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Study of the Coordinated Development of Distributed Photovoltaic Power Grid and Smart Grid

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Abstract. As smart grid technology and distributed photovoltaic power generation continue to advance rapidly, their integrated and coordinated use is emerging as a key focus for optimizing future power systems. However, how to optimize energy storage technology on the basis of ensuring load balance is still a blank in research. This paper aims to study the effective integration of smart grid and distributed photovoltaic power grid, focusing on energy storage technology and load balancing issues. First, through a literature review, this paper analyzes the latest achievements in China in the field of smart grid and distributed photovoltaic power generation, revealing the problems of low energy storage efficiency and insufficient load balancing at this stage. Secondly, this paper proposes optimization solutions for existing problems, combining the load scheduling of the smart grid and the efficient energy storage of distributed photovoltaic systems and exploring the coordinated development path of the two. Finally, this study points out the future prospects of the coordinated development of distributed photovoltaic power grids and smart grids and provides theoretical support for research and practical applications in related fields.

Keywords: Smart Grid, Photovoltaic Power, Energy Storage Technology

1 Introduction

The excessive use of fossil fuels and other complex environmental issues have attracted much attention. Many countries and regions have entered a state of climate emergency, so it is imperative to standardize the construction of a new energy system and promote the coordinated optimization of smart grids and distributed photovoltaic power generation.

Nowadays, there have been many studies on the coordinated development of distributed photovoltaic power grids and smart grids. In the study of control technology of distributed photovoltaic grid-connected power generation system, Feng verified through simulation experiments that the active power and reactive power change within the specified setting to the smart grid distributed power supply energy saving control system to respond to power tracking [1]. This shows that this method can effectively maintain power stability. In research focused on voltage stability control methods for regional power grids considering the uncertainty of renewable energy output, Sun introduced a coordinated operation strategy for distributed energy storage and

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photovoltaic (PV) power stations. This approach aims to mitigate the variability in PV power generation and enhance the stability of regional grid voltage. [2]. In the experiment on the influence of distributed photovoltaic power station grid connection on regional power grid voltage and current stability, Zhu conducted patent research on a smart grid load controller and balanced the load of the controller affected by temperature problems by using the temperature difference inside and outside the controller [3]. Nowadays, the State Grid of China has established a control system of main distribution coordination, inter-cluster coordination, and cluster autonomy so that distributed power generation can be balanced under multi-level coordination. Most literature has not done systematic research on the energy storage efficiency of photovoltaic power grids and the load balance of coordinated development with smart grids.

Current energy storage technology still needs to be improved. After the photovoltaic system enters the power grid, it needs more stable transmission and storage. While meeting the efficiency requirements, safety factors must also be considered to the maximum extent [4]. Smart grids are characterized by high levels of informatization and automation, which are crucial for effectively managing distributed photovoltaic power generation and ensuring the stable operation of the power grid. However, the inherent randomness of distributed energy generation systems often leads to load imbalances, increasing the complexity and unpredictability of power generation.

In this paper, we study the energy storage problem of photovoltaic power generation and the load balancing problem of smart grid and summarize the development of new energy storage in China. It aims to provide suggestions for the problems that may be encountered in the process of new energy storage.

2 Current Status of Development of Distributed Photovoltaic Power Generation

A Photovoltaic (PV) Generation System is a power generation technology that utilizes the photovoltaic effect in solar cells to directly transform solar radiation into electrical energy [5].

According to relevant discussions on the new power system by the State Grid Corporation of China and relevant ministries and commissions, the core connotation of the new power system is low-carbon randomly coupled power sources + strong and flexible smart grid + multi-coordinated interactive loads + large-scale shared energy storage [6]. In traditional thermal and hydropower systems, the generator is tightly coupled with the power grid, providing system inertia and helping to maintain a relatively stable frequency. In contrast, photovoltaic power generation systems integrate renewable energy into the grid through power electronic controllers, which operate differently from conventional systems. First, the system's own inertia response-ability is weak, and the frequency regulation ability is poor. Second, new energy power generation inherently exhibits characteristics such as instantaneous fluctuations, intermittency, and unpredictability. The integration of a significant amount of renewable energy generation into the grid can lead to increased fluctuations in the power system. If the grid regulation ability is not matched, the stability of the grid frequency will face challenges, and the security of the grid will be impacted. Compared with traditional frequency regulation, energy storage systems focus on improving the response rate, regulation rate, and regulation accuracy, which can effectively avoid regulation delay, regulation deviation, regulation reversal, and other problems.

The inherent randomness, volatility, and anti-peak characteristics of renewable energy have imposed significant challenges on maintaining power system balance, emerging as the primary barrier to achieving a high proportion of renewable energy integration. Furthermore, the projected compound growth rate of renewable energy is expected to outpace the growth rate of electricity consumption while the peak-to-valley load difference continues to widen, with peak loads becoming shorter and more intense. Relying solely on expanding power supply and distribution network infrastructure to meet peak demand would impose substantial economic pressure.

To address the challenges posed by the output volatility and uncertainty of photovoltaic (PV) power stations on regional grid voltage, this paper investigates control methods for managing the voltage in distributed PV and energy storage systems, building on existing research. The combined system of distributed PV and energy storage is illustrated in Fig.1.

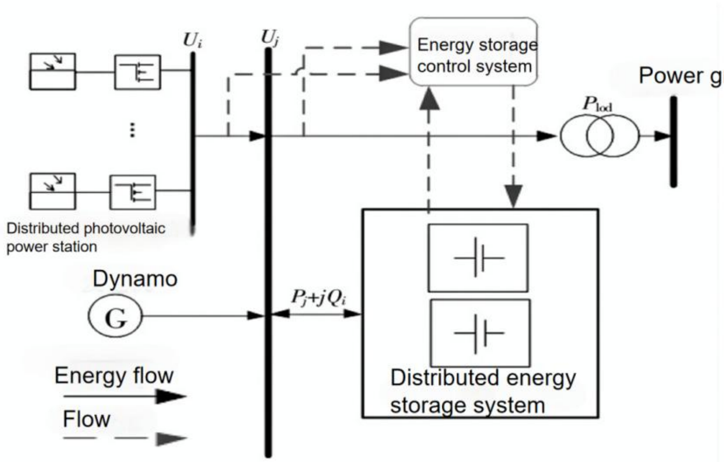

Fig. 1 Distributed photovoltaic and energy storage combined system [2]

To enhance the voltage stability of the photovoltaic (PV) energy storage system, a distributed energy storage system of a specific capacity is deployed at certain nodes within the regional PV energy storage system, as depicted in Fig. 1. The voltage levels at nodes with and without energy storage are analyzed to evaluate their impact. To effectively assess the voltage at each node, the voltage relationship between adjacent nodes is examined under the condition that no distributed energy storage is integrated into the regional system. The relationship is expressed as follows:

$$U_i - U_j = P_{ij}r_{ij} + Q_{ij}x_{ij} \tag{1}$$

In this context, U_i and U_j represent the voltages at nodes i and j within the regional power grid, respectively.P_{ij} denotes the active power flowing between nodes i and j, while Q_{ij} represents the reactive power flowing between these nodes. Additionally,r_{ij} is the line resistance between nodes i and j, and x_{ij} is the line impedance between the same nodes in the power grid.

3 Photovoltaic Energy Storage Technology

3.1 Energy storage process

The key factor of energy storage lies in the intervention of the time factor t, which is manifested as the action time in the technical indicators of the energy storage system. This characteristic serves as the key distinction between energy storage technology and traditional instant-on-demand systems, representing the most significant demonstration of its value. Three important parameters of energy storage technology: power capacity, endurance and actual operating output frequency.

Among the various methods of electric energy storage, electrochemical energy storage stands out as the most significant. Electrochemical energy storage primarily encompasses technologies such as lead-acid batteries, flow batteries, sodium-sulfur batteries, and lithium-ion batteries, among others. Taking lithium-ion batteries as an example, its working principle is to use materials that stably carry out lithium ion embedding or de-embedding reactions as the positive and negative electrodes of the battery, and to achieve energy storage and release through the reversible transfer of lithium ions between the positive and negative electrodes. By continuously tracking the real-time status of system components and weather conditions, the energy system can intelligently regulate the charging and discharging processes, maximizing the efficient use of solar energy. The operational structure of the distributed energy storage system is depicted in Fig. 2.

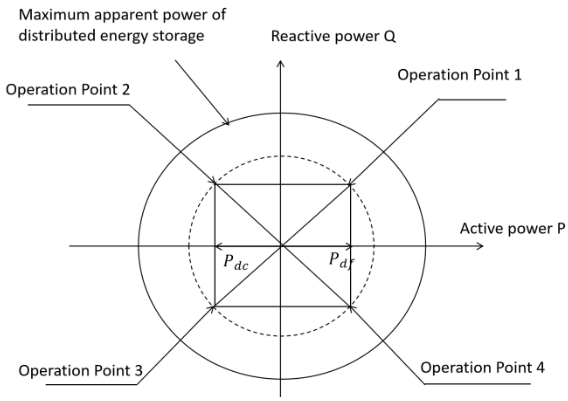

Fig. 2 Operation mode of distributed energy storage system [7]

P_{dc} is the charging power of the grid-connected distributed energy storage in the regional power grid, P_{df} and is the discharging power of the grid-connected distributed energy storage in the regional power grid. At operating point 1, it indicates that the distributed energy storage system sends active and reactive power to the power grid. Operating point 2, it indicates that the distributed energy storage system absorbs active power from the power grid and sends reactive power to the regional power grid. At operating point 3, it indicates that the distributed energy storage system absorbs active and reactive power from the regional power grid. At operating point 4, it indicates that the distributed energy storage system absorbs active and reactive power from the regional power grid [8].

When there is excess solar energy, the solar cell should be charged to store electrical energy. The formula for the charging process is:

$$\Delta E_{charge} = P_{dc} \times \eta_{charge} \times \Delta t \qquad (2)$$

Among them, P_{dc} is the instantaneous power input; η_{charge} represents the input power; Δt represents the input step size.

When photovoltaic power generation is insufficient or grid demand is peak, the battery is discharged to supply energy. During the discharge process, the amount of energy reduction in the battery can be expressed by the following formula:

$$\Delta E_{discharge} = P_{dt} \times \frac{1}{\eta_{discharge}} \times \Delta t \qquad (3)$$

Among them, P_{dt} represents the power output of battery discharge; $\eta_{discharge}$ represents the output efficiency.

Maximum Power Point Tracking (MPPT) technology is a core strategy in distributed photovoltaic power generation systems [6]. Its objective is to optimize and achieve the highest possible power output from the photovoltaic array. By adopting MPPT technology, distributed photovoltaic power generation systems can make full use of energy under different lighting conditions and improve the energy efficiency of the system [1]. The MPPT technology can be expressed in the formula:

$$P_{dc} = V_{dc} \times I_{dc} \qquad (4)$$

Among them, V_{dc} represents the input voltage of the battery pack; I_{dc} represents the input current of the battery pack [8].

Based on the experimental data from Feng's research, it is understood that the goal of MPPT technology is to achieve the maximum value of input power P_{in} [1]. The MPPT algorithm adjusts the working state of the battery pack according to the trend of input power in different periods of time, gradually approaching the maximum power point, thereby maximizing energy conversion [1].

3.2 Analysis of photovoltaic energy storage voltage and solutions to islanding effect

Regardless of whether the photovoltaic power generation system is in distributed access or centralized access mode, its grid-connected mode will use static voltage to adjust the system. As the stability of grid-connected photovoltaic (PV) power generation systems continues to improve, their forward output will play a direct role in regulating the reverse power flow of the distribution network. When power losses remain below the distribution network's rated capacity, adjusting the grid-connected operation mode can effectively ensure voltage stability across the power grid. When the output voltage of the photovoltaic power generation system changes from low to high, the grid-connected mode will change from a unidirectional connection to a bidirectional connection. When the output voltage changes from high to low, the grid-connected mode will change from a bidirectional connection to a unidirectional connection. Regardless of which method is used, the stable voltage of the photovoltaic power generation grid-connected system will be adjusted to a relatively stable level in a very short time [9].

To design a reasonable smart grid, it is necessary to make it operate normally on an isolated island and study the distribution of distributed power supply energy. Starting from the main characteristics of smart grids when running in grid-connected and isolated islands, it is possible to convert smart grids into grid-connected and isolated island modes, thereby improving the reliability of power supply.

After a power outage, the inverter operating parameters are tested. If the difference between its output power and load power is large, it indicates that an islanding effect exists. When the difference between the two power values is small, the detection effect is not ideal. In addition, active detection methods can be used. When a fault problem occurs, the abnormal parameters of the inverter will far exceed the standard value, so that the islanding effect can be detected [6].

3.3 Current achievements and prospects of photovoltaic energy storage

By the end of 2022, China's new energy storage capacity is expected to reach approximately 7 million kilowatts. It is estimated that in 2025 and 2030, the distribution network in the company's operating area will be 20 million kilowatts and 40 million kilowatts respectively, accounting for 4% and 2.4% of the world's maximum load [10]. As an integrated element of source and load characteristics, new energy storage has the characteristics of flexibility, adjustability, and rapid response, which helps to improve the self-balancing level of the distribution network and support the peak regulation of the main grid. On the power supply side, it can improve the power output characteristics and effectively deal with the problems of randomness and volatility of distributed power output; on the grid side, it strengthens the power supply capacity in areas with weak grids and enhances the system's emergency response capabilities. On the load side, it improves the adjustability and controllability of loads, enabling peak shaving and valley filling to optimize energy consumption.

In the planning of distributed new energy sources for smart grids, it is necessary to better integrate scientific and technological elements, take the physical network as the core foundation, cooperate with advanced measurement technology and information technology, jointly maintain the balance of grid integration applications, and improve the comprehensive application benefits of the power system [11]. In the future, the top priority will be the coordinated development of smart grids and new energy storage technologies, with more standardized and improved industry standards. According to the development and safe operation needs of energy storage, improve industry access conditions and trading mechanism standards, establish and improve the technical standard system of the entire energy storage industry chain, and the safety standards and management system for energy storage equipment manufacturing, construction, installation, and operation monitoring should be specifically targeted at different application scenarios, and strengthen the connection between energy storage applications and relevant standards of the current energy and power system. On the other hand, establishing an online monitoring platform, real-time monitoring of battery performance parameters, regular maintenance and safety assessment, ensuring the safety and reliability of energy storage configuration.

By achieving more stable and efficient energy management, distributed photovoltaic systems can be better integrated into the stability and reliability of energy storage configuration. This is of great significance for achieving sustainable energy development and promoting clean energy transformation.

4 Conclusion

This paper describes in detail the distributed photovoltaic system energy storage technology, taking lithium-ion energy storage technology as an example. Energy storage technology is one of the core technologies to promote clean, electrified, and efficient world energy, break the constraints of energy resources and the environment, and realize the global energy transformation and upgrading. Facing the access and consumption of high-penetration new energy in the future, it is necessary to build a high-proportion, ubiquitous, shareable, and wide-area coordinated energy storage form, and through new energy and energy storage, change the form, structure, and function of the traditional power system. In future development, after the energy storage system is connected to the smart grid, flexible scheduling and source-grid-load-storage interaction will become possible. During peak power generation periods, the energy storage system's charging process will effectively reduce the curtailment rate. Under no-light conditions, the energy storage system discharges promptly and accurately to support the normal operation of the power maintenance system.

In the next step of the paper, the voltage imbalance problem caused by load imbalance in isolated photovoltaic power grids will be further studied, and then distributed collaborative optimization control of voltage imbalance will be realized.

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