectric Group to construct a 200 MW/800 MWh energy storage station for peak shaving & valley filling on users' side. In the second half of 2017, Beijing Puneng and Hunan Dovop Electric announced their plans to construct a 10 MW/40 WMh vanadium flow battery energy storage station, in combination with renewable energy, to provide functions such as tracking planned output, peak regulation and frequency regulation for power grid. Table 2 shows some recent projects of flow battery energy storage stations.

3.3 Lead-carbon batteries

Lead-carbon batteries are improved lead-acid batteries and have the characteristics of both traditional lead-acid batteries and super capacitors. Lead-carbon batteries can significantly improve the performance of traditional lead-acid batteries in terms of the charging rate and recycle service life, and have such advantages as good safety, high recycling rates (up to 97%), and low costs. Large-scale applications are on the increase. Leading suppliers of lead-carbon batteries such as US East Penn Manufacturing and Xtreme Power have constructed multiple MW-scale demonstration projects. The largest project is the one constructed by Xtreme Power in cooperation with Duke Energy. They built the world's largest 36 MW lead-carbon battery energy storage project at the Duke Notrees wind plant in the US to facilitate the utilization of wind power. In China, Narada Power was the first lead-carbon battery supplier to launch commercial operation. Multiple MW lead-carbon battery demonstration projects

Table 2 Recent projects of flow battery energy storage stations

Location	Storage System Scale	Functions	R&D Unit	Time
Ireland wind plant	2 MW×6h	Wind power storage, power generation, and grid integration	VRB Power System Inc. Canada VRB Power System Inc.	Aug. 2006
Hokkaido	4 MW/6 MWh	Smoothing wind power output		2005
US Gills Onions	3.6 MWh	Improving the overall quality of power generation, distribution, and utilization	Puneng	May 2012
Zhangbei Wind and Photovoltaic Energy Storage Demonstration Project	2 MW/8 MWh	Tracking planned power output, and smoothing renewable energy power generation	Puneng	2012
Guodian Longyuan 50MW wind plant in Woniushi, Faku County, Liaoning Province	5 MW/10 MWh	Tracking planned power output, smoothing output, and improving the acceptance of renewable energy power generation in power grid	Dalian Rongke	Nov. 2013
Dalian City Thermoelectric Group energy storage station	200 MW/800 MWh	Peak clipping & valley filling, and improving the penetration rate of renewable energy	Dalian Rongke	2016

have been constructed so far. The most typical project is the distributed energy storage station in Wuxi Singapore Industrial Park, which is currently the largest commercial energy storage station in China. Its total capacity is 20 MW/160 MWh, and stage I of the project (9 MW/72 MWh) was put into operation in June 2017. Stage II is now in the overall commissioning phase, and it is expected to put into operation by the end of this year. Table 3 shows some recent projects of lead-carbon battery energy storage stations.

Table 4 lists the relevant parameters and characteristics of the energy storage batteries stated above.

Table 3 Recent projects of lead-carbon battery energy storage stations

Battery Energy Storage System	Location	System Capacity	Application	Date
Kaheawa I&II, Kahuku wind power station	Maui and Oahu in Hawaii	10MW/20MWh 15 MW/10 MWh	Harmonic control Filtering Voltage regulation Frequency correction	2011
Duke Notrees wind power storage station	Goldsmith in western Texas, USA	36 MW/24 MWh	Peak clipping Power stabilization	2012
North America superconducting power transmission	Clovis in New Mexico, USA	~100 MW, ~200MWh	Auxiliary services Wind power stabilization Peak clipping	2013
Singapore industrial park energy storage station	Wuxi, Jiangsu	20 MW/160 MWh	Peak clipping & valley filling	2017
Energy storage station in Wuxi Xingzhou Industrial Park	Wuxi, Jiangsu	15 MW/120 MWh	Peak clipping & valley filling	2017

Table 4 Parameters and characteristics of different types of energy storage batteries

Energy Storage Type	Recycle Life (Times)	Safety	Energy Density (Wh/kg)	Cost	Energy Efficiency
Lithium-ion batteries	2000~10000	Effective monitoring is required for ensuring safety in use.	70~200	(1500~4500) Yuan/kWh	>90%
Vanadium flow batteries	10000	Aqueous electrolyte, relatively safe	30~50	15000 Yuan/kW, 3000 Yuan/kWh	>60%
Lead-carbon batteries	2000~3000	Aqueous electrolyte, relatively safe	40	(1000~1500) Yuan/kWh	>80%

4 Key technologies of battery energy storage under the GEI framework

4.1 Battery materials

At present, batteries for which demonstration projects of energy storage have been carried out or major breakthroughs have been made include vanadium flow batteries, lead-carbon batteries, lithium-ion batteries, and sodium-sulfur batteries (mainly in Japan). Cutting-edge batteries worth paying attention to in the future include solid lithium batteries, sodium ion batteries, and other new types of batteries.

Lithium-ion batteries have many advantages such as long service life, high efficiency, high energy density, and high power density. $LiFeO_4$ batteries were initially developed for electric vehicles and are therefore relatively safe, with mature industrial chain development and rapid cost reduction. The key aspect for future breakthroughs is to further improve the recycle service life and lower costs. Zero-strain material lithium titanate is used as the negative electrode for lithium titanate batteries, which perform better than $LiFeO_4$ batteries in terms of the recycle service life and recycling rate. Lithium titanate batteries are promising because the cost can be lowered to meet the overall demand for large-scale energy storage application. Traditional liquid organic electrolyte and diaphragm in traditional lithium-ion batteries is replaced by solid electrolyte for solid lithium batteries, to prevent potential risks related to organic liquid electrolyte and prevent scenarios where charging, internal short circuit, or other abnormalities cause the liquid electrolyte to overheat or even cause fires and explosions. In this way, issues of safety could be resolved. Besides, compared with liquid electrolyte, solid electrolyte can diminish the occurrence of side reactions and could extend the service life in theory. By virtue of these characteristics, solid lithium batteries will have a very bright prospect in the field of large-scale energy storage. The key issues are developing high-ion-conductivity electrolyte and resolving the interface issues between solid electrolyte and the electrodes.

Sodium-sulfur batteries have pioneering advantages, and there has been abundant engineering experience. However, in terms of the overall performances, especially safety, sodium-sulfur batteries can hardly compete with other batteries. Vanadium flow batteries have lots of advantages such as long cycle life, easy adjustment (thanks to separate energy and power design), recyclable electrolyte, and optimal safety, but the applicable temperature range should be further extended, energy efficiency should be further improved, and costs should be further lowered. Lead-carbon battery is a new type battery developed on the basis of traditional lead-acid battery, and has made significant improvements on the recycling rate and recycling service life. Their production process is relatively simple, and the costs are relatively low.

Sodium ion battery is a new technology used to replace lithium-ion battery. Sodium is a cheap, non-toxic, and rich element, evenly distributed around the world. Compared with lithium-ion batteries, sodium ion batteries can free us from dependence on lithium resources, help lower costs, and be applied to large-scale energy storage. At present, sodium ion battery R&D is in a transition from laboratory research to industrialization. Hopefully, with the existing technology and equipment of lithium-ion batteries, proper sodium ion batteries can be produced within a short time to meet the demand for energy storage.

4.2 System operation control

A large-scale battery energy storage station usually consists of multiple battery packs and power conversion systems (PCSs). The design of the operation control strategy for the station and the distribution of power among battery packs will have a direct impact on the operation of the station. At present, there are two aspects in the research on the operation control strategy of energy storage stations. On one hand, various functions (such as stabilizing and inhibiting fluctuation of renewable energy, tracking planned power output, and peak shaving & valley filling) are used to determine the total output of energy storage stations. On the other hand, the internal power distribution methods and operation strategy of energy storage stations is studied [7]. PCSs play a key role in the operation management of energy storage stations, serving as the medium between batteries and large power grids, as well as a control management unit for the charging and discharging of batteries. Therefore, research on the operation control of large-scale energy storage stations is currently focused on PCS optimization control for situations of multi-unit parallel operation.

In [8,9], a unit is selected as the master control unit, and other slave control units carry out instructions from the master control unit to implement power control. However, once the master control unit fails, the entire system will breakdown. In peer-to-peer control mode, each energy storage unit operates independently and plays an equal role. In [10], an energy storage system is connected to a microgrid as a distributed power source, and active and reactive power equalization is studied. In [11], a layered energy storage control system is adopted, consisting of two layers: fluctuation stabilization layer and energy control layer. The fluctuation stabilization layer calculates the total power demand of the energy storage unit from the perspective of power grid, whereas the energy control layer calculates the power output from the perspective of energy storage. [12] establishes the transfer function between different excitation sources and grid-connected current and puts forward the idea that resonant peaks will gradually move towards the low-frequency end as the number of parallel-connected units increases. [13] uses the superposition principle to deduce the grid-connected current for LCL inverters under parallel operation and proposes that when all inverters have the same structure and reference power, n inverters under parallel operation can be simplified as one single inverter under operation with the grid-side impedance increasing n times. [14] considers the impact of controller parameters on device stability and the different output powers of inverters, and proposes methods for analyzing the stability of multiple grid-connected PCSs operating in parallel at a large-scale energy storage station.

4.3 Monitoring and management

Large-scale energy storage stations mostly adopt a layered structure for their monitoring systems. This structure usually consists of a station control layer and a separation layer. The station control layer usually consists of one or several local monitoring work stations. The separation layer is responsible for information collection and control of the local unit. The monitoring systems of large-scale energy storage stations mostly adopt dual configuration and redundancy configuration for their networks and station control layers in order to improve reliability and to perform functions such as programmable control, communication, data processing, computing, statistical reporting, and automatic/manual control. [15] provides a detailed analysis of the functional requirements of large-scale energy storage stations for monitoring systems, summarizes the structure of typical monitoring systems of energy storage stations as well as their application development, and proposes requirements regarding the composition and structural layering of such monitoring systems. [16] takes into account the collection and analysis of electricity data and non-electricity data, and it develops an energy storage monitoring system for vanadium flow battery energy storage stations through optimization of control strategies and software/hardware design, achieving good results in optimizing energy effects.

For optimization management, investment cost or energy effect of energy storage station is usually served as optimization targets, and battery power is served as control object to solve energy distribution problems of batteries. Besides, the economic efficiency of energy storage stations is restricted by battery efficiency and capacity, and most current studies are focused on battery State of Charge (SOC) control. [7] analyzes restrictive conditions such as battery SOC, SOD (State of Discharge), and the maximum charging and discharging powers allowed for a single energy storage unit, and then the document proposes a battery power control method based on energy consistency among storage units, which effectively resolves the issue of real-time power distribution for energy storage stations. [17-19] detect battery voltage or SOC to restrict the charging and recharging powers. [20] collects the SOC of batteries and then changes the filtering time constant to adjust the SOC. In [21,22], based on the SOC feedback, a charging or recharging power value is directly added. If the SOC is too small, a preset charging power value is added to the energy storage system. If the SOC is too large, a preset discharging power value is added. Thus, quick SOC control is implemented. [23] proposes a layer-based and zone-based control optimization method to improve the monitoring and energy management of large-scale battery stations, effectively resolving core control issues such as optimized management of station energy, optimized control of reactive power, energy storage, smooth power generation by renewable energy, and tracking planned power output.

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