

Technologies for Photovoltaic Power Generation

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Abstract:

Stepping onto the energy stage of the 21st century, the rise of renewable energy marks a profound transformation in the global energy landscape. In this context, photovoltaic power generation technology has emerged as a shining highlight in the new era of energy systems due to its direct energy acquisition, environmental friendliness, and sustainability. The purpose of this study is to analyze the key progress of the current photovoltaic power generation technology in detail through the method of comprehensive literature review, including the promotion strategy of conversion efficiency, the optimization way of system performance, the rationalization means of cost control, and the enhancement way of energy storage efficiency. Through extensive collection and systematic summary of domestic and foreign research results in related fields, this study has launched a comprehensive and in-depth discussion and comprehensive evaluation of the core issues such as system efficiency, energy storage solutions and cost composition of photovoltaic power generation, aiming to contribute to promoting the future development of photovoltaic power generation technology. The research conclusion emphasizes that the dual drive of technological innovation and system integration plays a decisive role in achieving the significant growth of photovoltaic power generation efficiency and the improvement of system operation economy.

Keywords: Photovoltaic power generation; conversion efficiency; system efficiency; energy storage technology; cost analysis.

1. Introduction

Faced with the increasingly scarce global fossil fuel resources and the increasingly severe problem of environmental deterioration, human society is experiencing a profound transformation of the energy

system. During this transition, photovoltaic power generation technology has emerged in the field of renewable energy with its unique advantages of direct conversion, environmental friendliness and sustainable supply. At present, the rising capacity of photovoltaic installations worldwide not only marks the in-

creasing influence of photovoltaic power generation in the global energy pattern but also reflects the high attention and broad expectations of the technology worldwide. By converting sunlight directly into electricity, photovoltaic power generation technology provides human society with an energy utilization model that both protects the environment and is highly efficient. In this energy conversion process, conversion efficiency and cost control have become the key elements to judge the development maturity and market competitiveness of photovoltaic power generation technology.

The core focus of this study is on the important aspect of photovoltaic power generation technology, and it explores in detail the basic theory and current development trend of photovoltaic power generation, the enhancement strategy of conversion efficiency, the improvement approach of system efficiency, the cutting-edge application innovation of energy storage technology, the in-depth analysis of cost efficiency, and the issues of inverter construction and efficiency upgrade. In the face of these core issues, the study adopts the research method of literature review, through the integration of analysis and evaluation of existing academic literature, industry reports and technical specifications, aiming to provide a comprehensive reference framework for the academic exploration and industrial practice of photovoltaic power generation technology.

This paper aims to lay theoretical support and practical guidance for the evolution of photovoltaic power technology, and promote its wide application and sustainable development in the field of energy.

2. Application of Energy Storage Technology in Photovoltaic System

2.1 The Importance of Energy Storage Technology

In the solar photovoltaic system, energy storage technology occupies a pivotal position. It can not only effectively cope with the challenges of power fluctuations caused by meteorological changes, but also greatly enhance the stability and reliability of the power system. By storing energy during periods of reduced electricity demand and releasing this stored energy during peak periods, energy storage systems help achieve flexible regulation of the grid.

2.2 Main Types of Energy Storage Technologies

2.2.1 Battery energy storage technology

The conversion and storage technology of electric energy to chemical energy - battery energy storage, is the pro-

cess of energy accumulation and release with the help of electrochemical reaction, which has the characteristics of repeatable execution and high efficiency, thus confirming the superior performance of the battery in the field of energy conversion and reserve. Its advantages are summarized as high-efficiency energy conversion, fast response rate, intensive energy storage and flexibility of application. Compared with other energy storage means, battery energy storage technology shows a faster energy storage to release state conversion ability, timely adapt to the dynamic adjustment of power grid load [1].

2.2.2 Flywheel energy storage technology

This is a cutting-edge and efficient mechanical energy storage technology; the key mechanism of its operation is to rely on the high-speed rotating flywheel contained in the kinetic energy to complete the energy saving and release. When there is a surplus, the electrical energy is efficiently converted into the rotating kinetic energy of the flywheel and stored. The technology is known for its millisecond reaction speed, powerful power processing efficiency, long service life and excellent energy conversion efficiency, and is considered as an ideal power-based energy storage solution.

Flywheel energy storage systems show unique value in power systems due to their rapid response ability (up to the millisecond level) and high conversion efficiency (generally exceeding 90%). Despite their superior performance, flywheel systems suffer from a relative lack of energy density and require periodic maintenance to maintain their mechanical accuracy and ensure continuous and stable operation [1].

2.2.3 Superconducting energy storage technology

The system is based on the zero-resistance effect of superconducting materials, thus achieving a high-end solution for energy storage. Its operating principle involves a direct current path circulating inside the superconducting magnetic coil for energy storage, showing many advantages such as fast response capability, high efficiency performance, and long-term energy storage capability. When the grid system generates excess electricity, this energy is converted to produce a strong magnetic field in the coil, thus achieving the purpose of energy storage. Instead, the energy stored in the magnetic field can be converted into electricity in reverse when demand for electricity rises, and then returned to the grid.

This technology, with its excellent energy conversion efficiency of more than 90%, as well as significant large-capacity energy storage advantages, shows its huge application potential in the field of power systems. There is almost no loss in the process of transferring energy,

and it can quickly adapt to fluctuating electricity demand. However, it must be noted that while technology itself has a high complexity barrier, the operation of the superconducting system depends on the extremely low temperature environment, which leads to the increase of refrigeration and maintenance costs [1].

2.2.3 The specific application of energy storage technology

Energy storage technology plays a pivotal role in the new energy system, and its core value is to ensure the stability of energy supply and storage efficiency, while enhancing the stability of power grid operation, it has played a role in promoting the efficient use of new energy. The peak and valley characteristics of energy storage technology are used to effectively calm the load of the power grid, that is, release energy when the demand is high, and store energy when the demand is weak, so that the operation efficiency of power generation facilities and the overall operation efficiency of the power grid have been effectively improved. In addition, in the emergency situation of power grid failure or even system collapse, the energy storage system plays a vital role in reducing the loss that may be suffered by key load areas due to power interruption and has an irreplaceable position in emergency protection. In short, energy storage technology plays a pivotal role in the new energy system, which cannot be underestimated in promoting the efficient use of new energy, enhancing the stability of power grid operation and coping with emergencies.

In addition, the use of energy storage technology to enhance the stability and adaptability of the power grid, improve power quality and power supply reliability, and promote the use and development of renewable resources, to make important contributions to the sustainable development of new energy systems. In the process of the transformation of energy consumption structure, the promotion and application of energy storage technology is of great significance. The real case shows that the strategy of “peaking and valley filling”, that is, the use of energy storage devices to store energy during the low power demand at night and release the stored energy during the peak power consumption during the day, in order to reduce the frequent start-up and shutdown of power plants and improve the overall operational efficiency of power generation facilities. At the same time, as an emergency energy supply scheme, it is especially suitable for critical infrastructure such as hospitals or data centers. In addition, it is of great significance to ensure that the energy storage system can quickly start the backup power mode and maintain the uninterrupted operation of the core business when the main power supply fails [2].

3. The Application of Photovoltaic Inverter Technology

3.1 Types of Photovoltaic Inverters

3.1.1 Centralized inverter

Centralized inverter technology involves the aggregation of direct current energy generated by photovoltaic modules or solar panels located throughout the area and its conversion into grid-compatible alternating current via a single or small number of inverters. Such inverters are routinely deployed in the core area of the photovoltaic power generation system and bear the important task of comprehensively regulating the power output and intelligent management of the system.

Early photovoltaic power plants widely adopted the application of centralized inverters, the technology by collecting and converting the direct current generated by multiple photovoltaic modules into alternating current and then connecting to the grid. However, its performance is limited by the consistency of the photovoltaic array and the maximum power point tracking (MPPT) performance of the inverter. The advantages of centralized inverters are mainly reflected in the convenience of system-level monitoring and control, which plays a key role in improving the quality and stability of power output. The problems we face include natural factors, such as temperature fluctuations, local shading, etc., as well as energy loss and efficiency reduction that may be caused by photovoltaic modules and inverters in the system [3].

3.1.2 Series inverter

As a key equipment used in solar photovoltaic power generation system, series inverter is designed to convert from DC power to AC power to adapt the grid and can be directly connected with the photovoltaic series and completed efficiently. The design incorporates a high level of protection against harsh weather and environmental factors. The DC input side is directly connected with the solar panel by omitting the traditional DC busbar link, which greatly simplifies the installation procedure and also reflects the convenience of later maintenance. In addition, this inverter supports maximum power point tracking technology, which can accurately lock the peak power of each panel, and play a strong role in promoting the energy conversion of the entire photovoltaic system. In order to solve the limitation problem of centralized inverter, series inverter technology has been developed and applied. The technology can be matched with one or more PV module strings to achieve independent maximum power point tracking (MPPT) control of each module string, thereby

enhancing the performance of the entire system.

The series inverter can effectively alleviate the power loss caused by the matching difference of photovoltaic modules or partial occlusion, and significantly improve the energy conversion efficiency of solar power generation system. In addition, its modular structural design facilitates future expansion and maintenance of the system [3].

3.1.3 High-frequency link grid-connected inverter

As a key component of the interconnection between the new energy power generation system and the power grid, the high-frequency grid-connected inverter effectively pushes up the working frequency of the inverter system, strengthens the system stability and improves the dynamic response rate by using high-frequency pulse signal technology. Its DC input voltage range is wide enough to cope with variable input conditions and ensure efficient operation in a variety of environments and conditions. In addition, the inverter integrates a maximum power point tracking (MPPT) mechanism to follow the solar panel output changes in real-time, ensuring maximum solar energy collection and utilization. In terms of design, the inverter's current output phase and frequency accurately match the grid standards, in line with the grid's stringent standards for power quality. In particular, this inverter exhibits a high level of conversion efficiency of over 92%, providing a more stable and efficient power output to the grid [3].

The use of high-frequency inverters can effectively reduce the energy consumption of transformers and filters, improve the overall efficiency of the inverter, and reduce the system cost. In addition, because of the high-power density characteristics of high-frequency link inverters, they have outstanding advantages in space-constrained deployment environments [3].

3.2 Application of Photovoltaic Power Inverter

As the core component of a photovoltaic power generation system, a photovoltaic inverter undertakes the important responsibility of transforming the direct current energy generated by solar panels into AC electric energy for residential, commercial buildings and industrial facilities. In addition, it also acts as a bridge between the photovoltaic power generation system and the grid, realizing the efficient transmission of electric energy through the grid to the user, and optimizing the energy allocation and utilization strategy. In terms of function, the inverter also has the ability to regulate and control the output electric energy, ensure the power quality (including stable voltage and current supply), and strive to reduce the loss in the power conversion process, so as to enhance the performance of the entire system [4].

4. Improve the Efficiency of Photovoltaic Power Generation System

4.1 Factors Affecting the Efficiency of Photovoltaic Power Generation

In the operation of solar photovoltaic systems, the occlusion effect caused by dust accumulation is a widespread major problem, which can greatly reduce the light energy of photovoltaic modules to the conversion efficiency of electric energy, and in extreme situations, the reduction of power generation efficiency can exceed 20%. Practical evidence shows that the average power generation output of the 11 photovoltaic sites that have been cleaned by dust accumulation has increased by 14.6%, which strongly proves the necessity of regular maintenance and cleaning [5]. In addition, PV modules will experience natural performance degradation over time, including light-induced and age-related attenuation, which also contribute to the loss of PV conversion efficiency. Specifically, the decay ratio of crystalline silicon components should be controlled within 3% in the first year, and the annual decline thereafter should not exceed 0.7%[5]. At the same time, the impact of temperature change on the efficiency of the components also needs to be paid attention to. The increase of ambient temperature and the heat generated by the components due to the absorption of solar radiation can cause the efficiency to decline. Studies have shown that when the temperature rises by about 1°C, the photovoltaic conversion efficiency will be correspondingly reduced by about 0.35%[5]. Moreover, the light intensity is directly related to the level of energy output of the photovoltaic system, during the day when the solar height Angle is small, such as in the morning and evening, the energy attenuation caused by the increase of the distance between the light and the atmosphere is intensified, and the effective radiation received by the photovoltaic panel is reduced. Finally, the loss of transformers and lines in the transmission process will also affect the total power supply of photovoltaic power stations to the grid, among which the core loss of transformers and wire resistance loss are the main sources of such losses.

4.2 Measures to Increase Photovoltaic Power Generation

In order to improve the power generation efficiency of photovoltaic systems, a series of system optimization strategies can be adopted. The implementation of regular cleaning plans can effectively reduce the accumulation of dust and stains on the surface of photovoltaic modules and enhance the absorption efficiency of solar light. By

optimizing the layout of the components and the series connection mode, each component is fully bathed in sunlight, reducing the efficiency loss caused by local occlusion or performance mismatch. According to the Angle and intensity of local solar radiation, the inclination and spacing of components are adjusted to reduce the adverse effect of shadows on power generation efficiency. Select high-quality PV modules, such as those with UV-resistant backplanes and EVA packaging materials, to enhance the durability and anti-aging performance of the modules and mitigate power degradation. In addition, the assembly design of components is improved, and heat dissipation facilities such as heat sinks and vents are added to improve heat dissipation efficiency and reduce the negative effect of temperature rise on efficiency [6].

5. Future Challenges and Market Opportunities of Photovoltaic Power Generation

5.1 Future Challenges

At the same time as the rapid development of the photovoltaic industry, the field has suffered from severe overcapacity problems. This global problem has led to a sharp decline in the price of photovoltaic products, a sharp contraction in corporate profits, a sharp decline in gross margins, and even a loss [7]. Although the government has promulgated a number of supportive policies, it still faces practical obstacles such as photovoltaic power station footprint, equipment assembly, and cost recovery cycle in practice. In addition, the effectiveness of the policy is limited by the lack of legal support, and it is difficult to accurately docking market demands. At the same time, with the aging of photovoltaic facilities, how to efficiently recycle photovoltaic materials to reduce the environmental burden has become a major issue that needs to be solved. It is predicted that by 2030, waste solar photovoltaic materials will accumulate between 1.7 million and 8 million tons, and by 2050, this figure may rise to between 6 million and 78 million tons [8].

5.2 Market Opportunities

The growing energy consumption in Europe, Asia, Africa, the Middle East and Latin America has opened up new market opportunities for China's solar PV manufacturing industry. Technological innovation is the core driving force for the continuous evolution of the photovoltaic industry. Specifically, by improving the energy conversion efficiency of photovoltaic cells, reducing manufacturing costs and exploring new materials, it can further consoli-

date the competitive advantage of the photovoltaic industry in the market. After decades, the photovoltaic industry has achieved significant cost reductions, indicating that this trend will continue, making photovoltaic power more economically viable, conducive to the expansion of market share. Research shows that solar photovoltaic technology is now maturing and becoming a cost-effective technology of choice, driven by rapid learning and continuous expansion. By the end of 2019, solar photovoltaic power generation accounted for 2.8% of the global electricity supply, and the cumulative installed solar photovoltaic capacity worldwide exceeded 600 GW. It is predicted that by 2050, the total installed capacity of solar PV in the world will exceed 4500 GW. According to the average forecast of IAMs, the total global solar photovoltaic power generation is expected to reach 4.9 PEh/year, and solar electricity has become one of the lowest cost power options in many regions of the world [9].

In addition, solar photovoltaic technology is gradually infiltrating the urban regional market, achieving a transition from remote applications to urban environments. At present, the application of solar photovoltaic in the residential field has become a hot issue that attracts global attention [10].

6. Conclusion

Several core aspects of photovoltaic power generation technology are deeply studied, including how to improve the system efficiency and promote the improvement of conversion efficiency; To further achieve the purpose of cost control. The research results show that the adoption of the above technology and system configuration can significantly enhance the conversion efficiency of photovoltaic power generation and the overall efficiency of the system, and can reduce the cost. Some factors of the efficiency of photovoltaic power generation system are investigated, including dust shielding temperature effect and module aging, and corresponding improvement methods are put forward. In addition, the role of energy storage technology in PV system integration and the technical characteristics and applications of different types of inverters are deeply analyzed. It is concluded that energy storage technology is essential to balance power output and enhance the stability of power grid operation. The performance efficiency and reliability of the inverter directly affect the realization of the overall efficiency of the photovoltaic system's energy conversion. Therefore, the research results provide useful reference and guidance for further development and application of photovoltaic power generation technology.

Although the photovoltaic power generation technology

has been comprehensively and deeply analyzed, there are still some limitations. First, it is based on literature review. Second, because of the rapid development of photovoltaic power generation technology, some data and analysis need to be updated. The third reason is that there is a lack of research on non-technical factors such as the impact of economic policies and measures on society. Future research on photovoltaic power generation technology will focus on the following core directions: First, explore the application of new materials and technologies in photovoltaic materials and battery technology to improve efficiency and reduce costs; Secondly, focus on energy storage technology, especially improving energy storage efficiency, reducing costs and extending life; At the same time, the integration of photovoltaic and smart grid is studied to optimize the power system; Finally, the economic feasibility of photovoltaic power generation and the impact of market policies on industrial development are assessed. These multi-angle studies will drive the continuous progress and wide application of photovoltaic technology, play a key role in the energy transition, and provide guidance for research in related fields.

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