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Grid Connection and Transmission Scheme of Large-Scale Offshore Wind Power

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Abstract: Offshore wind power is an important direction of global wind power development. The economical and efficient grid connection of large-scale offshore wind power is a core challenge for offshore wind power construction in China. This article first summarizes the status of offshore wind power development in China and other countries and global development trends. It then describes the technical characteristics and representative examples of two typical scenarios: the grid connection of single offshore wind farms and transmission of large-scale offshore wind power clusters. After analyzing the challenges associated with the grid connection and transmission of offshore wind power in China, we propose an overall development strategy and analyze the adaptability of grid connection and transmission schemes under these scenarios. To build first-class offshore wind power grid connection and transmission projects that are suitable for conditions in China and to promote energy transformation, we propose that China should conduct unified planning after verifying its national reserves of offshore wind power; strengthen independent innovation to support breakthroughs in key technologies; improve the support mechanism to ensure the development of high-quality offshore wind power; and promote international industrial cooperation.

Keywords: offshore wind power; cluster; grid connection and transmission; planning scheme; adaptability analysis

1 Introduction

Offshore wind power, which has shown an average annual growth of nearly 30% in 2010–2020, is an important direction of global wind power development. At the end of 2020, the cumulative installed capacity was 35.2 GW, and 6.07 GW of capacity was installed in 2020, reflecting continuous high-speed growth. According to forecast data from the International Renewable Energy Agency, the rapid development of offshore wind power is expected to continue, and the installed capacity of offshore wind power worldwide is expected to reach 1000 GW in 2050.

The global offshore wind power has been planned and constructed on a larger scale, in larger clusters, at greater offshore distances, and in deeper water because regions with offshore distances exceeding 100 km and water depths exceeding 50 m have a much larger sea area and more abundant wind energy resources. European countries with advanced offshore wind power technologies, for example, Germany and the United Kingdom (UK), have taken the lead in deploying offshore wind power in deep-sea areas. Offshore wind power transmission projects are more complicated than onshore projects. With increasing offshore distance of wind farms, the cost of transmission projects increases, and the type of transmission plan also affects a project's revenue. Therefore, the development of economical and efficient methods of large-scale offshore wind power grid connection has become a core challenge in offshore wind power construction.

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Offshore wind power in China is entering a rapid development stage, and more than 3 GW of capacity was installed in 2020, accounting for 50% of global newly installed capacity. The cumulative installed capacity of offshore wind power in China ranked second worldwide (Figs. 1 and 2) [1]. The development goals of reaching peak carbon emissions and carbon neutrality provide historic opportunities for new energy development in China, and it has become urgently necessary to construct new types of power systems dominated by new energy sources. Offshore wind power has very good development potential.

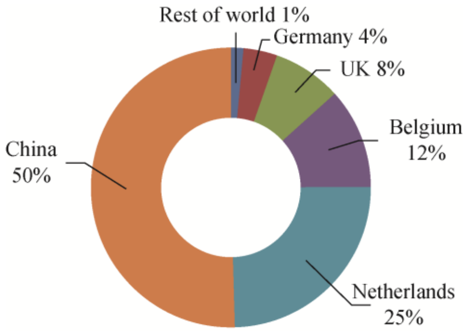

Fig. 1. New installations of offshore wind power worldwide (2020).

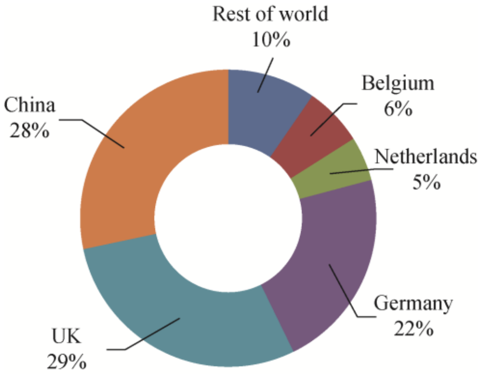

Fig. 2. Total installation of offshore wind power worldwide (2020).

In light of the rapid development of offshore wind power and the urgent need for the development of new types of power systems, this study investigated large-scale schemes for offshore wind power grid connection and transmission. The development trend of offshore wind power in China and other countries was assessed, and the technological progress and application of offshore wind power grid connection and transmission was summarized. In this paper, China’s offshore wind power grid connection and transmission scheme is discussed in terms of national conditions to provide a basic reference for industrial planning, technological development, and industrial cooperation.

2 Status of offshore wind power development in China and other countries

2.1 Offshore wind power development in other countries

The development of offshore wind power began earlier in Europe than in China. Europe is the world’s largest offshore wind power market and is represented by the UK, Germany, and Denmark [2–5].

In 2020, the newly installed offshore wind power capacity in the UK was 483 MW, which accounted for 16.6% of the newly installed capacity in Europe, but the growth rate has decreased to the lowest in the last five years. Four offshore wind farms in the UK have begun offshore construction, and they are expected to be connected to the power grid in the next three years with an additional capacity of more than 3 GW [2].

In 2020, Germany’s newly installed offshore wind power capacity was 219 MW, which accounted for 7.5% of that in Europe. The EnBW Albatros wind farm is 105 km from the German North Sea coast; it is the offshore wind farm with the greatest offshore distance [2,3].

Denmark was the first country in the world to develop offshore wind power, but the growth rate has declined in

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recent years. In 2019, Denmark's newly installed offshore wind power capacity was 374 MW, which accounted for 10% of that in Europe. In 2020, no new offshore wind power was installed, although several large offshore wind farms are under construction. It is estimated that before 2027, Denmark will build offshore wind farms with a single-farm capacity of more than 800 MW [2].

2.2 Offshore wind power development in China

Offshore wind power has continued to develop rapidly in China in recent years. According to statistics from the National Energy Administration, at the end of April 2021, the offshore wind power grid-connected capacity was 10.42 GW. In addition, wind power industry statistics show that the average annual utilization of offshore wind power is approximately 2500 h, which is approximately 500 h higher than that of onshore wind power. From January to April 2021, the offshore wind power generation capacity was 9.94×10^9 kW·h. In addition, the cumulative capacity of offshore wind power under construction exceeds 10 GW, and it is expected that by the end of 2021, the cumulative installed capacity of offshore wind power in China will surpass that of the UK and become the largest worldwide.

For example, in June 2021, the China Huaneng Group Co., Ltd. built the Jiangsu Rudong offshore wind farm, which is currently the largest offshore wind farm in China, with a total installed capacity of 700 MW and the largest domestic use. It is the first offshore wind farm to apply 5-MW-class domestic wind turbines on a large scale. The wind turbines afford a 100% domestication rate of the primary system, and the domestication rate of all the component-level parts exceeds 95%. This project is important for achieving the development goals of reaching peak carbon emissions and carbon neutrality, breaking the foreign monopoly on advanced equipment technology, and realizing overall industrial chain domestication and parity gird integration of offshore wind power in China.

2.3 Development trend of global offshore wind power

The rated capacity of offshore wind turbines has gradually improved to 15 MW. Since 2014, the average rated capacity of newly installed offshore wind turbines in Europe has increased by 16% annually, reaching 8.2 MW in 2020. The batch production of offshore wind turbines with a rated capacity of 8 to 10 MW has been realized, and some manufacturers have developed wind turbines with a rated capacity of 15 MW.

Offshore wind farm capacity is increasing. The maximum capacity is currently more than 1 GW, and large-scale development is expected. The average capacity of European offshore wind farms increased from 313 MW in 2010 to 788 MW in 2020. The Hornsea One offshore wind farm in the UK, which began operation in 2019, has reached a capacity of 1.218 GW.

The offshore distance and water depth of wind farms are increasing; the maximum values exceed 100 km and 100 m, respectively, and this trend is expected to continue. The offshore distances of the Hornsea One project in the UK and the EnBW Hohe See and EnBW Albatros projects in Germany exceed 100 km, and that of the Sandbank and DanTysk projects in Germany is 160 km. The water depth of floating wind power projects such as Hywind Demo, Hywind Scotland, and Windfloat Atlantic exceeds 100 m.

Competitive bidding for feed-in tariffs has become a new model for offshore wind power development, and the cost of offshore wind power has steadily declined. In recent years, the bidding model has become widely used in Europe for the development of offshore wind power projects, and the related subsidies have decreased significantly. Since 2012, the cost of offshore wind power has decreased by approximately 25%, and it is expected to decrease by another 8% to 10% by 2025.

3 Offshore wind power grid connection technology and applications

3.1 Grid connection technology for single offshore wind farm

Some technical solutions have been extensively studied, including high-voltage alternating current (HVAC) transmission systems, high-voltage direct current transmission systems based on thyristor phase-controlled converters (which are also known as conventional DC transmission systems), high-voltage direct current transmission systems based on voltage-source converters (VSC-HVDC systems, which are also known as flexible DC transmission systems), and fractional frequency transmission systems.

The HVAC transmission system is a mature technology that is economical and widely applied. However, the problem of reactive power resulting from HVAC cable charging limits the transmission capacity and distance, and

HVAC systems must be equipped with reactive power compensation equipment. Conventional DC transmission systems must include filtering devices and reactive power compensation equipment, which increase the construction volume and complexity of the offshore booster platform. To date, there has been no practical application of these systems for offshore wind power transmission. The flexible DC transmission system uses fully controlled devices to avoid commutation failure problems; thus, it can realize the decoupled control of active and reactive power and improve the fault ride-through capability. There are many practical projects in Germany. In addition to AC and DC transmission methods, fractional frequency/low-frequency transmission technology and related technologies based on uncontrolled rectifier devices are also under discussion [6–17].

3.2 Grid connection technology for large-scale offshore wind power clusters

Integrated solutions for grid-connected transmission from large-scale offshore wind power clusters can be realized by the comprehensive utilization of existing transmission technology. The most common integrated solutions include parallel AC lines for transmission between wind farms with AC transmission for clusters, parallel AC lines for transmission between wind farms with flexible DC transmission for clusters, multi-terminal flexible DC transmission, and hybrid DC transmission [18].

The capacity of wind farm clusters in China and other countries is typically at the 1 GW level. The use of AC transmission technology for offshore wind power with a short offshore distance has clear technical and economic advantages. However, as offshore wind power development extends to deeper water, some projects have begun to adopt VSC-HVDC transmission schemes [19]. For example, the SylWin1 project in Germany brought together three offshore wind farms with a capacity of 288 MW each. The DC rated voltage is ±320 kV, and the transmission lines include submarine and land cables with lengths of 160 km and 45 km, respectively.

With the development of offshore wind power and DC technology, multi-terminal flexible DC transmission and hybrid DC transmission schemes have attracted increasing attention [20–24]. However, the application of hybrid multi-terminal DC transmission technology still faces challenges such as rapid DC fault clearing and recovery and the design and optimization of multi-terminal hybrid DC control and protection strategies [25–28].

3.3 Application of offshore wind power grid connection technology

Most offshore wind farms currently in operation in the UK use AC transmission. For example, the Hornsea One project, because of its long offshore distance and high power transmission loss, ultimately adopted a scheme with three offshore booster stations and one offshore reactive power compensation station. The reactive power compensation station was built approximately 60 km offshore and is the world’s first offshore reactive power compensation station. The output power of the offshore wind farms is collected and connected to the low-voltage side of the three offshore booster stations and then boosted and sent out via three loops of AC submarine cables (Fig. 3).

Germany prioritizes the centralized development of offshore wind power and unified planning of grid-connected transmission projects to make full use of channel resources. Since 2012, nine HVDC grid-connected projects have begun operation in the North Sea. In 2019, the BorWin3 offshore high-voltage converter platform, which has a capacity of 900 MW, began operation. The power generated by the wind farm is boosted to 155 kV, connected to the DC converter station by an AC cable, and converted to DC power at ±320 kV. The output power of the offshore wind farms is sent to the onshore power grid by submarine and land cables with lengths of 130 km and 30 km, respectively (Fig. 4) [4].

Most offshore wind farms in operation in Denmark use AC transmission. The voltage of the collection system is generally 33 kV. It is boosted to 155 kV or 220 kV by the offshore booster station and sent to the onshore power grid.

In China, all offshore wind farms in operation use AC collection and AC transmission for grid-connected transmission, and the transmission voltage is typically 110 kV or 220 kV. For example, the Jiangsu Dongtai offshore wind farm of the Luneng Group Co., Ltd. has an offshore distance of 36 km and an installed capacity of 200 MW, which is sent out by a 220 kV AC submarine cable. Several offshore wind farms that are planned or under construction will use flexible DC transmission methods.

In summary, grid-connected offshore wind farm projects in operation in China and other countries all use HVAC or flexible DC technology [5]. Ultimately, the coexistence of multiple transmission technologies and multiple grid-connected structures is expected to be the dominant development trend of grid-connected offshore

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wind power systems.

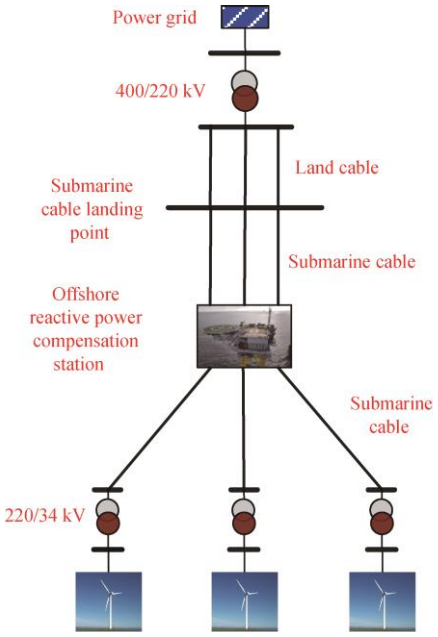

Fig. 3. Illustration of UK Hornsea One offshore AC transmission project.

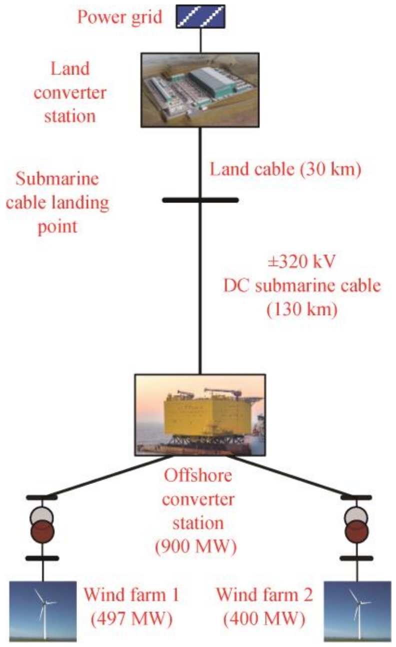

Fig. 4. Illustration of BorWin3 offshore VSC-HVDC transmission project.

4 Basic characteristics and grid connection challenges of offshore wind power in China

4.1 Basic characteristics of offshore wind power in China

China is located in the Northwest Pacific Ocean and has a long coastline, a large sea area, and abundant offshore wind resources. The characteristics of China's offshore wind resources differ from those of the European market.

The average wind speed offshore in China is 6.5–11 m/s, and that in the North Sea in Europe is 9–12 m/s. Because the average wind speed is clearly low overall, China needs more installed capacity to achieve a similar proportion of offshore wind power generation; consequently, power system balancing will become more difficult.

China has a long coastline, and the seabed structure differs significantly from that in Europe. The development of offshore wind power is difficult because of the poor marine/geological environment. For example, the Yellow River and Yangtze River outlets of China are alluvial seabed with high mud content and low carrying capacity, whereas European offshore wind power is generally located on sandy seabed with high carrying capacity. The foundations of wind turbines and transmission systems on alluvial seabed will face very large horizontal and overturning forces under various loads such as wind, waves, and ocean currents. The structural foundation must extend more deeply into the seabed to resist these forces. In addition, the differences in geological conditions increase the technical difficulty and engineering cost and thus significantly affect the economy of grid-connected systems.

Large-scale offshore wind power is connected to the power grid of the southeast load center, which has many ultrahigh-voltage DC (UHVDC) transmission lines and large-scale distributed photovoltaic power. Power grid security is important. For example, the highest electricity loads of Jiangsu, Guangdong, Shandong, and Zhejiang provinces all exceed 9×10^7 kW, and more than 10 UHVDC lines are located in East China. Most nuclear power plants are also located in these areas and are in base load operation.

Various renewable energy, nuclear power, and cross-regional external power sources do not participate in the peak shaving of the power grid, resulting in runs on peak shaving resources. The risk that large-scale renewable energy will be cut off from the grid and multiple UHVDC lines will be simultaneously blocked because of AC failure is also increasing. All of these factors present challenges for the consumption of offshore wind power.

4.2 Grid connection challenges of offshore wind power in China

Most of China’s offshore wind energy resources are located in economically developed areas along the southeast coast. Marine activities are frequent, and sea area is in demand for various purposes. The offshore wind power demand in sea areas is in competition with the needs of transportation, maritime affairs, fisheries, national defense, environmental protection, etc., and channel resources that can be used for offshore wind power development and grid connection tend to be in short supply.

Existing offshore wind power projects are concentrated in the offshore area and are densely connected to the local power grid, which poses challenges to the accommodation and transmission capabilities of the power grid. For example, almost all the wind power in Jiangsu Province is located in the coastal areas north of the Yangtze River. The offshore wind power capacity of the cities of Yancheng, Nantong, and Lianyungang accounts for more than 75% of the capacity of the province. The power source is concentrated in northern Jiangsu, and the load is concentrated in southern Jiangsu. The strength of the grid and the transmission capacity of the north–south cross-river channel directly affect the grid connection and transmission of offshore wind power.

Because of factors such as resource potential, power accommodation capacity, and limited sea area, offshore wind power at longer offshore distances and deeper water depths is expected to be an important future direction, and relevant basic and perspective studies have been performed. However, the requirements for transmission channels and grid connections for wind farms further offshore are more stringent than those for wind farms near the coast. Flexible DC transmission, a representative large-scale offshore wind power transmission technology, is still in the experimental and demonstration stage in China. Many technical problems must be solved for the development and utilization of deep-sea wind power according to national conditions.

Because of the northwestern Pacific monsoon, typhoon disasters occur frequently in China. More than 600 typhoons have made landfall in China since 1949, covering all coastal provinces, with an average of approximately 7 per year. Guangdong, Fujian, and Zhejiang provinces are the most strongly affected by typhoons in China. Severe weather such as typhoons poses a direct challenge to the reliability and safety of offshore wind power transmission systems, and operation and maintenance have become significantly more difficult.

5 Grid connection and transmission scheme of offshore wind power in China

5.1 Overall strategy

5.1.1 Implementing unified planning and centralized transmission

To develop offshore wind power grid connection and transmission, we should first consider the distribution of sea area resources and guide the construction and grid connection of offshore wind farms. Transmission channel resources should be uniformly allocated to minimize the impact of offshore wind power on the natural environment. Costs should be minimized by avoiding inefficient and repeated investments.

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5.1.2 Strengthening the interconnection level

Large-scale development is important for reducing the cost of offshore wind power. To achieve large-capacity offshore wind power transmission requires the construction of a higher-voltage power grid, more extensive interconnection, a stronger structure, and a more robust power grid.

5.1.3 Selecting AC or DC transmission type suitable for local conditions

Because each country is in a different development stage and has a unique power grid structure and economic constraints, the requirements for transmission plans also differ. Small-capacity offshore wind farms near the coast generally use HVAC transmission. By contrast, flexible DC transmission is suitable for large-capacity offshore wind farms far from the coast. Offshore wind farms in China should adopt a grid-connected technical solution suitable to local conditions to ensure safe, reliable, economical, and efficient operation.

5.1.4 Balancing economy and reliability

Economic considerations are an important factor in the selection of HVAC or flexible HVDC transmission for offshore wind farms, but they are not the only factor. Offshore wind farm capacity is large, and the cost is high. The natural environment in which offshore wind farms are located is relatively demanding, and their accessibility is poor; consequently, operation and maintenance are difficult and time-consuming. Therefore, reliable transmission methods are highly valued. In the planning, design, program comparison, operation, and maintenance stages, it is necessary to apply technical measures to ensure the reliability of the transmission system under harsh conditions and reduce potentially significant losses caused by possible failure.

5.2 Grid connection of single offshore wind farms

Because of their technical maturity, economic advantages, and engineering practicality, China will use mainly HVAC and flexible DC transmission technologies for offshore wind power in the 14th Five-Year Plan and beyond.

For comparable transmission capacity and reliability, DC converter stations are more costly than AC substations, whereas DC transmission lines are less costly than AC transmission lines. With increasing transmission distance, AC and DC transmission become equally costly at the equivalent distances. (Fig. 5). In general, when the transmission distance is greater than the equivalent distance, it is economical to use DC transmission; otherwise, it is economical to use AC transmission. The equivalent distance depends on the capacity and voltage of the system and is typically considered to be approximately 50–75 km [29–31]. With the development of power electronics technology, the price of converter devices is decreasing, and the equivalent distance will also decrease.

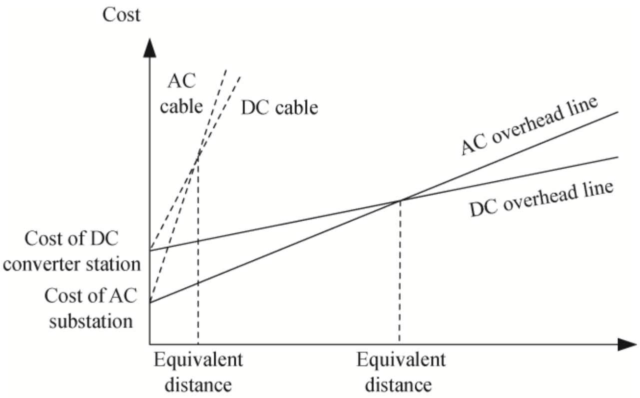

Fig. 5. Plot of equivalent distance for AC/DC transmission.

Considering the overall technical economy and reliability, the following is recommended for offshore wind farms in China. (1) When the wind farm capacity is less than or equal to 200 MW and the offshore distance is less than 50 km, an HVAC method is recommended. (2) When the wind farm has a capacity of 400–600 MW and is located in a deep-sea area, a VSC-HVDC method is recommended. (3) When the wind farm capacity is 200–400 MW, a technical economic analysis according to the offshore distance should be conducted to identify the optimal solution.

5.3 Grid connection of large-scale offshore wind power clusters

5.3.1 HVAC transmission

For wind farm clusters with a capacity of approximately 1 GW and a short offshore distance, HVAC transmission is recommended. Taking into account the transmission distance of 35 kV submarine cables and the transmission capacity of 220 kV submarine cables (with a cross section of 1600 mm^2, an approved carrying capacity of 1320 A, and a transmission capacity of approximately 500 MW), it is recommended to limit the capacity of a single wind farm to 300–400 MW, set up a boost station for each wind farm, and connect to the power grid using multiple 220 kV submarine cables. If the transmission capacity of 500 kV submarine cables (with a cross section of 1800 mm^2, an approved carrying capacity of 1411 A, and a transmission capacity of approximately 1.2 GW) reaches the gigawatt level after the technology matures, it is also possible to consider using a single 500 kV submarine cable. The reactive compensation and resonance problem should also be taken into account.

This method was used for the Yangxi Shapa offshore wind farm of the China Three Gorges New Energy (Group) Co., Ltd., which is under construction. The project has five phases, with a total capacity of 1.7 GW, and the first phase (300 MW) is in operation. The capacity of the second to fifth phases is 1.4 GW. In these phases, two offshore booster stations will be built. Electricity generated by wind turbines will be connected to the offshore booster stations by a 35 kV collection submarine cable, boosted to 220 kV, sent to an onshore control center via two circuits three-core submarine cables (with a cross section of 3 × 500 mm^2), three circuits three-core submarine cables (with a cross section of 3 × 1000 mm^2), and boosted to 500 kV for transmission.

5.3.2 VSC-HVDC transmission

For wind farm clusters far from the coast (more than 100 km), a flexible DC transmission scheme is recommended. For a wind farm cluster with a total capacity of approximately 1 GW, in light of economic factors, it is recommended to construct one public offshore converter station after multiple booster stations and use one flexible DC submarine cable to connect to the onshore power grid.

This method was used in the offshore wind farms of China Three Gorges New Energy (Group) Co., Ltd. and China Guangdong Nuclear Wind Power Co., Ltd. in Jiangsu Rudong. Three 220 kV offshore booster stations were built for each wind farm; the electricity will be collected at an offshore converter station and sent to an onshore converter station via a ±400 kV DC submarine cable with a length of more than 100 km. It will be the first offshore wind power project to use flexible DC transmission at this voltage level and transmission distance.

With increasing rated capacity of offshore wind turbines, usable sea area, and transmission distance of collection systems, the demonstration application of the 66 kV collection system has begun, and higher-voltage collection systems (90 kV or higher) are also under technological development to improve the transmission capacity and decrease loss. With the application of higher-voltage cables, it is also possible to use an integrated solution in which the AC booster station is omitted, and its function is integrated into the offshore DC converter station. Power from offshore wind turbines can be directly connected to the offshore converter station via 66 kV or higher-voltage cables.

5.3.3 Future expansion

The continuous application of flexible DC transmission technology in offshore wind power projects is a technically feasible approach to the construction of an HVDC power grid. As a DC transmission system containing a mesh, a DC power grid can support the grid connection of a large-scale offshore wind power base and significantly reduce the impact of power fluctuations on the grid because of its high redundancy and reliability. An integrated energy island based on offshore wind power is also a possible approach. It would organically integrate offshore wind power with energy storage facilities, hydrogenation systems, or other electrical conversion techniques and achieve offshore wind power transmission and comprehensive utilization relying on electricity transmission, hydrogen transmission, or a mix of electricity and hydrogen transmission.

According to the technology development guideline of “apply a batch, study a batch, reserve a batch,” the planning, evaluation of design layouts, and testing and demonstration of new types of offshore wind power transmission technology, such as multi-terminal flexible DC transmission and hybrid DC transmission, should be performed as offshore wind power and DC technology advance. Cutting-edge technology exploration and practice of offshore wind power DC grids and offshore wind power integrated energy islands should be conducted.

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6 Suggestions

6.1 Exploring national offshore wind power reserves and using the development concept of unified planning

Before the large-scale development and utilization of offshore wind power, the reserves and distribution characteristics should be accurately determined; resource assessment is the first step in this process. Because China has a long coastline and the ocean and geological environments vary widely, the development conditions vary. With the rapid development of technology, existing resource data must be updated, and the latest developable capacity based on technical economy should be determined. Offshore wind power will inevitably shift from offshore to the far ocean and from shallow to deep seas. It is necessary to understand the wind energy reserves and the distribution of deep-sea area as soon as possible and apply unified planning to guide the large-scale development and utilization of offshore wind power and achieve unified planning and project layout for various types of regions.

6.2 Strengthening independent innovation to achieve breakthroughs in key technologies of offshore wind power grid connection

After years of development, offshore wind power in China has shifted gradually from the intertidal zone and offshore area to the deep sea, and it is necessary to plan for deep sea technology. Efficiently solving the problem of large-scale offshore wind power grid connection is a core challenge that must be met to strengthen independent innovation. Systematic in-depth research on the technical economic basis of AC/DC grid connection, key technology development, operation and control optimization, and the application of new technologies should be performed. It is necessary to build a research and development system for offshore wind power grid connection technology, construct a comprehensive demonstration platform with innovative integrated applications, and break through monopolies on key equipment.

6.3 Improving the support mechanism to ensure high-quality development of offshore wind power

After rapid construction in recent years, China's offshore wind power installed capacity has become the highest in the world. As offshore wind power subsidies have ended, offshore wind power capacity has grown explosively, which is not conducive to its sound and sustainable development. It is recommended to investigate the centralized transmission mode, explore a gigawatt-level demonstration project, unify project resources, perform grid planning, and develop a new type of long-distance centralized transmission for offshore wind power clusters. To improve equipment reliability and the offshore wind power utilization rate and ensure the high-quality development of offshore wind power, it is also recommended to accelerate standards development, promote the construction of a national-level offshore wind power detection and certification base, improve the inspection and certification of key equipment, including large-capacity offshore wind turbines, key components, and support structures.

6.4 Improving international communication to promote international industrial cooperation

Offshore wind power was developed early in Europe, and a policy of comprehensive, systematic, and long-term support centered on the electricity price policy played a key role. Competitive bidding for feed-in tariffs has become a new model for offshore wind power development, and a social consensus has been reached on the acceleration of technological improvement and cost reduction.

Considering the offshore wind power subsidy policy in China, it is recommended to strengthen foreign exchange, study and learn from the competitive configuration of European offshore wind power projects, and establish clear long-term competitive development concepts and technology routes for China. European countries such as the UK, Germany, and Denmark have abundant applicable experience in offshore wind power, such as efficient pre-work, one-stop service from management agencies, and support for the investigation and application of new technology. These capabilities are also important for the development of the wind power industry in China. Drawing on mature market development experience and exploring high-quality sustainable development paths for relevant industries are conducive to stable and healthy industrial development.

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