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The Technical Key Points and Development Prospects of Smart Grid

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Abstract. Against the backdrop of global energy demand growth and prominent environmental issues, traditional power grids have exposed problems such as low efficiency and poor reliability, giving rise to the emergence of smart grids.This article conducts an in-depth study on the key technologies for the development of smart grids, including the current status and development challenges of distributed generation technology, as well as energy storage technology for balancing power supply and demand. Studies have shown that smart grids, by leveraging these core technologies, are able to markedly boost energy usage and efficiency while also enhancing the power grid's stability and reliability.In the future, smart grids are projected to be deeply integrated with emerging technologies such as the Internet of Things and big data, facilitating the transformation of the energy structure and taking on an increasingly significant role in the global energy system. They have broad development prospects, but also face challenges such as the unification of technical standards and cybersecurity protection.

Keywords:Development Prospects, Smart Grid, Technical Key Points

1. Introduction

Amid the global wave of energy transformation and upgrading, the smart grid, as a highly automated and informatized modern power grid system, has achieved real-time monitoring, efficient management, and two-way interaction of power grid operation by leveraging advanced communication, sensing, information, and control technologies, thus becoming a core hub for promoting the transformation of the energy structure towards clean and low-carbon.Its high level of automation allows real-time monitoring of the power system's operating status, enhancing safety and reliability; its powerful interactivity supports bi-directional information and power flow, optimizes supply-demand matching, and improves energy usage efficiency. It is also compatible with the integration of distributed generation and other renewable energy sources, promoting efficient energy utilization.Distributed generation technology harnesses renewable energy sources like solar and wind to produce electricity locally. This not only cuts down on transmission losses and eases the burden on the main power grid but also ensures the rationality of power distribution and the economic efficiency of the distribution network.Energy storage technology, featuring high efficiency and flexibility, tackles the intermittent issue of renewable energy. It not only facilitates peak shaving

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and valley filling but also ensures the safe and stable operation of the power grid. As the core and key technologies of the smart grid, the two work in coordination and synergy to jointly drive the sustainable and efficient development of the smart grid. However, they also face challenges in terms of technology and cost in application. In the future, continuous innovation is still needed to promote the smart grid to a new stage that is smarter, more efficient, cleaner and more reliable.

2. Distributed generation technology

Distributed generation technology refers to a power generation system that is arranged in a small-scale and decentralized manner at the user end or near the user side. Compared with centralized large-scale power stations, distributed generation is decentralized, modular and uses more flexible technologies. It usually has a capacity of less than 10 megawatts (MW) and is located near the load it serves. It covers a variety of types, including solar photovoltaic power generation, wind power generation, biomass power generation, small hydropower and fuel cell power generation etc. This technology has significant advantages, effectively reducing power transmission losses and enhancing energy utilization efficiency. It can achieve diversified utilization of energy and reduce reliance on traditional fossil energy. In remote areas or emergency scenarios, it can be used as an independent power supply system to ensure power supply. Meanwhile, distributed generation technology can be complementary to the large power grid for grid-connected operation. When a distributed generation system is grid-connected, the electricity generated by the power generation units can be directly supplied to the load or connected to the grid, or stored in energy storage units, which then supply the load or connect to the grid. The power grid can also directly supply power to the load [1], enhancing the stability and reliability of the power grid. However, its development also faces some challenges, such as intermittent power generation and complex grid connection technology. With the continuous advancement of technology, distributed generation technology is gradually becoming an important support for the sustainable development of energy.

2.1. Main distributed generation technologies

At present, distributed power generation technologies cover various types such as micro-turbines, biogas power generation, small-scale hydropower generation, rooftop solar photovoltaic systems, small-scale wind power generation devices and fuel cells. This type of technology has achieved remarkable results in promoting the integration of clean energy into the grid and enhancing the reliability and availability of power supply. It not only maintains independent operation when the distribution network fails, reducing the impact of the failure of a single power generation unit, but also realizes a multi-energy coordinated supply mode of combined heat, power and cooling, and effectively reduces energy loss in the transmission and distribution links.

In response to the national dual-carbon policy, among renewable energy sources, photovoltaic and wind power have a broader application scope than hydropower [2], have less adverse impact on food and ecosystems than bioenergy [3], and may require a lower cost than carbon capture and storage (CCS) [4].

Take the photovoltaic system as an example (as shown in Figure 1 below), its working mechanism follows a strict energy conversion and regulation process: The photovoltaic array converts solar radiation energy into direct current through the photovoltaic effect, and then the photovoltaic charging controller performs overcharge and overdischarge protection and voltage and current stabilization processing. The processed electrical energy is stored in the battery pack. When the user-side power demand is triggered, the direct current from the battery pack is converted into

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alternating current via the DC-AC inverter to power household appliances. When solar irradiation is insufficient or the battery energy storage level is low, the system automatically switches to the municipal power supply mode, thereby ensuring the continuity and stability of power supply. Meanwhile, we can also employ colored photovoltaic panels, which integrate aesthetics with functionality. Colored photovoltaic panels use advanced coating materials and printing techniques to produce a range of colors and patterns while maintaining high energy efficiency [5]. For instance, by applying optical interference films on photovoltaic modules, light gray or white photovoltaic panels can achieve 80-90% of the efficiency of traditional dark panels, thus striking a balance between energy production and visual appeal [6]. Photovoltaic integrated pavilions or shading structures above existing roof structures create dual-purpose Spaces, providing shading areas for entertainment while generating energy [7].

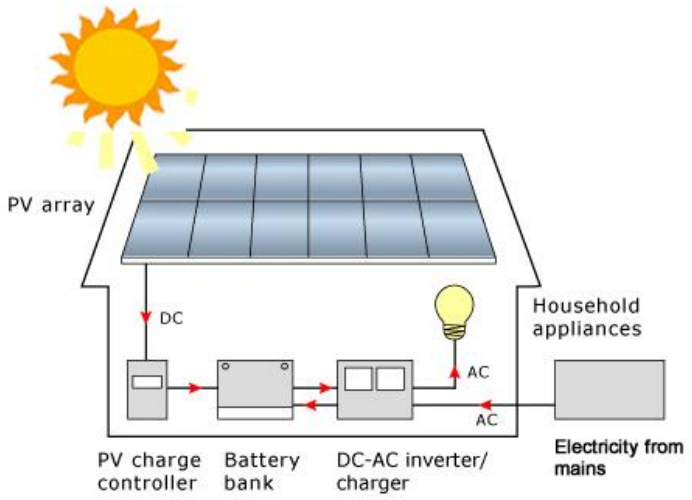


Figure 1. Solar power generation system

Take a small wind turbine as another example (as shown in Figure 2): The overall energy operation principle involves capturing wind energy via the wind wheel, converting it into mechanical energy, and then further transforming that mechanical energy into electrical energy through the generator.

In the specific operation of small-scale wind power generation systems, each component unit operates in coordination, achieving a stable supply of electricity through energy conversion, transmission, regulation and utilization.As a key supporting structure, the guyed tower is designed to lift small wind turbine to an appropriate height to optimize the capture efficiency of wind energy resources. The cable system configured for the tower frame enhances the overall stability of the structure through a tension restraint mechanism and effectively resists environmental forces such as wind loads.The power transmission link mainly relies on the cable trench infrastructure. The underground laying method can significantly reduce electromagnetic interference and enhance the operational reliability of the cable system through physical protection measures, ensuring the efficient transmission of power to the subsequent processing units.The wind turbine controller integrates real-time monitoring and intelligent regulation functions, and precisely regulates the generator's rotational speed through a closed-loop control algorithm. It is also equipped with multiple built-in protection mechanisms. When the system experiences abnormal conditions such as overload and overvoltage, it can trigger a rapid response strategy to ensure the safe operation of the

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equipment. Given that the output electrical energy of wind turbine generators is in direct current form, it is necessary to rely on grid-connected inverters to achieve the conversion between AC and DC electrical energy. Through phase-locked loop technology, frequency and phase synchronization with the grid voltage can be realized, thereby meeting the grid operation and terminal power consumption demands. Switchgear, as a circuit on-off control component, has the dual functions of normal operation and maintenance isolation. It realizes the safe switching of circuits through mechanical or electronic control methods. Electrical equipment, as terminal loads, encompasses various electrical devices in both household and industrial fields and serves as the ultimate carrier for the consumption and application of electrical energy.The metering electricity meter adopts high-precision measurement technology and has a bidirectional metering function. It can record the energy interaction data between the power grid and the user end in real time. The system realizes bidirectional power transmission with the external power grid through the grid connection interface, building an intelligent power supply and consumption system with the characteristic of bidirectional power flow, significantly improving energy utilization efficiency and system operation flexibility.

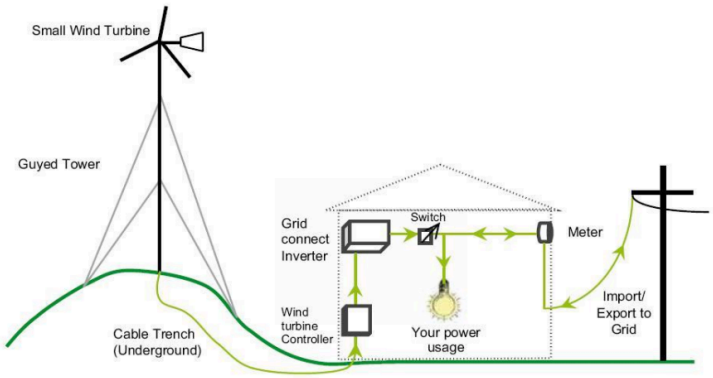


Figure 2. Working diagram of a small wind turbine

2.2. The important position of distributed generation

In conclusion, distributed generation technology demonstrates multi-dimensional application value and broad development prospects. This technology, through the user-side deployment mode, not only significantly enhances the accessibility and convenience of power supply, but also effectively strengthens the continuity of power supply with the help of a redundant power supply architecture. From an economic perspective, its relatively low initial investment cost, combined with the two-way revenue model formed by the surplus power fed to the grid mechanism, has maximized the economic benefits for both users and power generation entities. This technological paradigm not only improves the reliability and availability of the power system but also infuses new momentum into the power industry's economy via a market-oriented electricity trading mechanism. It is highly consistent with the characteristics of informatization, automation and intelligence emphasized by the smart grid, and has become a key supporting technology for building a modern smart grid system.

From the strategic perspective of energy transition, distributed generation technology has broken through the limitations of traditional centralized generation. Boasting high energy utilization efficiency, it has emerged as a key technical approach to implementing the concept of green and low-carbon development. It is worth emphasizing that distributed generation and smart grids have significant synergy effects at the functional level. Through the deep coupling of information flow and energy flow, the two have formed a new type of power ecosystem with two-way interaction.This

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technological integration not only effectively meets users' diverse power demands but also promotes high-quality development of the energy economy by optimizing energy allocation and enhancing system resilience. Based on the laws of technological evolution and the trends of industrial development, the coordinated development model of distributed generation and smart grids will become the core direction of technological innovation and industrial transformation in the future energy field.

3. Energy storage technology

3.1. Main energy storage technologies

At present, the existing power energy storage technologies include: mechanical, electrical, electrochemical, chemical and thermal energy types.

Take mechanical-pumped storage as an example (as shown in Figure 3 below: Mechanical-pumped storage technology works as follows: during periods of low grid load, excess electrical energy is used to drive pumps that pump water from the lower reservoir to the upper reservoir, thereby converting electrical energy into the gravitational potential energy of water for storage. During peak load periods, water is released from the upper reservoir to impact the turbine and drive the generator to produce electricity, converting potential energy back into electrical energy. The system achieves the storage and regulation of electricity through the mutual conversion between electrical energy and potential energy, which helps to balance the supply and demand of the power system and enhance its stability and reliability. Its efficiency is between 70% and 85%. Its advantages include low cost and unlimited charge and discharge cycles, enabling dual use of recharging and discharging.Compared with other energy storage technologies, pumped storage technology is mature and has the advantages of large energy storage capacity, long service life, quick start-up, flexible operation and flexible adjustment [8]. Therefore, in recent years, pumped storage has been vigorously developed and its growth rate has steadily increased [9].

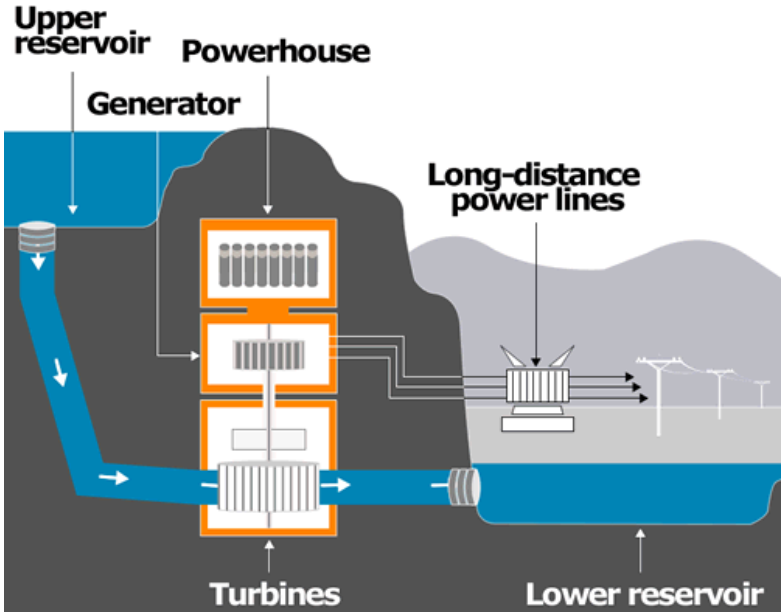


Figure 3. Mechanical - Pumped storage

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Similar to this is the mechanical compressed air energy storage technology (as shown in Figure 4 below). Ambient air is compressed and stored in underground caves. During off-peak electricity periods, the excess electricity is used to drive the compressor to compress the air and store it at high pressure.During peak electricity hours, compressed air is released and expanded by an expander to do work and drive a generator to produce electricity. It is also often combined with technologies such as heat recovery to improve efficiency. Natural gas combustion turbines are used to heat and pressurize the air to drive turbine generators.Its efficiency is between 50% and 75%. The advantages are quick start-up and timely activation. However, the drawback is that it has strict requirements for the environment and is relatively dependent on geological structures.

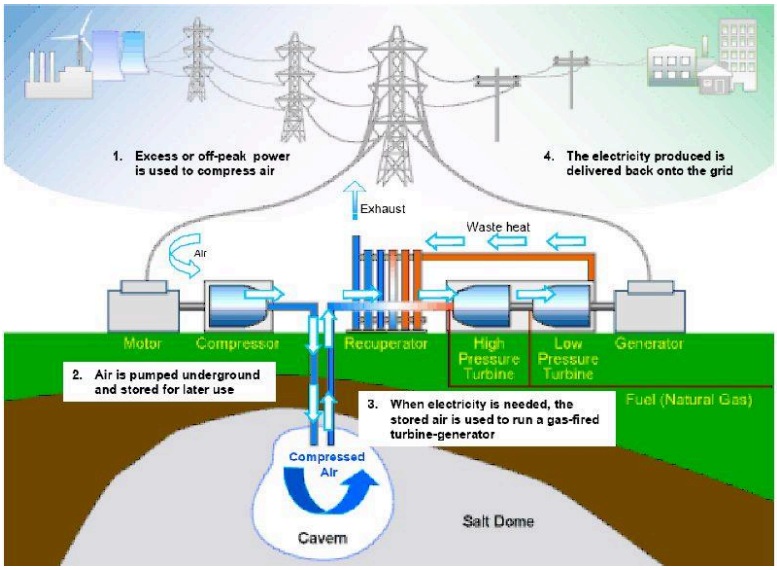


Figure 4. Mechanical compressed air energy storage technology

It is also worth noting the use and storage of hydrogen energy in the field of electrochemistry (as shown in Figure 5 below).

This fuel cell directly converts stored chemical energy into electrical energy. Here's how it works: hydrogen flows through the anode (negative electrode) while oxygen passes through the cathode (positive electrode), leading to the formation of hydrogen ions and electrons at the anode. As electrons travel through the external circuit to generate electricity, hydrogen ions migrate from the anode to the cathode, where they combine to form water molecules.

The advantage of this energy storage technology is its high energy conversion efficiency, which can reach 40% to 60%. And it is clean and environmentally friendly, with only water as the product. It actively responds to the "dual carbon" policy and generates almost no greenhouse gases or pollutants.It operates quietly with low noise at the same time. The module combination is flexible and the scale can be adjusted according to different needs. However, there are also certain shortcomings, such as the current high technical difficulty and cost in the production, storage and transportation of hydrogen.The key materials of fuel cells, such as catalysts and proton exchange membranes, are costly, resulting in a relatively high overall cost of fuel cells. It has rather strict requirements for the environmental conditions of use. These remain the difficult problems and challenges that need to be addressed in the future. If they can be overcome, energy construction will reach a new level.

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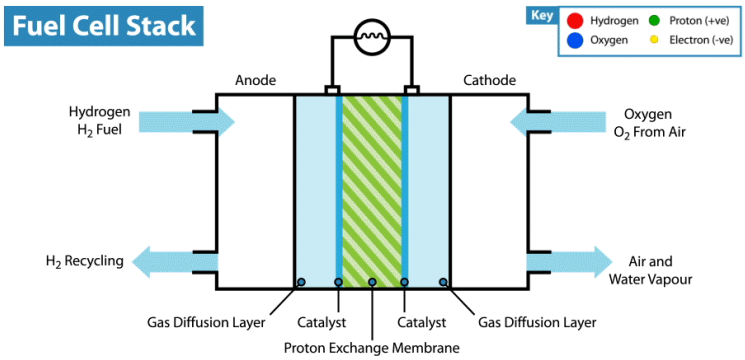


Figure 5. Hydrogen fuel cell

3.2. The barriers of energy storage technology are extremely high and of great significance

Energy storage technology is of great significance to smart grids and distributed generation.It can not only balance the supply and demand of the smart grid, alleviate the peak-valley difference, but also enhance the acceptance capacity of renewable energy and the resilience of the power grid. Moreover, in distributed generation, it can smooth out output fluctuations, ensure a continuous power supply, and promote local energy consumption.It serves as a core technology for propelling energy transformation and the sustainable development of the power system.

From the perspective of power system optimization and energy market mechanisms, energy storage technology has built a solid technical foundation for the economic and efficient operation of smart grids.In the electricity market system, energy storage systems, with their flexible bidirectional power regulation capabilities, deeply participate in auxiliary service markets such as peak shaving and frequency regulation. They not only create considerable economic value for themselves but also reduce the system's reserve capacity configuration requirements through precise power throughput, achieving cost-intensive management from the perspectives of power source structure optimization and grid investment planning. The millisecond-level response characteristic of the energy storage system can quickly capture and correct the frequency fluctuations and voltage deviations of the power grid. In scenarios with a high proportion of renewable energy integration, it effectively compensates for the system's inertia deficiency and significantly enhances the dynamic stability of the power system.

In the field of distributed generation, energy storage technology acts as the core hub for the coordinated interaction of the "source-storage-load" system. It leverages the microgrid energy management system to realize the dynamic optimal allocation of distributed energy and its market-oriented trading.By accurately aligning the intermittency of the power generation side with the volatility of the load side, the energy storage system not only elevates the energy efficiency management of the user side but also drives the transformation of the power system from the traditional one-way power supply mode to a new multi-interactive power ecosystem. This provides key technical support for the large-scale construction and operation of the energy Internet.

From this, it can be seen that new energy storage can play a significant role in ensuring the balance of power and electricity, increasing the safety margin of the system, and promoting the efficient utilization of new energy.It is an important technology and fundamental equipment for constructing a new power system, as well as a key support for attaining the goals of carbon peaking and carbon neutrality.In the process of building a new type of power system, in addition to the support of new energy and energy storage technologies, it is also necessary to achieve in-depth

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coordination among power sources, grids, loads and storage, as well as digital intelligent management.The application of digital technology and intelligent equipment can enhance the management efficiency and technical level of the power system, thereby more effectively achieving the efficient utilization of clean energy and the optimization of the energy structure [10].

4. Conclusion

The development of a smart grid not only signifies a significant improvement in a country's overall strength but also acts as a key driver for advancing the nation's modernization drive and enhancing people's well-being.As a key carrier of the new energy infrastructure, the smart grid has reshaped the power supply system through intelligent and digital technologies, providing an efficient and convenient power usage experience for social production and life.The value of smart grids far exceeds power supply optimization: On the one hand, it has strongly driven the development of strategic emerging industries like artificial intelligence and big data, thus laying a solid energy foundation for the high-quality development of the digital economy; On the other hand, by means of intelligent monitoring, dynamic regulation and other technological approaches, a modern power grid system that is safe, reliable and economically efficient has been built. This enables the precise allocation and flexible dispatching of power resources.In addition, as the core hub for the integration of new energy into the grid, the smart grid, with its strong compatibility and regulation capabilities, effectively integrates distributed photovoltaic, wind power, and other clean energy sources, accelerating the green transformation of the energy structure. Essentially, the rapid development of smart grids is an inevitable result of the interplay between national strategic demands and the tide of technological innovation, undertaking the dual missions of energy revolution and industrial upgrading.

The smart grid embodies the future development trend of the power system, while research into power system automation technology constitutes a key direction for advancement in the power sector. Through automation technology, the smart grid has achieved real-time monitoring of the grid's operational status, autonomous diagnosis and recovery of faults, and efficient power allocation, etc. Through distributed generation technology and energy storage technology, it brings benefits to the user side, promotes the healthy development of the power market, and facilitates the transformation and upgrading of the energy structure. Under the call of the "dual carbon" policy, it not only promotes the green and sustainable development of energy and electricity but also significantly enhances the safety, reliability, and stability of the power grid. Looking ahead, it is believed that with the continuous advancement of technology, smart grids will play an even more critical role, driving the power industry toward a more intelligent and efficient future.

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