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Diverse Applications and Future Development Trends of Energy Storage Systems in Smart Grids

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Abstract. The notion of sustainable development has gradually become widely accepted worldwide, and the global energy system is undergoing a profound transition toward a low-carbon paradigm. As a result, renewable energy sources such as solar, wind, and hydropower are accounting for an increasing share of the overall energy mix. However, the inherent intermittency and volatility of renewable energy generation can lead to frequency and voltage fluctuations, potentially threatening the safe and reliable operation of power systems. It is against this background that the use of advanced energy storage systems in the construction system of smart grids, and the derivation of the key parts of the typical energy storage systems such as energy storage units, power conversion systems, monitoring and control systems, and auxiliary equipment are formally integrated into the framework of developing the paper, which proceeds to expound on the primary work principles; energy storage and conversion, dispatch, and the management. In addition, the paper also gives a comprehensive and ample discussion of how energy storage systems can be flexibly implemented in the power grid to equalise the extreme changes in new energy generation, as a dependable black start and emergency power supply to support steady power supply during grid outages or emergencies, and eventually enhance the stability, resilience and reliability of the power grid, thereby giving the major step towards integrating renewable energy on a large scale and achieving the global carbon neutrality target.

Keywords: Energy Storage System, Smart Grid, Distributed Energy Storage, Coordinated Control, Digital Integration

1. Introduction

As countries around the world increasingly focus on the concept of sustainable development, the global energy transition is accelerating. The large-scale use of renewable energy is replacing the role of traditional fossil fuels, but the instability of renewable energy has posed significant challenges to the operation of traditional power grids. For example, traditional energy networks face problems such as complex scheduling operations, imperfect market mechanisms, and impacts on grid harmonics [1,2]. Based on this, taking advantage of the high intelligence of smart grids and the bidirectional flow characteristics of energy storage systems, the combination of the two is the key to the large-scale application of renewable energy while ensuring stable operation.

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Nowadays, although the integration of energy storage systems with smart grids has already covered scenarios such as frequency regulation and voltage regulation, it still faces barriers in cost, coordinated control, and technology, which limit the large-scale development of energy storage systems in smart grids.

Based on this, this article reviews the diverse application scenarios of energy storage systems under the support of smart grids, delves into the development and future technological breakthroughs of energy storage systems, and finally proposes corresponding market policies to facilitate the development of energy storage systems within smart grids. It aims to provide a reference for the global energy transition and the integrated development of energy storage systems and smart grids.

2. Overview of smart grid

The smart grid is the core form of a new generation power system that deeply integrates traditional energy networks with modern technology. Its characteristics are mainly reflected in building a dynamic, controllable, and flexibly adjustable energy ecosystem through informatization, automation, and integration of big data analytics, achieving bidirectional interaction of power flow and real-time information sharing [3]. The essence of the idea of the smart grid is to increase the stability of the grid dispatching, power supply reliability, successfully trace the safety and cost-effectiveness of generation and user side, and more flexibly attend to any challenges caused by the process of energy transition and the diversification of the needs of users [4]. As per the schematic illustration of the smart grid in Figure 1, in contemporary cities, measurement equipment on various nodes is established with the smart grid. As an example, Advanced Metering Infrastructure (AMI) and Phasor Measurement Unit (PMU) are in use. Through the bidirectional communication characteristic of the smart grid, the energy demand response and management can be realized, and this assists in the effective management and use of energy [5]. Based on schematic figures of the smart grid in Figure 1, in the construction of a modern smart grid, the energy storage systems will be important in flexible regulation of the power supply network dynamic balance to ensure efficient operation of the smart grid; energy storage systems are a vital supporting technology in the establishment of a smart grid.

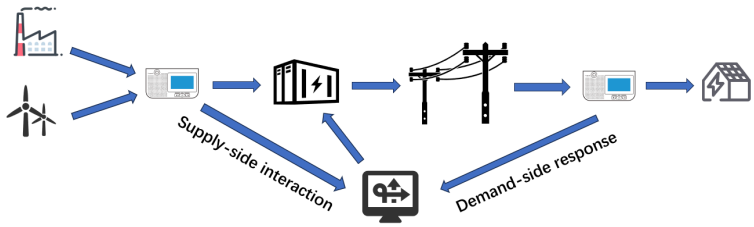


Figure 1. Smart grid diagram (photo/picture credit: original)

3. Basic components and technology of energy storage systems

3.1. Basic components and working principles of energy storage systems

The key value of an energy storage system is to hold the energy in different forms and then send it back out upon the request by the user of an increased amount of electricity than the amount supplied in the grid system, which causes the transfer of energy between different time scales. In modern energy storage systems, there are energy storage (S), power conversion system (PCS), energy

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management system (EMS), and auxiliary systems, as well as input and output equipment [6]. An energy storage system is all about the energy storage device, which is in charge of storing electrical energy. PCS transforms various types of electrical energy and aligns the power grid with the devices and power-saving. EMS is in charge of controlling the system regarding its performance, ensuring power system stability in general. The nature of an energy storage system is the temporary conversion of electrical energy into other forms of energy, and whenever it is required or because electrical energy is not always sufficient, then it can be converted back into electrical energy in order to maintain a stable power supply and a group running.

3.2. Diverse energy storage system technology applications

With the need for smart grids and renewable energy development, one energy storage system cannot maintain the multifaceted demands of the power systems and suffers from numerous constraints. Thus, to develop an energy storage system, one should take into account such factors as cost-effectiveness, the technical features of different storage technologies, policies and regulations, and environmental focus in the form of Table 1 in the appendix. In summary, it is noteworthy that the response times, application scenarios, benefits and drawbacks, and energy conversion rates of several popular energy storage technologies have to be found in Table 1. Table 1 summarizes the response times, application scenarios, advantages and disadvantages, and energy conversion rates of several common energy storage technologies.

Table 1. Comparison of key features of common energy storage technologies [7,8]

Energy storage system	Response Time	Application Scenario	Advantage	Disadvantage	Energy conversion rate
Electrochemical battery energy storage	$\leq$ 100ms	Distributed generation	High power density	High cost, high safety risk	85%-95%
Flywheel energy storage	$\leq$ 10ms	Power grid frequency regulation	Can be charged and discharged frequently	Low energy density, high technical barrier	85%-90%
Pumped storage	minute-level	Large-scale wind power base	Large storage capacity, low price	High geographical requirements	70%-85%
Compressed Air Energy Storage	minute-level	Centralized photovoltaic power generation	Zero carbon emissions	High construction costs and slow response times	40%-60%

As shown in Table 1, common energy storage technologies all have obvious advantages and disadvantages. To improve the operational efficiency of energy storage systems and promote their widespread adoption, it is necessary to use multiple energy storage technologies to build an energy storage system. Zhao is researching the energy storage system of a smart energy demonstration park. Through the optimized configuration of diversified energy storage, it is found that in this park, the electricity cost of a combination of battery storage and flywheel storage is lower compared to using only battery storage, and the total operating cost is reduced by 6.31% compared to using only battery storage [9]. In terms of photovoltaic utilization, diversified energy storage has increased by 4.31% compared to single battery storage [9]. In summary, using diversified energy storage technologies to build energy storage systems can significantly reduce electricity costs and also improve energy utilization.

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4. Application of energy storage systems in smart grids

4.1. Coordinated control of distributed energy storage systems

The distributed energy storage system mainly includes the energy storage inverter, energy storage battery unit, energy storage battery management unit (BMU), Building Control System (BCS), and fire protection system. The distributed energy storage system will help in better analysis of the regional grid and user loads, and in better management of the distributed energy storage information, which contributes to more efficient use of the system and increased flexibility of the system. Practically, the distributed energy storage systems may become targeted by dispatching the active distribution networks, mitigating the losses incurred in power transportation over a long distance, providing the basis of the implementation of the V2G innovation, and coordinating the scheduling and regulation of the integration of electric vehicles into the grid [10]. The environment has less influence on the distributed energy storage systems. When incorporated in the smart grid, they can modify the grid in real time, fast, based on the acquired information in the AMI and PMU, which is more effective in providing relief to the short-term shocks that are facing the grid [11]. Designed energy storage can organize power grid control to accomplish peak shaving, valley filling, minimize energy loss, as well as better utilization of the grid.

4.2. Level the new energy power generation variations

The new energy power generation is not usually predictable and may vary depending on numerous factors in the course of generation. In order to suppress the variability caused in the process of creating new energy power, energy storage is usually incorporated into a new energy power grid by a smart grid. Zhang suggested a hybrid energy storage two-layer power control scheme as a synthesis of different filtering algorithms and fuzzy control algorithms, and an energy storage system coupled. The theoretical calculations and sample analysis of this control scheme reduced the inertia rate of the grid to half, i.e., 13% was reduced to 6% [12]. This system would be able to address the capabilities of power volatility bound on the integration of new power generation into the grid. To counteract the fluctuations of new energy generation in layers, five hybrid energy storage systems exist: a flywheel energy storage system to smooth out its fluctuations due to gusts and cloud coverage, a lithium battery to smooth its fluctuations due to changes in sunlight intensity, and pumped storage to smooth its fluctuations due to changes in season.

4.3. Black start and emergency power supply of energy storage systems connected to the grid

Natural disasters vary each year across countries worldwide, and each area has a risk of failing to supply power when these disasters take place. This has caused all countries to use energy storage systems as a source to power a black start and emergency supply through real-time coordination by the smart grid [13]. Cai uses a grid-forming battery energy storage system (GFM-BESS) and obtained data through simulation tests. The GFM-BESS shows excellent performance in black start scenarios and has strong stability. The conversion time during the simulation process is consistently under 1 second, confirming the suitability of GFM-BESS for grid support applications [14]. In summary, compared to traditional black start and emergency power supply sources, GFM-BESS, with its advantages of fast response, strong stability, and high conversion efficiency, can address power outages more efficiently and provide a more reliable solution for grid black start and emergency power supply.

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5. Development and challenges of energy storage systems in smart grids

5.1. Coordinated interaction between the user side and the energy storage system

With the large-scale advancement of new energy power generation and the continuous opening of the electricity market, the small-scale photovoltaic installations in households have been steadily increasing, forming independent user-side energy storage systems (ESS) within the smart grid. Huang proposed a robust optimization method for user-side distributed energy storage. Through optimization algorithms and simulation experiments, it was found that the optimized system reduced the peak-to-average load ratio from 3.26 to 2.88 [15]. Using the robust optimization method compared to a single robust optimization method, the operating costs of each market participant have significantly decreased, with a maximum reduction of 22.15% [15]. It has been verified that robust optimization of user-side energy storage systems can improve coordination efficiency and stability, strengthen the interaction between the power grid and users, reduce transmission energy consumption, and provide economic benefits.

The production of alternative energy vehicles is fast, and their electric cars have a rate of penetration into the market of almost 50% [16]. Guo suggested building a V2G model on the parking lots of medium-sized companies and taking advantage of the coincidence between the time span of parking electric cars and the electricity peak consumption of the enterprise. Optimally, with subsidies on the participating users, the enterprise will save the cost of investing in energy storage systems and will reap the greatest good as the maximum load of the grid will be among 10 percent and 25 percent reduced [17]. Building a microgrid through the use of electric vehicles and smart charging stations can decrease the cost of creating the energy storage system, and by enhancing the level of relevant systems and subsidies, create better interaction and coordination between the user and the energy storage systems, and increase the socio-economic benefits.

5.2. Deep integration of energy storage systems and digital technology

The market share of renewable energy is expanding slowly but steadily, and demand-side compliance is escalating and which puts a greater burden on the working capacity of the energy storage systems to provide the users with a stable flow of electricity. As the modern digital technology evolves at high speed, a strong integration of energy storage systems and artificial intelligence (AI) with the aim of maximizing the timing of situations like new energy creation and load variations can enhance the accuracy and responsiveness of energy storage systems in the power grid [18]. The large-scale renewable energy production industry can also utilize the support of AI to analyze the charge and discharge data points of power stations and understand their health conditions to undertake timely system repair tasks; the issues of energy velocity slowness in energy scheduling and the development of variability reduction in the energy storage system can also be interpreted through the assistance of artificial intelligence and neural networks to determine how to optimally manage the system operation, and the system can change accordingly [19]. Dynamically empowered by the use of digital technology, the large-scale data collection and analysis conducted before constructing the large.

5.3. Safety and cost breakthroughs in large-scale applications

At present, the majority of the accidents to regular energy storage devices can be found in electrochemical energy storage devices due to their being a high energy density configuration type

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and a high response speed, which makes the electrochemical energy storage devices equally hazardous [8]. Based on current technological developments, it is proposed to use digital technology to intervene in and manage the monitoring of thermal data of electrochemical energy storage devices. If abnormal data is detected, the operation should be interrupted promptly and an alarm triggered. Firefighting facilities should be properly installed at the electrochemical energy storage devices, and regular inspections should be conducted to ensure the firefighting equipment is functioning properly.

Jiaxing analyzed the commercialization of electrochemical energy storage using the SWOT model, demonstrating that electrochemical energy storage systems can be applied in various scenarios [20]. Despite the rapid development of diversified energy storage systems, in residential settings, they remain mostly as electrochemical energy storage, since, due to constraints of geographical areas and costs, it becomes impossible to rely on electricity to balance peak loads, not to mention the emergency use of power. When there is not enough power in the grid to absorb generated electricity by electric vehicles, and can provide to the user the discounts of the parking fees and the parking facilities should be improved and optimized to make electric vehicles grid-connected charging and discharging more efficient and encourage the automobile companies to create the comprehensive system of charging and maintenance of batteries of the electric cars to secure the rights of the users of the electric vehicles.

6. Conclusion

Efficient functioning of smart grids is rooted in the energy storage systems. They are also indispensable in keeping the stability of power supply, enabling the utilization of renewable energy, as well as enhancing the efficiency of the energy systems in the smart grid environment. The introduction of the distributed energy storage system can optimize the grid structure and enhance the use of energy. Energy storage systems are useful in the management of the grid, evening out the wind and alleviation grid effects. They also demonstrate high functionality as a source of power in black starts and emergency power supply, causing the potential growth and the variety of value of the energy storage system.

As the energy storage systems ship through technological reiterations and maturation of the industry chain in the future, the safety and economic effectiveness of the same will be greatly enhanced. In the meantime, this paper puts forward the extensive intertwining of digital technology with energy storage systems to improve the safety of storage and the efficiency of dispatchability; V2G may be used to integrate the huge numbers of existing batteries of electric vehicles with the grid, which can significantly boost the energy use. Moreover, the relevant electricity market trading policies will be enhanced, which will contribute to the shift to clean energy and offer new methods to construct a new type of power system.

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