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Exploring the Development Status of Ocean Energy Applied to Power System

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Abstract:
Under the background of global energy transformation and sustainable development, ocean energy, as an emerging renewable energy, is gradually becoming an important supplement to the power system. This paper systematically sorts out the main types of ocean energy, such as tidal energy, wave energy and ocean current energy, and analyzes its power generation principles and key technical characteristics. It further explores the application mode of ocean energy in the power system, the grid connection strategy and its potential impact on system stability. Through the analysis of typical cases, this paper summarizes the current technical bottlenecks and economic challenges of ocean energy development. At the same time, combined with the development trend of smart grid and distributed energy, the future application potential of ocean energy is prospected. The research results show that ocean energy has the advantages of strong cleanliness and high predictability. It has broad application prospects in the green energy system in the future. This paper concludes that improving the technical level, reducing costs and improving industrial disadvantages are the keys to promoting the widespread application of ocean energy in the power system. This study provides a theoretical basis and practical reference for the development and utilization of ocean energy and the sustainable development of power systems.

Keywords: Ocean energy; power system; renewable energy; tidal energy; wave energy.

1. Introduction

Against the backdrop of intensified global climate change and accelerated energy transition, marine energy, as a clean, renewable energy form, is gradually gaining widespread attention. Marine energy mainly includes tidal energy, wave energy, ocean current energy, temperature difference energy and offshore wind power [1,2]. Among them, offshore wind power has become the most promising form of marine energy for large-scale development due to its mature technology and great development potential.

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China, Germany, the United Kingdom and other countries have made significant progress in the field of offshore wind power and have promoted the industry to move rapidly towards marketization. Most of my country's land wind and solar energy resources are distributed in the northwest[3,4]. Coal resources in the north and northwest account for 76% of the country's total, hydropower resources in the southwest account for 80% of the country's total, and load demand in the central and eastern regions accounts for more than 70% of the country's total[5].

As countries pay more and more attention to marine energy, many progress has been made in the application of marine energy to power systems in recent years. Lin Yi and other scholars proposed tidal power generation technology, which has been commercialized in some countries. The installed capacity of the Shihua Lake Tidal Power Station in South Korea is considerable, which has made an important contribution to the local power supply, and conducted an in-depth analysis of the construction cost and operation efficiency of tidal power stations. In terms of operation and maintenance, remote monitoring and intelligent inspection of wind power equipment are gradually becoming popular. Huang Huajuan and others pointed out that technologies such as power inspection based on artificial intelligence and underwater robot maintenance have become an important direction for improving the operation and maintenance efficiency of offshore wind power systems. At the same time, relay protection technology is also used in offshore wind power systems. Liu Siyu and Li Xiao proposed research on relay protection technology for distributed energy access in electrical technology and economy to ensure the safe and stable operation of power generation equipment and transmission systems[6,7]. In addition, technologies such as artificial intelligence and big data analysis are gradually being integrated into all aspects of the marine energy system. Through the predictive analysis of environmental data such as wind speed, tides, and water flow, the power generation efficiency and the level of intelligent scheduling are improved. In the management of power equipment, Sun Dayan proposed to improve the regulation ability of the power system and the level of intelligent scheduling to help construct a new power system and lay the foundation for the construction of an intelligent marine energy system in the future.

However, the complex marine environment, difficult equipment maintenance, and high costs still restrict the widespread application of marine energy. Therefore, it is of great significance to study the status quo and challenges of marine energy power generation technology, explore the integration path of artificial intelligence and power system technology, and analyze the development trend of offshore wind power in terms of job requirements and technical systems in order to promote the sustainable development of marine energy. This article will systematically review the current major marine energy power generation technologies, focus on analyzing the development trend of offshore wind power and the progress of operation and maintenance technology, explore the application prospects of artificial intelligence in marine energy systems, and combine key power technologies such as relay protection to propose development ideas for the deep integration of marine energy and modern power systems. The subsequent content will first elaborate on the application technology and development status of various marine energy sources such as tidal energy and wave energy in power systems, then analyze the challenges and opportunities faced by marine energy applications, and finally propose strategies and suggestions to promote the widespread application of marine energy in power systems.

2. Application of marine resources in power system

At a time when the global energy landscape is undergoing profound changes, environmental pollution and other serious problems, the combustion of which produces a large amount of greenhouse gases, are exacerbating global warming. Marine energy is a renewable energy source hidden in the ocean, mainly including tidal energy, wave energy, ocean current energy, seawater temperature difference energy and salinity difference energy. Tidal energy is generated by the gravitational force of the moon and the sun, and the kinetic energy of the rising and falling tides is converted into electrical energy through tidal power stations, such as the Jiangxia Tidal Power Station in Zhejiang, China [8]. Wave energy uses the energy of the up and down movement of waves, and can generate electricity through oscillating water columns, pendulum devices, etc. Ocean current energy relies on the kinetic energy of surface or deep water currents in the ocean and is suitable for development in straits and areas with strong ocean currents. Seawater temperature difference energy uses the temperature difference between surface warm water and deep cold water to generate electricity, and tropical waters are rich in resources. Salinity difference energy comes from the chemical energy of seawater with different salinities and is currently in the research and development stage. These energies are clean and environmentally friendly, with huge reserves, and are an important direction for future energy development[9]. In recent years, a series of remarkable progress has been made in the development of global marine energy.

In terms of tidal energy development, some countries have built large-scale tidal power stations. The Hwahu Tidal Power Station in South Korea has a capacity of up to 2,540,000 kilowatts, which can transmit a large amount of clean electricity to the grid every year. While alleviating the pressure on the local energy supply, it also greatly reduces carbon emissions. Actively explore innovation in the field of wave energy use. Zhang Yunqiu proposed the tidal energy power generation technology and its development status. The paper systematically expounds the principle of tidal energy power generation, divides tidal energy power stations into three types: single reservoir unidirectional, single reservoir bidirectional, and double reservoir continuous, and compares the working modes of different types of power stations. Analyze the loss). In addition, relevant personnel have developed various types of wave energy power generation devices and carried out demonstration projects in their coastal areas. Guo Xiaoping, wave energy can convert wave mechanical energy into electrical energy through oscillating water columns, pendulum devices, etc., which explains the adaptability of different devices to wave frequency and amplitude, as well as the efficiency differences in different sea areas (such as nearshore and offshore); although the current wave energy generation has problems such as low capture efficiency at the technical level and poor stability of power generation devices, these practical projects have accumulated valuable experience and operational experience, and the ocean temperature difference experiment is progressing steadily, so that ocean energy temperature difference power generation can be commercialized as soon as possible. Ocean current energy is similar to wind power generation, which uses ocean currents to drive turbines to generate electricity, and analyzes the impact of ocean current speed and direction on power generation; ocean temperature difference energy is based on the temperature difference between the surface and deep layers of seawater, and realizes the conversion of heat energy and electrical energy through Rankine cycles, etc., which explains the role of temperature difference and working fluid selection on efficiency. At present, the technical path for integrating ocean energy into the power system, such as tidal power stations, can match the peak and valley of the power grid load by adjusting the power generation period (when the tide rises and falls, if the load is low, energy storage can be considered or participate in peak load auxiliary services). Wave energy and ocean current energy have large power fluctuations, and energy storage systems (battery energy storage, pumped storage, etc.) need to be configured to smooth the power or virtual synchronous machine technology is used to simulate the characteristics of traditional synchronous generators to improve grid adaptability. Different strategies and applicable scenarios for distributed and centralized grid connections can also be mentioned. Li Peng, Wang Bing, and Zhao Qiang proposed a study on the impact of tidal power grid connection on the frequency characteristics of the power system. The scholar constructed a “virtual synchronous machine grid connection control strategy” to simulate the inertia and damping characteristics of traditional synchronous generators so that tidal power generation units have frequency support capabilities[10]. Taking a 20MW tidal power station in Fujian as an example, after configuring a virtual synchronous machine, the grid frequency deviation dropped from 0.3Hz (without control) to 0.1Hz (with control), improving grid stability.

3. Current status of ocean energy generation technology

3.1 Key technologies

The principle of tidal dam power generation is to build a dam at the estuary or bay, and use the water level difference during the ebb and flow of the tide to drive the turbine to generate electricity. The technology is mature and the power generation is stable. The investment in large tidal power stations abroad is 2-5 times higher than that in river hydropower stations, and the unit kilowatt investment in tidal power stations in my country is also about 2-3 times higher than that in river hydropower stations. Therefore, in order to promote the scale and industrialization of tidal power generation, we must first find an effective way to reduce the construction cost of tidal power stations[1].

The principle of tidal power generation is similar to that of underwater “wind turbines”, which directly use the seabed tide to drive water wheels to generate electricity. Ocean thermal power generation (OTEC) uses a temperature difference of about 20°C between the surface and deep layers of the ocean to generate electricity. Its core technology is a closed-loop system, which uses low-boiling-point working fluids (such as ammonia) to evaporate in surface warm water to drive turbines to generate electricity, and then condenses back into liquid form through deep-sea cold water for recycling. This technology is clean and renewable and suitable for tropical waters. Offshore wind power has a “multi-energy system”, such as the “wind power + tidal energy + liquid flow battery + diesel generator” solution. The principle is to use tidal energy to generate electricity at night to supplement the low wind power, liquid flow batteries to store excess electricity, and diesel generators as emergency backup. There is also “wind power + gas turbine + green hydrogen energy storage”, where wind power gives priority to meeting the load, excess electricity is used to produce hydrogen for storage, and gas turbines

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use hydrogen to generate electricity when wind power is insufficient (low-carbon transformation).

3.2 Development trends

3.2.1 Large-scale

Focus on increasing the capacity of tidal and wave energy units, aiming to develop tidal turbines exceeding 5MW and wave energy generation devices exceeding 10MW. Optimize fluid mechanics design, such as using bionic blades for tidal turbines and adapting wave energy devices to wide spectrum capture, break through the efficiency bottleneck of high-power units, and reduce unit power costs.

Project implementation: Plan and build large-scale ocean energy bases, such as the million-kilowatt tidal-tidal energy base in Zhoushan, Zhejiang, integrate marine resources, rely on large-scale development to spread the initial investment, promote ocean energy from “demonstration project” to “energy base”, and enhance the support level for the power system.

3.2.2 Intelligent

Intelligent dispatching builds a collaborative intelligent platform of “ocean energy power generation - power grid”, integrating tidal forecast, wave monitoring, and load forecast data to achieve real-time dispatch of multi-energy complementarity (ocean energy + wind power/photovoltaic power). Use AI algorithms to optimize power generation plans, dynamically adjust unit output according to tidal cycles, match peak and valley demands of the power grid, and smooth out power fluctuations.

Intelligent operation and maintenance introduce digital twins and drone inspection technologies to build a full life cycle management system for equipment. Real-time simulation of the operating status of ocean energy devices, early warning of corrosion, wear and other faults; drones equipped with sensors inspect offshore power stations to reduce the risks and costs of manual operation and maintenance and ensure high reliability of equipment operation.

3.2.3 Fusion.

Multi-energy complementarity is to deepen the integration of “ocean energy + offshore wind power/photovoltaic/hydrogen energy” and create a “marine comprehensive energy island”. Taking the South China Sea as an example, promote the coordinated power generation of tidal energy, wave energy and offshore wind power, and store surplus electricity through seawater hydrogen production to resolve the intermittent problem of ocean energy and provide a stable energy supply for deep-sea development (ocean ranches, offshore platforms).

Industry coupling is to expand the coupling of ocean energy with ocean ranches, seawater desalination and other industries to build an “energy-industry” ecology. The cofferdam of the tidal power station also serves as a marine ranch breeding platform, and wave energy power generation is used to power the seawater desalination device. The benefits of multiple industries are used to feed back the development of ocean energy and solve the dilemma of single power generation profitability.

3.2.4 specialization

The accelerated scale development of offshore wind power in my country and the gradual move of project development to the deep sea have put forward higher requirements for equipment such as transportation, installation and construction, and operation and maintenance. Further improving the professional level of cable-laying vessels, installation vessels, and operation and maintenance vessels has become one of the important issues facing the industry, which requires all parties to work together to promote the research and development of related technologies and the design and manufacture of advanced equipment.

This article focuses on marine energy power generation technology and takes “technical combing - problem analysis - trend analysis” as the path to systematically explore the development status of tidal energy, wave energy, and temperature difference energy. The study found that marine energy has moved from the laboratory to engineering demonstration, demonstrating its value in island power supply and multi-energy complementary scenarios, but due to factors such as cost, reliability, and grid-connected adaptation, there is a gap in large-scale application.

4. The integration of Marine energy and artificial intelligence in the future

4. 1 Future Directions

First, the future needs to develop in the direction of intelligent prediction and scheduling optimization. For example, tidal prediction uses historical data + neural networks to predict tidal changes and improve the efficiency of tidal power generation. At the same time, energy scheduling AI optimizes the coordinated operation of multiple energy sources in microgrids (sea breeze, waves, energy storage). Secondly, drone inspection and intelligent operation and maintenance need to be integrated in the future. Drone aerial photography + defect identification uses drones equipped with high-resolution cameras or infrared thermal imagers to take aerial photos of blades, towers, bases and other components of offshore wind turbines. Image recognition algorithms can automatically detect problems such as blade cracks, wear, icing, tower rust, loose bolts, and base marine organisms adhesion and seawater erosion. Compared with manual inspections, it is more efficient and avoids the risk of high-altitude operations. Dynamic monitoring is to analyze the deformation and displacement of equipment components (such as blade vibration amplitude) through time-series image comparison and warn of structural safety hazards in advance. Submarine cable inspection uses drones to fly along the cable laying path to identify threats such as exposed submarine cables, floating objects entangled, and ship anchoring, and combines AI algorithms to mark risk areas to help protect submarine cables. The marine environmental analysis uses drones to identify oil pollution, floating ice, and areas where large marine organisms are active on the sea surface, providing data support for wind power equipment anti-corrosion and anti-collision strategies, while also assisting in ecological and environmental assessments.

Finally, the ocean temperature difference can be used to power deep-sea data centers. Submarine cable transmission is the most common transmission method for ocean temperature difference power generation. The processed electricity is transmitted to the land power grid through submarine cables. Submarine cables need to have good insulation performance and pressure resistance and corrosion resistance to adapt to the marine environment. For example, in some ocean temperature difference power generation projects on islands, electricity is transmitted to the island power grid through submarine cables to supply power to residents and enterprises. Hydrogen production, storage and transportation is to use the electricity generated by ocean temperature difference power generation to electrolyze water to produce hydrogen and store hydrogen. Hydrogen can be transported to where it is needed through pipelines or transportation tools and used as clean energy. When used, hydrogen can be converted into electricity again through equipment such as fuel cells. For example, in some remote areas or industrial fields with a large demand for clean energy, stored hydrogen can be used to meet energy needs. On-site consumption at sea is to build some facilities that require electricity at sea, such as offshore aquaculture platforms, offshore data centers, etc., and use the electricity generated by ocean temperature difference power generation directly for the operation of these facilities to achieve on-site consumption. This can reduce the cost and loss of power transmission and improve energy utilization efficiency.

4.2 Innovation Areas

With the development of digital twin technology, the real-time status of power stations can be simulated based on digital twin technology and displayed intuitively and dynamically on the background monitoring platform (Figure 1). Digital twin technology can collect real-time operating data of wind farms, such as wind turbine speed, power, temperature, etc., as well as voltage, current and other indicators of submarine cables, and update them synchronously with virtual models. Managers can monitor the operating status of wind farms in real time through virtual models in the control center and fully understand the operation of equipment. The Turbine Smart Control system is embodied in the Maximum Power Point Tracking (MPPT), which uses AI algorithms to dynamically adjust the angle of the wind turbine blades and the speed of the generator to achieve maximum output power. It also implements anti-wind disturbance control and uses adaptive control algorithms to stabilize wind turbine operation in extreme weather conditions such as typhoons and strong gusts. It also optimizes load balancing, coordinates multiple wind turbines to reduce local overload and eddy current interference, and improves overall efficiency.

The intelligent autonomous operation and maintenance platform (Autonomous Operation & Maintenance) is reflected in the unmanned ship (USV) inspection system at sea, which can automatically navigate and inspect wind farms, equipped with radar, cameras, and infrared sensors to monitor equipment. Underwater robots (AUV/ROV) can automatically inspect and clean wind turbine foundations (underwater pile foundations). The intelligent booster station control system can dynamically manage the operating status of booster station electrical equipment through AI, and realize remote diagnosis and recovery control.

Intelligent environmental perception and adaptive control systems can optimize wind speed and direction perception, and perform real-time wind resource detection + AI micro-meteorological model prediction to guide wind turbine direction (yaw) adjustment. Wave recognition and platform attitude control In floating wind power platforms, sensors and AI control platforms are used to stabilize and improve power generation efficiency and structural safety.

In the future, with the gradual application of intelligent monitoring and operation and maintenance technology, offshore wind farms will be further promoted to transform from corrective maintenance to preventive maintenance, thereby reducing the frequency of maintenance and enhancing the system’s fault resistance. Online status monitoring and intelligent fault analysis will become an important part of future wind turbine maintenance systems and will be applied to more and more offshore wind farms[2].

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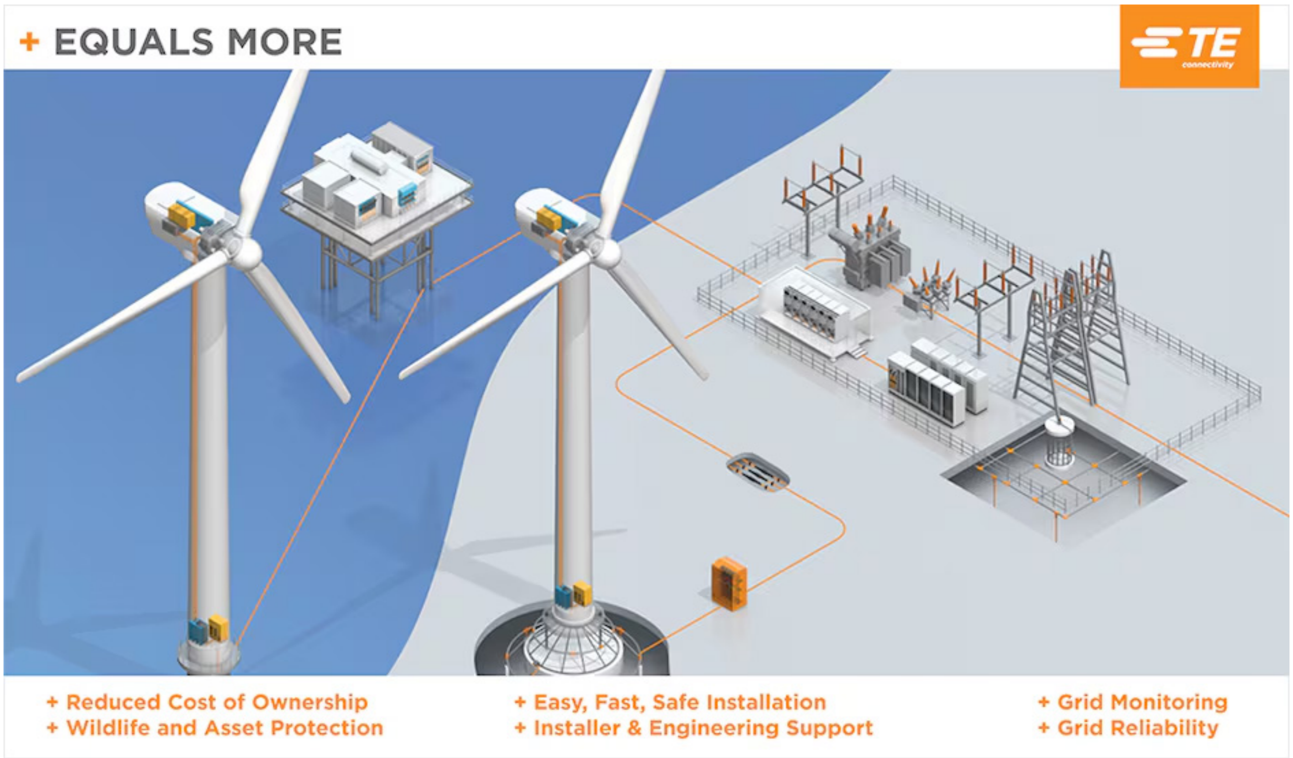

Figure 1 Design of offshore wind farm

5. Application of tidal energy generation

Tidal power generation is a clean way of generating electricity by converting the kinetic energy of ocean tidal flows (tidal currents) into electrical energy. Its core principle is similar to wind power generation, except that the "medium" changes from air to seawater.

Horizontal axis turbines are similar to underwater windmills. The blades are driven by the tide to rotate and drive the generator through a gearbox, such as the British SeaGen tidal generator (installed capacity 1.2MW). Vertical axis turbines have blades perpendicular to the direction of the water flow, and are highly adaptable to changes in the direction of the water flow, suitable for complex sea conditions. The oscillating water column type is that the tide drives the water column to reciprocate, and the compressed air drives the turbine to generate electricity. The structure is relatively simple.

It is highly predictable and stable, because the tidal current is caused by the gravitational force of the moon and the sun, and has a strong regularity, and can accurately predict the power generation capacity for decades or even hundreds of years. Compared with wind energy and solar energy, tidal current energy is more continuous and stable. It has high energy density because the density of water is more than 800 times that of air. At the same flow rate, the kinetic energy obtained by tidal current turbines is much greater than that of wind turbines. In straits or waterways with suitable flow rates, even lower flow rates (1~2 m/s) can provide higher energy output.

In the future, it can be integrated with artificial intelligence to use AI for tidal forecasting, equipment health diagnosis, energy output optimization, etc., which can improve the system's adaptive ability and operation and maintenance efficiency. Unmanned equipment (such as underwater robots) can assist in equipment installation and maintenance, reducing labor costs and safety risks. It is expected to form a comprehensive "marine energy platform" with offshore wind power, ocean temperature difference energy, hydrogen energy production, etc.

6. New operation and maintenance equipment

The offshore wind power intelligent operation and maintenance management system is a comprehensive management system that uses information technology and Internet of Things technology to conduct real-time monitoring, data analysis, fault diagnosis, predictive maintenance and other functions on offshore wind farms. It can realize remote monitoring and management of wind turbines, substations, transmission lines and other equipment, improve the operating efficiency and safety of offshore wind farms, and reduce operating costs.

6.1 Unmanned equipment system

The offshore wind power unmanned equipment system is a composite system that integrates automatic control, intelligent perception, communication technology and mechanical engineering (Figure 2). Its principle can be summarized as a closed-loop process of "perception - decision-making - execution - collaboration". With unmanned inspection drones, underwater robots, unmanned installation ships and other equipment as carriers, intelligent operations in offshore wind power scenarios are realized through multi-level technical modules.

Due to the complexity and unknown nature of the working environment of intelligent underwater robots, it is necessary to continuously improve and perfect the existing intelligent system architecture, enhance the ability to predict the future, strengthen the system's autonomous learning ability, and make the intelligent system more forward-looking. At present, a series of studies have been carried out in the fields of intelligent system architecture, environmental perception and task planning to improve the intelligence level of underwater robots[3].

Figrue 2 Offshore wind power platform

6.2 Centralized control system

The centralized control system is based on a "layered distributed architecture" and uses sensors to collect operating data from equipment such as wind turbines, submarine cables, and booster stations, and transmits it to the central control unit via a communication network (such as a fiber optic ring network, 5G). It uses controllers such as PLC/DCS to perform logical operations, combines with the SCADA system to achieve real-time monitoring, and then outputs control instructions (such as pitch control and power adjustment) through algorithms such as PID adjustment. Its core is to solve the problem of offshore wind power equipment being dispersed and the environment is complex through data fusion and collaborative strategies. It has functions such as fault warning, power optimization, and remote operation and maintenance. It ensures reliability through redundant design (hardware/communication), and is the nerve center for achieving efficient and safe operation of offshore wind power.

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7. Offshore wind power outlook

(1)Artificial intelligence reduces the operating costs of wind farms, and the construction of intelligent wind farms will continue to advance, with the hope of achieving unmanned operation.

(2)Ocean energy will be mostly used in offshore wind power (Figure 3 and Figure 4).

(3)The multi-energy complementary system refers to the integration of offshore wind power and other energy forms (such as energy storage, gas, tidal energy, solar energy, etc.) through technical integration and intelligent regulation to form a coordinated power supply network, solve the volatility and intermittent problems of offshore wind power, and improve power supply reliability and energy efficiency. Its essence is to achieve low-carbon and stable power supply in offshore areas through "energy complementarity, time and space mismatch optimization, and multi-source coordinated control."

Jiangsu has carried out a "wind power + photovoltaic + ocean energy" demonstration, sharing infrastructure such as booster stations, reducing construction costs by 20%. The "wind power + ocean ranch" project in Shanwei, Guangdong has achieved a unit sea area output value of 150,000 yuan per hectare, and the comprehensive utilization rate has increased to 85%.

(4)Offshore wind power is the main form of marine energy application. With the saturation of offshore resources, deep-sea floating technology has become a new growth pole.

Figure 3 Floating wind power platform

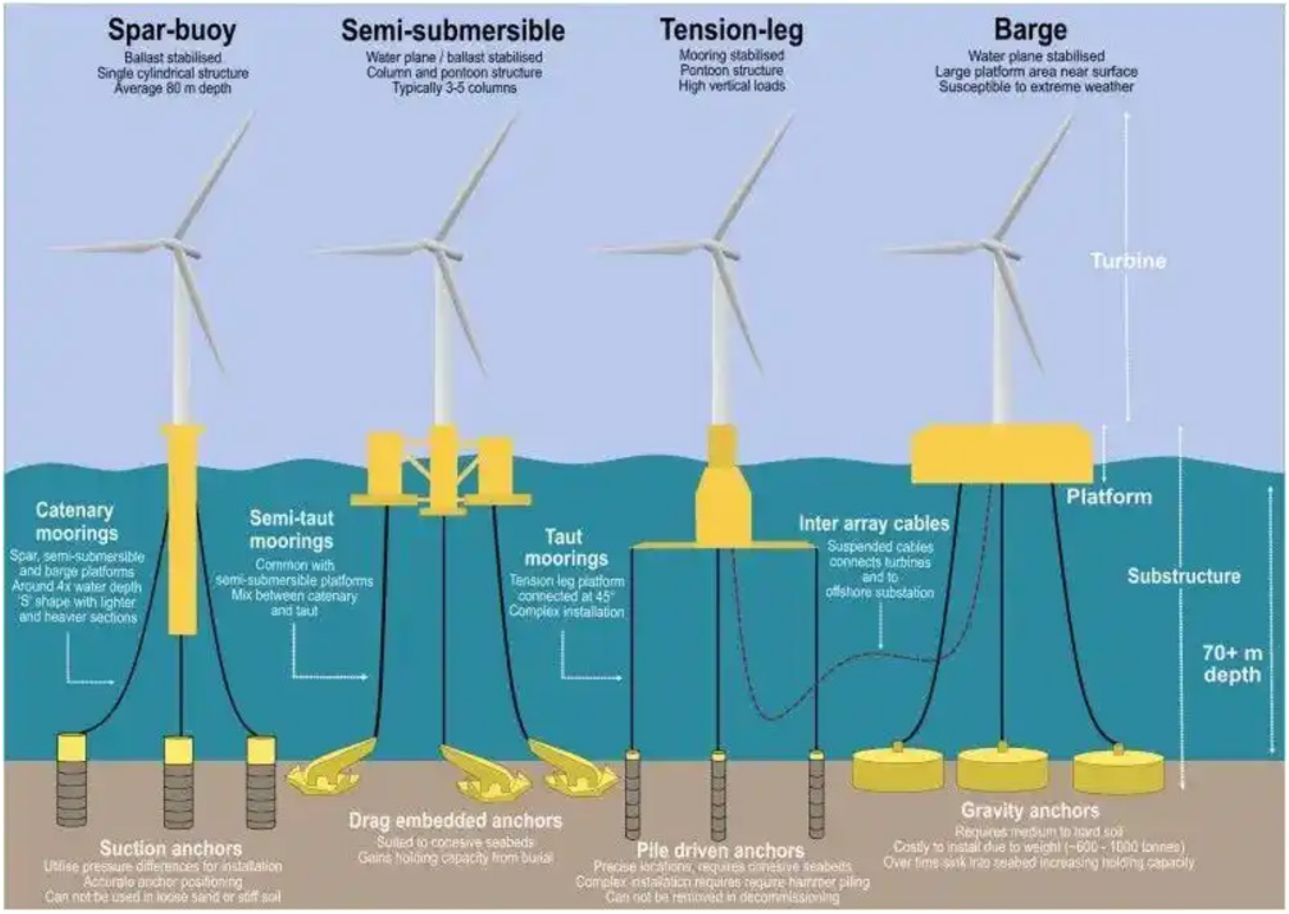

Figure 4 Structure diagram of floating wind power platform

(5) In the future, floating technology will realize ultra-large units and intelligence. In 2025, the world's first 20MW floating wind turbine will be put into operation in Yangjiang, Guangdong. It uses an AI-driven "digital twin" system with a fault prediction accuracy of 95% and a 40% reduction in operation and maintenance costs. Breakthroughs have been achieved in materials and structures. Ultra-high performance concrete (UHPC) is used in floating foundations, with a compressive strength of 115MPa, a 20% reduction in weight compared to steel structures, and a 15% reduction in costs. The proportion of carbon fiber composite blades will increase from 12% in 2024 to 35% in 2030, and the blade length will exceed 120 meters. In addition, deep-sea adaptability has been improved, and the tension leg platform (TLP) technology has accelerated its maturity. The WindFloat Atlantic project of Principle Power in the United States operates stably in waters 100 meters deep, and the movement amplitude is 50% lower than that of semi-submersibles.

(6) In recent years, offshore floating wind power technology has become increasingly mature along with the global offshore wind power commercial development boom and is in the initial stage of commercialization. For China's offshore wind power industry, conducting floating wind power technology research and engineering practice will help expand the scope of offshore wind power space, which is an important direction for the sustainable development of the offshore wind power industry and an important means for my country to maintain its competitive advantage in the offshore wind power industry in the future[4].

8. Conclusion

The use of tidal energy needs to comply with the objective laws of the moon's revolution and cannot be predicted. On the other hand, tidal energy is a future renewable energy form with high predictability, high energy density and environmental friendliness. With technological progress and policy support, tidal power generation is expected to be commercialized and applied on a large scale in the next ten to twenty years, becoming an important part of the blue low-carbon energy system. The application of floating offshore wind power will reduce development costs and later maintenance costs. Offshore wind power will accelerate my country's energy transformation with

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a stronger momentum in the future. The artificial intelligence smart platform combined with it will be fully invested in large-scale wind farms. With the blessing of AI, it is expected to achieve unmanned operation soon, and smart wind power will be born. There is also a multi-energy complementary system, imitating the "photovoltaic + energy storage + charging pile" model in the photovoltaic field. Offshore wind power also has a "wind power + energy storage + fishing light + marine ranch" model. These combinations with traditional industries will greatly give play to the comprehensive utilization efficiency of offshore wind power.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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