Article

Research on Monitoring and Operation and Maintenance Technology of Far-Reaching Sea Smart Wind Farm

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Abstract: With the rapid development of global offshore wind power, the demand for offshore wind power operation and maintenance is also increasing. Wisdomization of offshore wind farms is a practical need to improve the operation level and benefit of offshore wind farms. This paper first introduces the current development situation and characteristics of global offshore wind power, and expounds the current situation and main challenges of offshore wind power operation and maintenance market. Therefore, our paper discusses the innovation of offshore wind power operation and maintenance from the aspects of operation and maintenance management of offshore wind power, monitoring and analysis technology of units, far-reaching wind field monitoring and operation and maintenance risks. Then, combined with information technology and lean management concept, a smart operation and maintenance management platform for wind farms in far-reaching sea areas is built to explore centralized and intelligent operation and maintenance management mode, improve operation and maintenance efficiency of wind farms in far-reaching sea areas, and minimize operation and maintenance costs. Finally, through the research on the characteristics of 5G technology, combined with the practical experience of operation and maintenance, and in view of the characteristics of offshore wind farms, we analyze and propose several typical application scenarios of 5G technology in the intelligent operation and maintenance of offshore wind farms, which provides a new solution for the efficient operation and maintenance of offshore wind farms.

Keywords: Offshore Wind power; Operation and maintenance management; Intelligent operation and maintenance robot; Smart wind farm technology; 5g technology

1. Introduction

In recent years, in the face of increasing greenhouse effect and air pollution, countries around the world have accelerated the pace of exploration for clean energy and renewable energy power generation. As one of the main clean energy, wind energy, especially offshore wind energy, has developed rapidly. Compared with land wind energy, the capacity benefit of offshore wind energy resources is 20%~40% higher, and has the advantages of less land occupation, fast operation speed, large production power, stable operation of the system and no dust. In addition, the wind speed at sea is large, the wind speed, wind direction change and turbulence intensity are small, which can effectively reduce the mutual wear of wind turbines and improve the service life of wind turbines. It is suitable for large-scale development in coastal areas.

Compared with land-based wind power, offshore wind turbines are in a harsh marine environment for a long time, and the failure rate of offshore wind power is significantly higher [1]. With the large scale of global offshore wind power installation, the demand for offshore wind power operation and maintenance is also increasing. The whole life cycle of wind power operation and maintenance is becoming the focus of offshore wind power market. On the other hand, the construction site selection of offshore wind

power is developing towards deeper water depth and farther offshore, and floating wind turbines are increasing, which also means that the operation and maintenance environment will be worse and the maintenance will be more difficult. According to Wood Mackenzie, the investment scale of the global offshore wind power operation and maintenance market will grow at an annual rate of 16% from 2021. By 2029, the total investment in the global offshore wind power operation and maintenance market will exceed $12billion.

In the harsh environment at sea, the operation and maintenance of wind turbines are significantly affected by climate and tide. The operation requirements are high, and the effective working time is short. The ships, personnel configuration and maintenance time required to maintain different types of components are quite different. Therefore, how to select the appropriate installation mode and operation and maintenance strategy in the complex and changeable environment and limited working time at sea is of great significance to promote the development of offshore wind power. It is urgent to improve the operation level and benefit of wind farms through digitalization and intelligence, and the construction of smart offshore wind farms has become an industry consensus. The future construction of smart offshore wind farm depends on good operation and maintenance management, which requires the support of scientific operation and maintenance strategy, intelligent fault diagnosis and monitoring technology and stable and efficient operation and maintenance vessels.

In the context of the rapid development of global offshore wind power, in view of the operation and management of offshore wind farms and the development status of smart wind field technology, this paper introduces the current development situation and characteristics of global offshore wind power, and expounds the current situation and main challenges of offshore wind power operation and maintenance market. The innovation of offshore wind power operation and maintenance is discussed from the aspects of operation and maintenance management of offshore wind power, monitoring and analysis technology of units, new wind power operation and maintenance vessels and operation and maintenance robots.

2. Development and Characteristics of Far-Reaching Sea Breeze Electric Field

At present, in response to global climate change, major economies have formulated carbon neutrality targets. Carbon emission reduction has driven the accelerated transformation of the global energy structure, moving from the era of fossil energy to the era of renewable energy. The energy revolution has ushered in new development opportunities for the wind power industry. Since Denmark put into operation the world's first offshore wind farm, Vindeby [2], in 1991, offshore wind power has entered a rapid development path. Compared with land-based wind power, offshore wind power resources are richer. Offshore wind turbines do not need to occupy land resources, are closer to the electricity load center, and have higher utilization hours of power generation [3][4][5][6]. Under the background of the rapid development of wind power industry, the development speed of offshore wind power is ahead of the industry as a whole.

At present, offshore wind power development and its areas are mostly concentrated in offshore waters, facing the problem of competing for limited resources with offshore aquaculture, fishing and transportation routes. Moreover, in the context of energy transformation, with the increase of energy demand, it is an inevitable trend to increase the development of offshore wind power in the far-reaching sea. The development space of offshore wind power in far-reaching sea is huge, which is of positive significance to the technological progress, economic development and energy structure optimization of the industry.

The cost of operation and maintenance of offshore wind turbines towards large offshore wind power mainly includes the operation and maintenance of wind turbines, ship maintenance and insurance. High unit failure rate and large maintenance workload are the biggest difficulties in offshore wind power operation and maintenance. The direction

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of development, the cost of leveling electricity is reducing. Fans with larger impeller diameter and larger power can provide greater annual power generation, thereby reducing costs.

With the rapid development of offshore wind power, the large-scale wind turbines, deepwater offshore layout and the use of floating wind turbines pose new challenges to the operation and maintenance of offshore wind power. In the future, smart offshore wind farms need intelligent and efficient operation and maintenance support. The existing operation and maintenance data show that under the same installed capacity, the operation and maintenance cost of offshore wind power is twice that of onshore wind power [7], and the operation and maintenance cost of offshore wind power accounts for more than a quarter of its power consumption cost [8].

The cost of offshore wind power operation and maintenance is shown in Figure 1, including wind turbine operation and maintenance, ship maintenance and insurance. Purchasing prices for offshore wind turbines are falling due to investors' cost considerations and the price war between machine suppliers, which also leads to the use of more cheap components, resulting in lower overall configuration and difficult quality assurance. High unit failure rate and large maintenance workload are the biggest difficulties in offshore wind power operation and maintenance.

Due to the influence of tide and other conditions, there are window period constraints in the operation and maintenance of offshore wind power, the accessibility of offshore wind turbines is poor. The adverse meteorological conditions and harsh sea conditions limit the maintenance time [10][11], and also bring greater security risks. At present, the operation and maintenance mode of offshore wind farm mainly draws lessons from the mode of onshore wind farm and adopts three modes: fault maintenance, regular maintenance and condition-based maintenance [12].

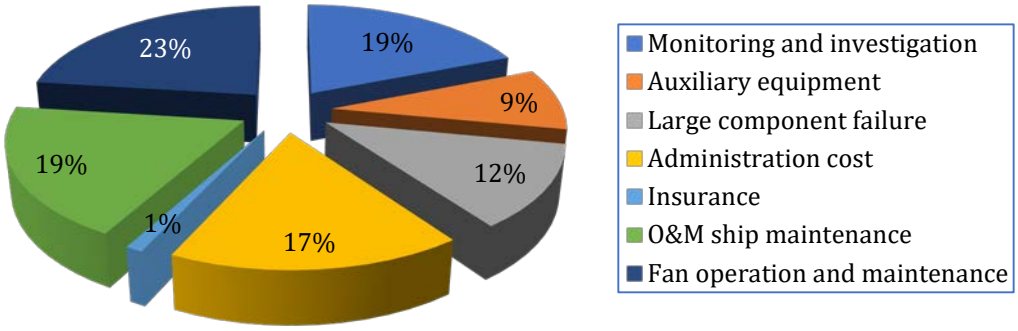

Figure 1. Operation and maintenance cost of offshore wind power [9]

1. Fault maintenance refers to the maintenance after the fault occurs, which is an inevitable maintenance method under the current technical conditions of offshore wind turbines [13]. Fault maintenance requires operation and maintenance personnel to investigate the causes of the fault on the spot, so there are high requirements for weather conditions, ships and spare parts. The maintenance cost and outage loss are related to the fault type and maintenance time, which will affect the reliability of the unit and the power generation income of the whole wind farm.
2. Periodic maintenance is the preventive inspection and maintenance of wind turbines based on the maintenance plan formulated in advance, mainly for the state inspection and functional test of wind turbine components [13]. Regular maintenance can make the wind turbine in the optimal operation state. At the same time, considering the utilization rate of wind resources, regular maintenance is generally arranged for implementation in small wind season. Reasonable periodic maintenance time interval is very critical, too large time interval is easy to lead to insufficient maintenance of the unit, reliability decline; small time interval will lead to increased maintenance costs.

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3. Condition-based maintenance refers to the maintenance strategy based on the relevant state information extracted by the wind turbine condition monitoring system and the results of online or offline health diagnosis or fault analysis system [14]. Its advantage is to combine the health status of wind turbines, spare parts, weather conditions, etc., select the optimal time point to arrange maintenance in advance to ensure high availability of wind turbines. However, so far, due to the imperfection of the wind farm data analysis system and the limitation of the effectiveness of the collected data, the offshore wind turbine usually needs to further analyze and confirm the health and fault state of the wind turbine by means of manual on-site detection [13].

This operation and maintenance mode cannot well adapt to the operation characteristics of offshore wind power. In terms of fault maintenance of offshore wind power, the maritime traffic of operation and maintenance personnel is greatly affected by sea conditions. Large uncertainty may cause long-term shutdown of units, which seriously affects the production efficiency of wind farms. The key problems to be solved in the field of offshore wind power operation and maintenance are as follows:

1. Improve the offshore wind turbine operation condition monitoring system, using the unit health diagnosis technology, realize the unit abnormal identification, predict the unit life.
2. Further optimize the maintenance strategy of offshore wind farm, standardize the operation and maintenance mode, optimize the operation and maintenance resource management scheme, and rationally allocate the operation and maintenance resources. The formulation of operation and maintenance strategy should be combined with the reliability data of the unit, so as to improve the efficiency of a single seagoing operation as much as possible, so as to avoid frequent seagoing and save operation and maintenance costs.
3. Units with fault-tolerant operation ability can still work smoothly in a certain period of time after some faults occur. In the case of offshore wind turbine failure is difficult to avoid, the fault-tolerant operation function of the unit has important research value.
4. The correlation of multi-component faults of offshore wind turbine is studied, and the correlation of function and structure between multi-component is analyzed.

3. Monitoring and Operational Maintenance Technology

3.1. Offshore Wind Turbine Monitoring and Analysis Technology

The intelligent monitoring of offshore wind power includes underwater intelligent monitoring, structural fatigue and damage monitoring, cable monitoring and foundation scouring monitoring. Intelligent analysis technology covers weather forecasting and early warning system, window management system, ship, route, personnel management system and maritime security system. Online monitoring technology transmits and visualizes observation data in real time through a variety of communication media, which facilitates data processing. With the help of underwater robots, underwater intelligent monitoring can directly monitor the overall state of the foundation by inspecting the underwater part of the target unit. For the fatigue and damage monitoring of the support structure, the deformation, stress, displacement, vibration and corrosion status of the structure are monitored by sensors, and the data are transmitted to the monitoring system in real time. The specific monitoring items and the location of the monitoring points can be selected according to the specific operation and maintenance and safety assessment requirements of the wind farm. Marine environmental parameters monitoring acquires real-time project sea area data through sensors and high-speed transmission technology, including wave data, wind data, current data and temperature and salinity data, and accumulates background parameters for offshore wind power operation and maintenance. The submarine cable monitoring is usually based on the cable online monitoring method of optical fiber and partial discharge, and the operation state of submarine cables is monitored [15]. Sea

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area monitoring reduces the cable damage caused by ship mooring by continuously monitoring the passing ships around the submarine cable. Foundation scouring monitoring can obtain parameters such as scouring depth through data acquisition equipment, which can be combined with support structure response monitoring to provide higher security for offshore wind power foundation structure.

3.2. Operation and Maintenance Management Technology of Offshore Wind Power

Among the life cycle costs of projects in far-reaching sea areas, the operation and maintenance costs are only second to the costs of wind turbines. According to statistics, offshore wind farm operation and maintenance costs accounted for 18%~23% of the total cost of offshore wind power projects, far higher than the land wind farm operation and maintenance costs accounted for 12% of the total cost of the project [13]. According to the estimation of DNV Classification Society, the average annual outage of an offshore wind turbine will be as high as 40 times, and the overall probability of failure is maintained at about 3%. On average, about 30 offshore wind turbines need a professional offshore wind turbine maintenance ship for daily maintenance work. Therefore, the demand for offshore wind turbine maintenance ships (see Figure 2) for offshore wind farm supporting services is increasing, and the professional requirements of ships are also increasing. While improving the reliability and safety of operation and maintenance, reducing the cost of operation and maintenance is also a major problem of offshore wind power.

Figure 2. Self-elevating and floating operation and maintenance platform [9][18]

3.2.1. Operation and Maintenance Operations

Operation and maintenance operations are mainly divided into the following three types.

1. Periodic Maintenance

Periodic maintenance refers to the periodic detection, maintenance and maintenance of wind turbines according to the technical requirements of wind turbine manufacturers and operation time. The work content is relatively fixed, and generally there are relatively standard procedures and requirements [16]. Through regular testing, the equipment can keep the best running state, prolong the service life of wind turbine, produce more economic efficiency, make full use of resources and maximize benefits.

2. Daily Operation and Maintenance

The daily operation and maintenance work is mainly the disposal of various faults. The prediction, detection and elimination of wind power equipment faults require personnel to have professional ability in electrical and communication [16]. This work is also one of the most technical and challenging tasks for the operation and maintenance of wind turbines. The working experience, technical level and knowledge reserve of personnel determine the speed and effect of processing, which directly affects the normal operation of wind power [16].

3. Accident Maintenance

When some large components of wind turbines are damaged, such as blades, generators and gearboxes, they need to be removed for repair. This failure will generally produce a large amount of repair costs, and the repair process is more complex. After an

 doi:10.20944/preprints202204.0253.v1

accident occurs, experts should be organized to analyze the causes and treatment measures immediately, and a detailed repair plan should be developed and fully evaluated before implementation.

3.2.2. Operation and Maintenance Ship

Offshore wind farm operation and maintenance ship is an important means of transportation for wind farm to maintain normal construction, operation and maintenance. Common wind power ship can be divided into four types: ordinary ship, professional ship, mother ship, jack-up ship.

At present, 400 offshore wind power carriers are put into use globally. The new type of offshore wind power carriers is larger in size and can carry more equipment and components. They have good riding comfort, faster speed, higher safety of personnel transfer and stronger ability to resist wind and waves. There are many types of professional wind power operation and maintenance ships. The special bow can not only be used for operation and maintenance personnel to climb stairs from the bottom of the wind turbine, but also reduce the ship's shaking. The main types of wind power ship include mono-hull ship, twin-hull ship, three-hull ship, small hydroplane catamaran, surface effect ship and small hydroplane trimaran. The typical parameters of various types of ship are shown in Table 1.

Table 1. Typical parameters of different types of ship

Major parameter	mono-hull ship	twin-hull ship	three-hull ship	small hydroplane catamaran	surface effect ship	small hydroplane trimaran
Master /m	*21*	*20*	*18*	*20*	*28*	*27*
Maximum speed /kn	*23*	*25*	*20*	*23*	*33*	*25*
Maximum manning	*12*	*12*	*12*	*12*	*12*	*12*
Dead weight /t	*5.0*	*10.0*	*1.0*	*2.0*	*4.0*	*4.5*
Maximum significant wave height /m	*1.5*	*2.0*	*2.5*	*2.5*	*2.5*	*3.0*

Operation and maintenance vessel is the main means of transportation for offshore wind farm construction, operation and maintenance, which plays the role of platform carrier. It provides services for the operation and maintenance of wind turbines in offshore wind farms, minimizes and reduces the operation and maintenance time and cost, reduces fan failure and shutdown, improves power generation efficiency, and improves the economic benefits of wind farms. It can quickly and comfortably reach the wind column site, and can be reliable and stable to ensure that people can go safely and quickly. The operation and maintenance of traffic vessels are shown in Figure 3.

Figure 3. Operation and maintenance of traffic vessels [17]

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The main performance characteristics of the operation and maintenance of the transportation ship are as follows:

1. Rapidity and Flexibility. The ship requires high speed, reduces midway sailing time and reaches the wind field quickly.
2. Comfort The ship has good seakeeping and low noise to maintain the combat effectiveness of operators.
3. Berthing. Good maneuverability of the ship, excellent equipment, and the ability to reach and stabilize the wind power column.
4. Safety. Operators can safely and smoothly get up and down wind power columns by means of operation and maintenance of traffic vessels.

Large-scale offshore wind fields in Europe mostly use large carriers, which are far away from the shore and have deep operating water depth. This kind of operation and maintenance mother ship generally adopts the catamaran type, which can meet the operation and maintenance of offshore wind power under the harsh sea conditions of Pu's 7 wind, 2.5m wave height and 2kn surface velocity. With the development of offshore wind field towards far-reaching sea areas, the demand for large-scale carriers will increase significantly in the next 5~10 years.

3.2.3. Operation and Maintenance Platform

The main operation projects of the wind power operation and maintenance platform include the maintenance and replacement of the support tower, cabin and blade of the wind turbine. In the sea, whether it is the installation of the wind turbine or the foundation or the replacement of large components, it needs the corresponding transportation tools to transport it to the wind field, and equipped with corresponding equipment to be installed in place. The wind power operation and maintenance platform in the late stage of wind field construction usually shuttles between several adjacent wind fields to maximize the platform capacity. Wind power operation and maintenance platform (see Figure 4) mainly has the following three characteristics.

Figure 4. Wind power operation and maintenance platform [17]

1. Fast Lifting Speed

Unlike offshore oil drilling platform, the offshore operation environment of wind power operation and maintenance platform is complex, the operation window time is short, and the sea condition is bad. The operation and maintenance platform needs to move the ship station piles frequently, and the platform lifts frequently. Therefore, there are high requirements for the lifting speed, reliability and durability of the lifting system equipped on the platform. At present, the world's mainstream platform lifting system is mainly divided into hydraulic plug type and gear rack type. Compared with the hydraulic pin lifting system, the gear rack type has the characteristics of fast speed and easy platform adjustment.

2. Operation Depth

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With the continuous progress of technology, offshore wind power will develop to a farther and deeper sea area, and the operating water depth will reach 60 m. In the future, offshore wind power will move towards the deep sea. At present, the planned water depth of offshore wind field can reach 50 m. Therefore, the operating water depth will become the operating range and decisive factor of the wind power operation and maintenance platform. At this time, the importance of leg length is highlighted. The leg form of operation and maintenance platform is mainly divided into cylindrical leg and truss leg. Compared with the cylindrical leg, the truss leg can effectively reduce the force of waves, currents and sea wind on the platform due to its hollow structure, which greatly enhances the stability and safety of the platform. At the same time, due to its own structural characteristics, the cylindrical leg is generally suitable for platforms with operating water depth not more than 40m, while the truss leg can meet the deeper operating water depth.

3. Self-Propelled and Dynamic Positioning Capability

The operation and maintenance platform has the ability of self-navigation, which can realize the rapid ship relocation between wind farms and towers. Compared with the tugboat towing and mooring positioning, it is more accurate and faster, which greatly saves the time in place and the cost of tugboat anchor, and effectively improves the operating efficiency of the platform. The platform equipped with dynamic positioning system (DP) can automatically maintain the position and heading of the platform under the specified environmental conditions. At the same time, it also has independent centralized manual position control and automatic heading control. Moreover, the dynamic positioning system can realize the floating positioning of the platform due to its ability to resist waves and currents, which has significantly enhanced the security and reliability of the platform storm self-sustaining.

3.2.4. Wave Compensation Ladder

It is well known that the wind field is characterized by large waves and numerous dark currents, and the personnel up and down the tower is very dangerous. How to ensure the safety of personnel up and down the tower is very important. Traditional personnel up and down the wind tower is the use of ship to reach the wind tower, personnel seize the opportunity to climb the wind tower. This method is very dangerous, a little careless will trigger a safety story, after all, the wind sea condition is bad, the climate environment is complex and changeable, the ship is difficult to maintain a relatively stable state for a long time. Ordinary port ladders are widely used in marine engineering, but due to the limitations of their placement along the port, they can only be applied to the boarding of persons between ships or platforms and boats or docks. The common footbridge is also a kind of personnel boarding device commonly used in marine engineering. However, due to its design limitations, the wave is a little too large to be used. The wave-compensated starboard ladder boarding system can safely transport the operator to the wind tower platform under the condition of grade 4 sea. It has automatic control ability in the complex and changeable sea environment and can maintain relative balance, as shown in Figure 5.

Figure 5. Wave compensation ladder [17]

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The wave compensation starboard ladder mainly includes the six degree of freedom compensation ability of the compensation mechanism, the telescopic ability and pitching ability of the telescopic starboard ladder, and the bearing capacity of the starboard ladder. The basic part of the compensation structure is a six-degree-of-freedom self-balancing compensation platform, which realizes integration and modularization, and can compensate the relative displacement caused by waves. The special wave compensation ladder with high stability requirements is installed to form a safety channel between the ship and the wind turbine column, which is convenient for personnel safety and ensures personnel safety. In addition, the wave compensation ladder has the scalability, which takes up small space when it is not used for collection, saves the deck area, and can also be used for stacking other items.

3.2.5. Intelligent Operation and Maintenance Robot

The harsh marine environment brings a lot of inconvenience to the operation and maintenance of offshore wind power. In order to improve the convenience of operation and maintenance and reduce the safety risk of operation and maintenance personnel, robots and unmanned aerial vehicles are applied. Robot system is also a key part of intelligent operation and maintenance of offshore wind power. Figure 6 is the robot 'BladeBUG', which is designed for the maintenance of offshore wind turbine blades. The robot has a crawler and six crawling feet. The end of each foot has a vacuum bonding device, which can be firmly adsorbed on the surface of the blade and carry out flexible crawling. Using robots instead of manpower for operation and maintenance can reduce the risk of operation and maintenance accidents, improve detection efficiency and accuracy, and save maintenance costs. It is estimated that a good robot system in the future can help wind power projects save USD 33 million in their life cycle. The first European offshore wind power operation and maintenance robot test center was established in Portugal in 2020, which is dedicated to research on robot operation and maintenance operations in harsh environments.

Figure 6. Intelligent operation and maintenance robot [9][18]

4. Deep Sea Breeze Electric Field Monitoring and Operational Risk

The intelligentization of the whole life cycle of offshore wind power is the key to achieve the optimal power cost of offshore wind power leveling, and the intelligent operation and maintenance of offshore wind power is a systematic project.

The intelligent operation and maintenance system uses big data and intelligent data technology to make operation and maintenance decisions based on data. Using fine cost control, through the real-time calculation of fan operation and maintenance cost and income in the whole life cycle, the fine level of operation and maintenance management is improved, and the operation and maintenance cost is effectively reduced. Do a good job in offshore wind turbine component level test, build offshore wind power 'genetic engineering', formulate reasonable operation and maintenance plan, improve the reliability of unit operation. According to the early warning information of large parts, lock the lifting vessels and spare parts of large parts in advance, and shorten the shutdown time of large parts. Through the integrated system of fault warning and operation inspection and

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maintenance, the operation and maintenance plan and operation and maintenance scheduling are optimized to reduce the operation and maintenance cost of offshore wind power. The performance of offshore wind power generation and the cause of power loss are evaluated, and the research and application of control strategy optimization technology are carried out to further improve the power generation of wind turbines. Optimize regional wind transportation tools in different sea areas and scales, improve operation and maintenance efficiency and reduce daily operation and maintenance traffic costs.

It is the development goal of offshore wind power operation and maintenance mode to scientifically and reasonably plan operation and maintenance time and route, adopt pre-operation and maintenance mode to eliminate hidden trouble and reduce operation and maintenance cost. For the planning of operation and maintenance path, the safe, convenient and cost-optimal operation and maintenance transportation route should be selected based on the wind power prediction, the accessibility of operation and maintenance ships, the operation status and health status of units [19].

The operation and maintenance risks of offshore wind power construction projects are divided into the following parts.

1. Equipment Failure Risk

Equipment failure is a high risk of offshore wind power construction projects in the operation stage. Such as blade control system fault, transformer fault, generator, gearbox fault, and offshore booster station electrical equipment, HVAC equipment, fire equipment fault. Monitoring and video equipment failures, submarine cable failures and equipment failures bring uncertainty risks to the normal operation of offshore wind farms.

2. Personnel Safety Risk

During the operation and maintenance period, the maintenance personnel frequently travel between the offshore wind field and the land. The personnel board the wind turbine platform at sea, maintain operations in the wind turbine platform, and repair operations at high places inevitably produce personnel safety risks. There are personnel safety risks such as electric shock, falling high, personnel falling into water and equipment damage.

3. Maritime Traffic Risk

The following two means of transport (operation and maintenance) are often used in offshore wind farms ; 1 carrier ; 2 Helicopters and two types of transportation are affected by sea conditions and weather. The operation and maintenance vessel is the main commuting tool for the operation and maintenance of offshore wind power. The domestic offshore wind power has not started for a long time. At present, ordinary traffic vessels are still used as the main transportation tool, which has the disadvantages of poor wave resistance and poor berthing ability. It is difficult to meet the requirements of safe navigation such as wind and wave resistance, anti-collision and maritime rescue.

The risk-based maintenance method can reduce the overall maintenance difficulty and life cycle cost, and present the availability and unit performance satisfactory to all parties. The traditional operation and maintenance strategy of planned maintenance combined with fault maintenance consumes a lot of manpower, material and financial resources. With the continuous progress of operation and maintenance technology, the operation and maintenance strategy based on condition-based maintenance has become a development trend [20].

Condition-based maintenance takes the equipment status as the starting point, finds the latent fault through online monitoring and offline measurement, and evaluates the equipment status. Condition-based maintenance is highly targeted. Through the comprehensive analysis of equipment, it is better to determine whether the equipment is to be overhauled and the maintenance effect is also better [21]. The operation and maintenance strategy based on condition-based maintenance can facilitate the unified scheduling of operation and maintenance resources for the maintenance of multiple units, improve the efficiency of single outbound operation, reduce the number of outbound operations, and reduce traffic costs [22]. Condition-based maintenance is a major innovation in the operation and maintenance management of offshore wind power. The realization of condition-

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based maintenance needs to monitor and analyze the operation state of the unit, and strengthen the life cycle monitoring of components and the condition monitoring of large components in combination with the characteristics of different offshore wind farms.

5. Smart Wind Farm Technology

5.1. Definition of Smart Offshore Wind Farm

Smart offshore wind farm refers to a new offshore wind farm, which is widely used in cloud computing, big data, Internet of Things communication, artificial intelligence and other new technologies, integrates intelligent equipment, control and management technology, and breeds the equipment and system without perception and thought in the traditional wind farm into a safer, more efficient and more economical state perception, autonomous adaptation, intelligent integration and precise control.

5.2. Construction of Intelligent Operation and Maintenance Management Platform for Offshore Wind Farms

The intelligent operation and maintenance of offshore wind farms in far-reaching sea areas aims to achieve the lowest cost, high reliability and increase power generation of wind power operation and maintenance, and arrange the maintenance strategy, business process, time cycle, transportation tools and maintenance personnel of offshore wind farms through intelligent algorithms [23]. By building a far-reaching sea intelligent operation and maintenance management platform, the remote and centralized control mode of wind farm is realized, the reliability and availability of wind turbine are improved, and the economic benefits of wind farm are ensured.

The offshore wind farm intelligent operation and maintenance management platform includes: wind farm intelligent monitoring and operation optimization system, wind farm integrated information management system, wind farm operation and maintenance scheduling management system, wind turbine condition monitoring and health management system.

5.2.1. Wind Farm Intelligent Monitoring and Operation Optimization System

The intelligent monitoring and operation optimization system of wind farm is a system that integrates wind turbine monitoring, power dispatching, meteorological information and operation optimization based on big data. It enables wind farm managers to timely understand the operation status, fault information, meteorological environment and power dispatching information of wind turbines, and plays a guiding role in the operation and maintenance decision of wind turbines.

1. Meteorological information such as sea weather, typhoon, rainstorm and snow, disaster warning are analyzed and recorded. According to the meteorological information, the early warning and pre-processing schemes and the sea operation strategy are arranged.
2. Receiving and executing the instructions of the local power dispatching department, participating in the voltage regulation and frequency regulation of the power grid and peak and valley filling. At the same time, with the continuous development of the new power market, wind farms in far-reaching sea areas will also participate in power transactions to further meet the demand for load characteristics.
3. Condition monitoring, early warning and fault display of all equipment in wind farm, and embedded application of fault treatment scheme based on expert database can improve the informatization and intelligence level of wind farm ; at the same time, it carries intelligent data and information collection strategy to provide basic support for wind farm operation optimization.

5.2.2. Wind Farm Integrated Information Management System

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The wind farm integrated information management system includes at least four databases [24]: equipment archives, equipment information database, warehouse and component replacement maintenance management database, inspection and fault work order database, etc.

1. The equipment archives record the basic information of various types of equipment of wind turbines, such as wind turbine type, configuration, component type, ship information, etc., which is convenient for subsequent equipment classification statistics, device quality tracking, operation scheduling management, etc.
2. The object of the equipment information database is the technical specifications, operation and maintenance manuals, spare parts, tools and transportation tools involved in the maintenance process of wind turbines. Ships are the main means of transportation, and the basic information of ships and the seagoing operations are recorded. If the ship is temporarily leased, it is necessary to record the relevant information of leasing.
3. The warehouse and spare parts replacement and maintenance management library is used to record the quantity, quality, storage location, access and other basic information of spare parts and tools. At the same time, the relevant information before and after spare parts replacement and the whole process of spare parts self-maintenance or third-party maintenance are recorded in detail, which is convenient for subsequent inquiry and statistical analysis.
4. Inspection and fault work order database is used to record wind turbine fault information, maintenance information, etc. The fault work order information involves the historical fault of the unit, the fault treatment method, the time and type of the replacement parts, etc., and these experiences are used to establish and improve the expert database. Maintenance information records and tracks the whole process of maintenance according to the requirements of plan management, including requirements, plans, processes and reports.

5.2.3. Wind Farm Intelligent Monitoring and Operation Optimization System

Due to the constraints of marine factors, wind power in far-reaching sea areas cannot adopt the mode of real-time maintenance of land-based wind power. Instead, it is necessary to select appropriate maintenance strategies on the basis of a comprehensive analysis of offshore maintenance costs, outage power loss and marine climate conditions. Wind farm operation and maintenance scheduling management system includes planning scheduling management and trigger scheduling management.

The planning scheduling management mainly aims at the various maintenance requirements and inspection work of wind farms. Taking the maintenance of single unit as the task, the operation items, tools, spare parts and ship requirements are listed. After the maintenance, the maintenance work is summarized, including the evaluation of the quality of the maintenance work.

When the accumulated maintenance workload in the integrated information management system and the wind turbine condition monitoring and health management system reaches a certain threshold or sends out serious fault warning, the corresponding maintenance scheme is matched from the ability improvement and evaluation system according to the maintenance demand. Then the system puts forward the ship demand according to the maintenance scheme, and allocates maintenance resources such as tooling tools, maintenance personnel, spare parts and other maintenance resources to ensure the efficient and smooth development of maintenance business, so as to improve the operation and maintenance efficiency of offshore wind farms.

5.2.4. Wind Farm Intelligent Monitoring and Operation Optimization System

The structures of offshore wind turbines and onshore wind turbines are basically the same, and the common faults are also concentrated on several key components such as blades, gearboxes and generators [25]. The condition monitoring and evaluation system of wind turbine mainly monitors the status of blades, spindles, gearboxes, generators and electrical system components, and evaluates the health status of each component, such as

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faults or hidden dangers. Early warning and reasonable maintenance suggestions are given to prolong the service life of components.

The condition monitoring and health management system of wind turbines is associated with the integrated information management system of wind farms and the operation and maintenance scheduling management system of wind farms. The maintenance personnel call the operation and maintenance scheduling management system of wind farms according to the prediction results of the condition monitoring and health management system, and the plan is included in the plan management library. At the same time, the system is also associated with equipment unit archives, equipment information library, warehouse and component replacement maintenance management library, environmental weather information, etc., which can make arrangements for maintenance time, maintenance cycle, transportation, maintenance personnel.

5.3. Application Analysis of 5g Technology in Operation and Maintenance of Smart Wind Field

At present, the mobile communication technology represented by 5G is closely integrated with new technologies such as artificial intelligence, Internet of Things, cloud computing, big data and edge computing, providing more and more rich applications, opening a new era of interconnection. 5G changes the operation mode and operation mode of the core business of the energy industry with ultra-high bandwidth, ultra-low delay [26] and ultra-large-scale connection technology, and comprehensively improves the operation efficiency and intelligent decision-making level of the traditional energy industry.

According to the investigation and study, several offshore wind power projects have successfully applied mobile communication networks. Such as China's Jiangsu Rudonghaishang wind farm and Dafeng offshore wind farm have built4G mobile communication network. But 5G mobile communication network has not been successfully applied in offshore wind power projects.

At present, the operation and maintenance mode of offshore wind farm mainly draws on the operation and maintenance mode of onshore wind power. Artificial or local operation and maintenance is still the main means of current operation and maintenance work, and there are problems such as long operation and maintenance cycle and low operation and maintenance efficiency. In order to realize the intelligent, accurate and machine operation and maintenance work, the application of advanced technology is the key. According to the characteristics of offshore wind power, there are mainly the following typical application scenarios of 5G technology in the intelligent operation and maintenance of offshore wind farms in the future.

5.3.1. 5G Inspection Unmanned Aerial Vehicles and Robots

The eMBB and mMTC technologies in 5G are applied to endow the UAV with important capabilities such as real-time ultra-high-definition image transmission and remote low-delay control, so as to realize the fine multi-directional inspection of offshore wind power. Achieve offshore wind power 'unattended, less on duty' operation requirements.

The inspection robot of booster station is equipped with intelligent infrared imaging equipment, laser positioning and navigation, multi-axis universal arm, adaptive wheel chassis, intelligent charging pile and other intelligent components. By using 5G network and big data processing platform, the operation parameters such as temperature of electrical equipment of booster station, information of automatic control device, and switch position state are regularly cruised, collected, analyzed, and warned, and the on-site emergency disposal is carried out under the remote control of the on-duty personnel.

5.3.2. Tower Inspection and Real-time Feedback

In the traditional inspection of wind turbine towers and other parts, ground telescope visual inspection or high-altitude hanging basket manual inspection are mostly used. The inspection operation process is complex and the safety hazard is great. Since the tower drums of units are mostly made of metal magnetic conductive materials, the magnetic adsorption wall climbing robot can be considered for inspection [27]. With the continuous

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development of industrial Internet technology, combined with 5G technology, robot inspection can realize robot flaw detection and real-time feedback communication, tower surface fouling removal [28], and tower surface damage repair.

5.3.3. Fault Identification and Real-time Feedback of UAV Blade

The blade of wind turbine is far from the ground, and it is difficult to effectively identify the blade fault by conventional means. Due to poor accessibility and short window period of offshore wind power, it is more difficult to identify the blade fault. The traditional manual repair method will make the fan stop for a long time and cause serious power loss. The UAV can move synchronously with the blade of the wind turbine, without the need for the blade to remain static. UAV blade fault identification has the characteristics of safety, reliability and efficiency, which eliminates the safety hazards of personnel landing on the sea and falling objects at high altitude. UAV equipped with high-definition imaging equipment can obtain the blade image of the unit from all directions and angles, which makes the recognition results more reliable. Based on the '5G+ industrial Internet platform', the unmanned aerial vehicle (UAV) for fault identification of offshore wind turbine blades can realize the functions of autonomous route planning, unmanned aerial vehicle (UAV) servo blades, multi-machine cooperative operation, and intelligent identification of blade defects [29]. At the same time, combined with machine learning and artificial intelligence technology, the real-time feedback of UAV to blade faults can be realized.

5.3.4. Cabin Environment Perception and Internal Real-time Monitoring

The environment of offshore wind turbines is often accompanied by harsh conditions such as high temperature, high humidity and high salinity. When the gearbox, generator and other components in the cabin are running, a large amount of heat will also be generated. Combining the above two factors, the temperature and humidity inside the cabin will reach a relatively high level, which will have a certain adverse effect on the operation of the unit. By monitoring the real-time change of temperature and humidity in the cabin, the temperature field distribution diagram in the cabin can be established, and the components that are prone to overheating in the cabin can be found. Corresponding measures are taken in operation and maintenance to ensure the safety of the cabin and the normal operation of the unit [30].

The existing wind turbine engine room monitoring system mainly collects real-time parameters of wind turbine operation, such as temperature, humidity, wind direction and wind speed. Operators cannot directly and comprehensively monitor the operation status of equipment. With the continuous application of high-speed transmission technologies such as 5G, the problems such as network bandwidth and transmission speed are solved, and the realization of real-time monitoring in the cabin becomes possible. The real-time monitoring inside the engine room can be used to monitor the working state of the components inside the engine room. The combination of real-time monitoring images and operating parameters helps operators to better monitor the operation of equipment. In the daily maintenance, it is possible to supervise the standardized operation of field operators through real-time monitoring of images, and provide corresponding remote guidance.

6. Conclusion

The operation and maintenance mode of offshore wind power is developing towards digitalization, intelligence and precision. The intelligent operation and maintenance of offshore wind power aims to reduce the operation and maintenance cost and improve the power generation efficiency in the whole life cycle of the project. This paper introduces the current offshore wind power monitoring and operation and maintenance technology, builds a smart operation and maintenance management platform for wind farms in far-reaching sea areas, and draws the following conclusions:

1. The improvement of far-reaching maritime maintenance modes and equipment capacity will be the focus of the next phase of wind power operation and maintenance, and more far-reaching maritime maintenance modes and equipment will emerge to maximize operational efficiency.
2. In terms of operation and maintenance equipment, the rational use of operation and maintenance ships, operation and maintenance platforms, wave compensation trestles and intelligent operation and maintenance robots can achieve cost reduction and efficiency of offshore wind power operation and maintenance and improve the development capacity and level of wind power industry.
3. Building intelligent offshore wind farms and realizing intelligent monitoring and management of offshore wind farms are of great significance to improve the automation level and operation and maintenance efficiency of wind farms, reduce operation and maintenance costs, improve the economic and social benefits of offshore wind farms and improve the ability to resist risks.
4. 7Offshore wind farms have a wide range of operations, fewer personnel and poor natural environment. The intelligent operation and maintenance technology of offshore wind farms based on 5G and other technologies can reduce the operation intensity of operation and maintenance personnel of wind farms, improve the safety and reliability of equipment, effectively improve the management efficiency and management level of wind farms, and realize the digitization of operation and maintenance experience, which is an effective technical path to improve the core competitiveness of offshore wind power projects.

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