

Research on the Construction and Key Technologies of Wind-Solar-Storage Integrated Smart Grid

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Abstract:

Under the global carbon neutrality strategy and the ongoing transformation of the energy structure, renewable energy sources such as photovoltaics and wind power are rapidly being integrated into the traditional energy system rely on their green and clean advantages. Given the intermittent and fluctuating nature of these new energy sources, energy storage technologies serve as a crucial “bridge”, balancing power supply and demand through peak shaving and valley filling. This has led to the emergence of wind-solar-storage integrated smart grid systems. This paper systematically reviews the core structure and key technologies of such systems, including the basic components of photovoltaic and wind power systems, advanced energy storage technologies, and intelligent control mechanisms. Additionally, by examining real-world application cases, it analyzes the effectiveness of these systems in various scenarios such as households, communities, and industrial settings. The study provides a theoretical foundation and technical reference for the optimized design and widespread application of wind-solar-storage integrated systems.

Keywords: Photovoltaic Power Generation; Wind Power Generation; Energy Storage System; Smart Grid; Grid Integration of Renewable Energy.

1. Introduction

Against the backdrop of global climate change and energy structure transformation, renewable energy sources such as photovoltaics and wind power have become indispensable resources for countries striving toward sustainable development, owing to their green, low-carbon characteristics and abundant re-

serves. However, the intermittent and unstable nature of these energy sources makes it difficult for them to be integrated directly into traditional power grids, significantly limiting their practical application. To address this challenge, energy storage systems have been widely introduced, working alongside wind and solar power generation to form integrated “wind-solar-storage” systems.

In recent years, wind-solar-storage smart grids have emerged as a key focus in energy power system research and application. The United States has established various energy internet experimental platforms; Germany, under its “Energiewende” (energy transition) strategy, has promoted large-scale renewable energy access and microgrid technology research, emphasizing the systematic design of wind-solar complementarity and energy storage configuration [1]. Japan and several European countries have widely deployed community level smart microgrids and proposed virtual power plant (VPP) collaborative control models, with mature demonstration projects implemented on both commercial and residential user sides [2,3].

In China, following the introduction of the “carbon peaking and carbon neutrality” strategy and the promotion of the “new power system” concept, integrated wind-solar-storage systems have attracted increasing attention from both policymakers and researchers. Enterprises such as State Grid and China Southern Power Grid have partnered with universities and research institutions to conduct extensive studies, focusing on renewable energy grid integration technologies, optimization of energy management systems, energy storage capacity configuration, and intelligent control strategies. For example, under the “East Data, West Computing” initiative, several new energy bases in western China are exploring the use of integrated wind-solar-storage systems to enhance power supply resilience and overall energy efficiency [4].

This paper aims to review the key components, technologies, and real-world applications of wind-solar-storage smart grids, providing theoretical reference and technical support for the optimized design and widespread deployment of such systems in the future.

2. Wind-Solar-Storage Smart Grid System Structure

2.1 Overview of Wind-Solar-Storage Technology

The wind-solar-storage system integrates wind power generation, solar power generation, and energy storage systems to achieve mutual complementarity of multiple energy sources, improve energy utilization efficiency and power supply stability, and input them into a more stable and efficient power system. When sunlight is abundant or wind speeds are high, the wind and solar systems store excess electricity in batteries or other storage devices. When wind speeds drop or solar radiation is insufficient, the stored energy can be released to ensure continuous power supply. The intelligent energy management system opti-

mizes the operational efficiency of the wind-solar-storage system, accurately regulating the energy flow between different components, thus enhancing overall system performance and reliability. Wind power generation relies on wind turbines to convert kinetic energy into electricity, while photovoltaic (PV) systems use solar panels to convert solar energy into electrical energy. The energy storage system stores excess electricity and releases it when needed, ensuring stable operation and sustainable development of the wind-solar-storage system.

2.2 Basic Components of Photovoltaic, Wind Power, and Energy Storage Systems

As shown in Figure 1, wind and photovoltaic power generation are transported to energy storage systems, then to smart grids, and finally to households, communities, industries, and commerce. The Photovoltaic power generation system includes photovoltaic modules, inverters, power distribution units, and monitoring and management systems. The photovoltaic modules convert solar radiation into direct current (DC), which is then transformed into alternating current (AC) by the inverter for use or grid connection [5]. The wind power generation system consists of wind energy capture devices, power generation and conversion units, control systems, and grid-connection device. Using wind power to drive the impeller to rotate and drive the generator to work, converting kinetic energy into electrical energy and outputting it [6].

Due to the intermittent nature of both wind and solar energy, the integration of an energy storage system ensures stable system operation. Common energy storage units include lithium-ion batteries, sodium-sulfur batteries, supercapacitors, and pumped hydro storage. When power generation exceeds demand, the surplus electricity is temporarily stored and later discharged during periods of insufficient generation, thereby achieving dynamic supply-demand balance. The entire system relies on an energy management system and intelligent control units to operate, real time monitoring and optimization adjustments are carried out on it, improving both the utilization rate of renewable energy and the reliability of grid operation. Through precise scheduling, the wind-solar-storage system achieves a coordinated integration of wind, solar, and storage components, enhancing the efficiency of energy production, storage, and consumption, and ultimately ensuring a continuous and reliable power supply.

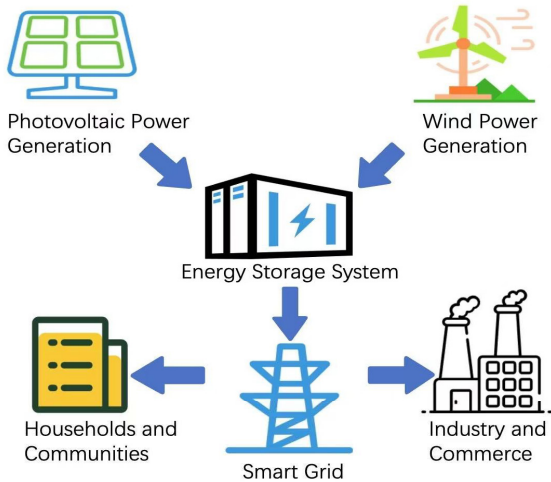


Fig. 1 Composition of a Wind-Solar-Storage Smart Grid

3. Key Technologies of Wind-Solar-Storage Smart Grid

3.1 Photovoltaic Power Generation Technology

As one of the core technologies in renewable energy, photovoltaic (PV) power generation has made significant technological progress in recent years. The photoelectric conversion efficiency of current commercial photovoltaic modules has generally surpassed 22%. For instance, LONGi Green Energy Technology Co., Ltd., headquartered in Xi'an, China, achieved a conversion efficiency of 26.81% under mass production conditions using heterojunction (HJT) solar cells based on full-size silicon wafers [7]. Modern PV systems widely adopt Maximum Power Point Tracking (MPPT) technology, which adjusts the operating point of silicon-based PV cells under different environmental conditions to enhance power generation efficiency. The synergy between PV generation and energy storage technologies helps address complex and variable conditions, thereby improving grid flexibility [8].

3.2 Advanced Energy Storage Technologies and Their Optimal Configuration

In wind-solar-storage smart grids, energy storage systems play a bridging role in enhancing the stability of renewable energy. Based on the principles of energy storage and conversion, storage technologies are generally divided into three categories: electrochemical storage, electromagnetic storage, and mechanical storage. By configuring different storage technologies, both energy density and power density requirements can be balanced, enabling smoother renewable energy output and enhanced system

stability. Using multi-objective optimization algorithms, such as improved Particle Swarm Optimization (PSO), allows for optimal matching of storage capacity and power rating, reducing operational costs and extending the lifespan of equipment [9]. Reasonable configuration of storage systems helps mitigate the volatility of renewable energy sources, achieve peak shaving and valley filling, and realize dynamic compatibility between electrical energy.

3.3 Control Technologies for Wind-Solar-Storage in Smart Grids

The key to controlling wind-solar-storage smart grids lies in multi-energy coordination and dynamic optimization management. Control systems built using predictive control, fuzzy control, and multi-source energy management algorithms can achieve optimal scheduling based on load forecasts, weather changes, and electricity price information. For example, using Model Predictive Control (MPC) technology allows short-term forecasting of sunlight and wind speed. The charging and discharging time of the energy storage system can be adjusted in advance, leading to more stable system operation and improved power quality. Intelligent energy management systems play a vital role in coordinated dispatch, load priority identification, and response strategy design, significantly enhancing overall system efficiency and operational safety.

4. Practical Applications of Renewable Energy Grid Systems

4.1 Residential and Community-Level Applications

At the residential and community levels, photovoltaic energy storage systems are increasingly being adopted. In Bendigo, Australia, a community implemented a distributed solar PV system by using rooftops as power generation platforms connected to a Virtual Power Plant (VPP) network for centralized dispatch. These distributed photovoltaic systems serve as the main source of community energy. Users can consume the electricity they generate, excess electricity can also be shared with other users or sold to the grid through VPP [10]. This localized production, utilization, and intelligent trading of renewable energy has driven green energy transformation at the community level. In China, pilot community microgrids have been launched in provinces like Jiangsu and Guangdong, integrating distributed renewable energy, storage systems, and electric vehicles to form local energy self-circulation systems. This enhances supply resilience and post-disaster recovery capacity.

4.2 Industrial and Commercial Applications

In industrial and commercial sectors, PV-storage systems have become key solutions for reducing costs and improving efficiency. For example, Tesla's Gigafactory in the U.S. is equipped with solar arrays and storage systems, meeting the daytime power demand and relying on stored energy at night to ensure uninterrupted production [11]. In the commercial sector, the IKEA store in Adelaide, Australia, has installed a 1.2 MW rooftop PV system and a 3 MW/3.45 MWh battery energy storage system, creating the largest commercial microgrid in Australia. This system supplies 70% of the store's energy demand and participates in the Frequency Control Ancillary Services (FCAS) market to support the South Australian grid [12].

5. Conclusion

With the rapid development of the renewable energy market—especially in sectors led by wind and photovoltaic power—unprecedented opportunities are emerging. However, the market still faces several challenges, including policy uncertainty, immature market mechanisms, and unresolved technological bottlenecks. On one hand, inadequate policy support and underdeveloped industrial chains in certain regions undermine investor confidence. On the other hand, traditional energy mechanisms struggle to adapt to the new energy structure with strong volatility and distributed access. Meanwhile, key enabling technologies such as energy storage and intelligent dispatch still need improvements in cost, efficiency, and safety. Moreover, the dependency of renewable energy equipment on rare metals also presents potential supply chain risks. Nevertheless, the outlook for the renewable energy market remains highly optimistic. As policy frameworks are refined, green finance and carbon trading mechanisms are further developed, and technological innovation continues to reduce the cost of power generation and storage, the renewable energy industry is expected to achieve broader application and higher-quality growth. Ultimately, it will occupy a more central position in the global energy system and form a virtuous cycle of sustainable development.

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